



CONSTRUCTION 4.0

ADVANCED TECHNOLOGY, TOOLS AND MATERIALS
FOR THE DIGITAL TRANSFORMATION
OF THE CONSTRUCTION INDUSTRY

Construction 4.0

Advanced Technology, Tools and Materials for the Digital Transformation of the Construction Industry

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Construction 4.0

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the Digital Transformation of the Construction
Industry

Marco Casini



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About the author

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He is an environmental engineer with a PhD in environmental engineering and is associate professor in Technology of Architecture at Sapienza University of Rome where, since 2002, he has been teaching in several master's degrees, PhD, and graduate schools on subjects pertaining to energy and environmental sustainability for buildings. Since 2014 he is also professor at the Italian National School of Administration (SNA)—Presidency of the Council of Ministers.

He is a member of the Scientific Committee of the master's degrees in "Building Information Modeling", in "Digital Twin and Artificial Intelligence" and in "Management of Heritage Real Estate," member of the Teaching Council of the PhD in Planning, Design, and Technology of Architecture, and member of the Technical-Scientific Committee on Sustainability of Sapienza University of Rome. He also has been the Director of the Sapienza International Summer School "BIM and GIS for digital integrated design" and faculty advisor and project manager of Team Sapienza participating in Solar Decathlon Middle East 2018.

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Introduction

At the beginning of the fourth Industrial revolution, the advent of digitalization, innovative technologies and materials, and new construction techniques, have begun transforming the way that infrastructure, real estate and other built assets can be designed, constructed and operated in order to create a more attractive, energy efficient, comfortable, affordable, safe, and sustainable built environment. Developments in artificial intelligence (AI), robotics, nanotechnology, 3D printing and biotechnology, have finally started to move the construction industry—traditionally reluctant to innovation and slow in adopting new technologies—towards a new era. Massive changes are occurring because of the possibilities created by big data and the Internet of Things (IoT), along with the technological advances which are driving down the cost of sensors, data storage and computer services.

From lifecycle building information modeling (BIM), generative design, extended reality and drones usage, smart and innovative building materials, techniques and technologies, to standardized, modularized, or prefabricated products and components, and on-site fully autonomous robotic 3D printing, up to AI and machine learning, there are more and more successful cases showing the potential of a transformation of the construction industry in order to increase its productivity and, at the same time, to address emergent global challenges such as resource shortage, climate change and increase of global population.

Similarly to what happened starting from 2014 in the manufacturing industry with the Industry 4.0 paradigm, a new revolutionary approach to the building process, so-called Construction 4.0 (C4.0), can exploit the new possibilities offered by the digital revolution, bringing significant opportunities for the whole value chain, from the early design stage to the very end of an asset's life cycle, giving rise to a new era for the industry characterized by a new set of connected capabilities.

This transformation is important both for the productivity of the sector—that has remained stagnant over the last 80 years, growing at a much slower rate than the manufacturing sector and the industry—and for the positive effects that this would have on the economy, on the environment, and on the whole society.

The construction industry has in fact a relevant significance in the global economy, as it employs millions of people and contributes massively to the GDP of individual nations and the world at large. With its broader ecosystem, it is responsible of the buildings, infrastructure, and industrial structures on which all economies and people's daily lives are founded. Indeed, all businesses rely on the construction industry to provide and maintain their accommodation, plants, and infrastructure, determining where and how everyone gets to live, work, and use any service. Therefore, the built environment heavily influences quality of life of nearly the entire population of the world. At the same time, the construction sector is also the largest global consumer of raw materials and primary energy, with a 40% share, and the built environment accounts for 40% of the world's total carbon dioxide emissions from related fuel combustion. The challenge of climate change and the need for a new circular economy model require materials manufacturing, construction processes and built assets that are more efficient in the use of resources and with less impact on the environment in terms of emissions and waste. The industry must also address the growing concerns over natural hazards (flooding, hurricanes, and earthquakes), and enhance the resilience of buildings and cities. Worldwide, the growing demand is for green buildings that are perfectly integrated into the surrounding environment, have efficient energy and resource consumption, use environmentally friendly materials and renewable energies, favor recycling and reuse, offer improved indoor comfort and air quality. These shall demonstrate environmental awareness in design, construction, and operation, by ensuring adaptability, resilience, recyclability of materials at the end of life, lower operating costs as well as increased asset value. Traditional practices must adapt quickly to this growing demand for environmentally sensitive construction. These challenges require new approaches and consideration to closed-loop circular design and construction principles, and are already causing substantial changes throughout the AECO sector regarding materials, technologies, methods, techniques, work tools and skills required. Moreover, the new, unprecedented needs required by the COVID-19 emergency have rapidly changed safety codes and rules of the built environment (concerning routes, spaces, air filters, standards), life and work models (social distancing, remote working), market demand for the various building

types (office spaces, remote education, health care, distribution of local facilities, etc.) and the need for new digital infrastructures. At the same time, construction companies had to quickly adapt to the new rules and methods of work imposed on the construction site for safety (e.g., how many workers can be on a site and how physically close they can work, or health and stress management issues), which require wider adoption of new connected technology (including smart wearables), remote collaboration solutions and digital workflows. In 2020, the rate of construction tech adoption reached in a single year what normally would have occurred in a 3-year span, with positive effects on productivity, pruning of inefficiencies, attraction of younger workers, and safer jobsites.

In this scenario, the C4.0 framework represents a “new operating model” based on a more efficient and effective way of working that, having data at the heart of business, aims to create more sustainable buildings over their entire life cycle. C4.0 is characterized by a holistic approach that, following the principle of “Life cycle thinking”, takes into account the environmental, social, and economic impacts of choices and actions along the entire life cycle of the building: from site identification, to construction, operation, until the final decommission and recovery or reuse of materials. The digital revolution of C4.0 can radically improve the whole construction value chain in terms of better performance at the company and project level, improved sustainability of the industry, cost savings, reduced time and delays of the whole construction process, enhanced safety, improved capital management and funding, and improved image of the construction industry. This evolution in turn allows to optimize building performance, cost-effectiveness, employee satisfaction and productivity, bringing substantial value across the industry and greater alignment among stakeholders, and resulting in greater profitability, enhanced project success, higher-quality built environment, and more empowered people. The C4.0 framework is founded on an integrated multidimensional design, construction, and operation process, based on a confluence of trends and technologies regarding data acquisition, digital information and analysis, construction automation and advanced materials and products, that bring the virtual and physical worlds together to create a truly networked world in which intelligent objects communicate and interact with each other.

The start of this revolution was made possible by an extraordinary triple convergence of factors: the first is the urgent needs of the sector to increase its productivity, reduce safety risks and address the labor shortage issues; the second is the emergence of the new world megatrends of sustainability, demographic trends, increasingly digital connectivity, and global health issues; the third is the growing and concomitant development in the last 10 years of several key enabling technologies, such as, in particular, Building information modeling, Cloud and edge computing, IoT, 5G network, AI and Machine learning, Big Data and advanced analytics, and Nanotechnology. These in turn kickstarted the diffusion of numerous other advanced—and still advancing—technologies, which are strongly interconnected and are driving the capabilities for much more efficient construction at scale: Additive manufacturing, 3D mapping and scanning, Autonomous and teleoperated vehicles, Blockchain, Building Automation Systems, Energy storage, Digital twin, Exoskeletons, Extended Reality (VR/AR/MR), Generative design, Geographic Information System (GIS), HD survey systems, Parametric design, Robots in construction, Smart meters and smart grids, Drones, Wearable technology.

Individually, each of these already has the potential to drastically change one or more aspects of the industry. Collectively, the interaction between these technologies can evolve the whole sector to a whole new level and fundamentally disrupt the very way in which buildings and infrastructure assets are designed, built, and operated, substantially improving the productivity, competitiveness, and efficiency in the use of resources over the entire value chain.

At the heart of this transformation towards a 4.0 model is the possibility to match the building life cycle with a “digital twin building life cycle” capable of interacting in a bi-directional way with the real world. More generally, C4.0 leverages the pervasive digitalization of the whole building process to bridge the operative gap that still separates the virtual and physical instances of the built environment.

C4.0 allows to anticipate the physical construction of the building with a perfect digital replica, containing both geometric data and technical parameters and information (building information model) with which to simulate and optimize performance, environmental impacts and construction costs, plan the sequence of construction and give input to the manufacturing of components or to the automation of on-site activities (3D printing, robots, autonomous vehicles, etc.). During construction, progress can be monitored and compared with respect to digital planning and perform trend analysis, risk prediction, corrections, optimizations, etc. IoT and technologies for the digital connection of construction machines, equipment, materials, and employees, can monitor in a continuous and integrated way productivity and reliability of both personnel and resources (connected construction sites). Digital fabrication and digital supply chain management support the implementation of the physical artifact, while machine-readable data supports the increasing practice of off-site construction. Robotic machines are able to turn digital design data directly into physical action, autonomously and safely.

After project delivery and handover, the constructed building can be monitored through the collection of its operational data to optimize its management and maintenance with predictive analyses, and advanced analytics. The integration of

sensing technologies in the physical world produces accurate data, both historical and real-time, which feeds realistic and accurate virtual models that can be freely analyzed and configured, knowing that each informed decision made in the virtual world will be valid, and automatically implemented, in the real world in turn. Thanks to AI and machine learning, all the enormous amount of data collected both in the construction and management phase of the building can be easily analyzed to identify patterns within, which can be used to create a data model to make predictions and support decision making along the whole value chain (predictive maintenance, risk analyses, management and resource optimization, costs prediction, etc.). Results of the data analysis can then serve as input for the design of new buildings, closing the information loop according to a circular model oriented towards continuous improvement.

Along with design and construction process, the diffusion of digitalization and innovative technologies and systems have begun transforming the way that infrastructure, real estate and other built assets can be operated and maintained in order to provide a more comfortable, energy efficient, sustainable and cost-effective built environment. AI, Big Data, and the IoT, along with the technological advances which are driving down the cost of sensors, data storage and computer services, have created unprecedented possibilities in these disciplines. Buildings and cities are getting smarter and more connected, and the digital and physical worlds are becoming deeply interconnected and interrelated, allowing to dramatically improve user experience. The ongoing technological and digital revolution allows buildings to become intelligent, connected to the global network and able to receive, process and take advantage of data and information, to communicate with their users and, in turn, to share their infrastructure with that of the smart city. The integration of the building's smart systems with the city's provides a more intelligent urban system, enabling data-driven, real-time decisions at both levels, such as, for example, intelligent energy management considering the relationship between availability and demand of energy and times of higher and lower consumption at both levels.

From what has been said, it is quite clear that in order for the transformation of the AECO sector to the C4.0 framework to take place quickly and widely and to fully deliver its benefits, it is necessary that all enterprises have access to qualified workforce. Indeed, a more resilient and sustainable industry is driven by how these technologies are used, therefore requiring a substantial investment in attracting and training a smart, educated, and diverse workforce as well as strategic leaders who work collaboratively with clients and partners for mutual success.

Concerning construction companies, lack of skilled workers has always been a main issue, partly due to the unappealing image of the construction sector. Compared to many other industries, in fact, the construction sector has traditionally been slow at technological development and has undergone no major disruptive changes in the last decades. Furthermore, jobs are often associated with long hours, harsh working conditions, and low salaries. As a result, companies struggle to recruit skilled workforce, as the sector is often not seen as a potential destination for (young) qualified individuals, in particular those studying ICT, who tend to prefer other sectors with a more innovative and dynamic image.

Transformation to C4.0 can happen only if construction companies are able to attract, develop and retain skilled and qualified talents. More specifically, tomorrow's construction workforce should master ICT, digital communication, data process, and digital content creation, should be able to communicate and work in digital environments, and should be familiar with the concept of data protection and with safely managing sensitive data. At the same time, the shift from exclusively manual labor, which is typically male-dominated, to new technology-enabled ways of working could mean increased interest from women. As construction needs to diversify its sources of talent to attract the best people, a higher female participation is a large opportunity, especially in emerging markets where male domination is even more pronounced.

Regarding Architecture and Engineering firms, there is little doubt that the current way of designing architecture, which has already significantly changed in the last 10 years, is destined to evolve even more profoundly following the new demands of contemporary society and the new innovative digital tools available, that were unthinkable only up to a few years ago. Technology has substantially changed both the way designers work and the products delivered to clients during a project's lifecycle, changing also career opportunities in the profession. C4.0 revolution inevitably requires new and important skills from the designers concerning both the physics of the building, the new materials and the circular economy, as well as the use of digital tools with particular reference to the more innovative ones such as parametric and generative design, VR/AR and digital twins. In addition to technical skills, the capacity to adopt new digital ways of working is also required, for instance moving from linear to iterative design processes in short test-and-refine loops. The requested change should come as no surprise as it reflects the fact that architecture is a frontier art that closely mirrors society and is contaminated by other disciplines, and architects are tasked with continually redesigning themselves as well. It is a trade poised between art and science that necessarily uses the tools and materials of its time to express, in spatial and technical terms, the will of the current era.

The goal of this book is to provide readers with a state-of-the-art review of the ongoing digital transformation of the AECO industry within the new 4.0 framework, presenting a thorough investigation of the emerging trends, technologies and strategies in the fields of smart building design, construction and operation and providing a comprehensive guideline on how to exploit the new possibilities offered by the digital revolution.

The book is divided into four main parts.

In Part I, *Challenges and opportunities for a new construction industry*, after a wide analysis of the regulatory, environmental, social and economic framework that affects the construction sector, the book provides an overview of the C4.0 framework, illustrating the new holistic design approach and the strategies, tools and methods necessary to face the new challenges of the 21st century architecture. It shows the new opportunities and benefits offered by the new digital technologies for the whole AECO value chain and how these are giving rise to a new era for the industry.

Chapter 1, *Toward a New Building Era*, provides an introduction to the C4.0 framework and its main components, illustrating how the advent of digitalization, innovative technologies and materials, and new construction techniques, can transform the way that infrastructure, real estate and other built assets can be designed, constructed and operated in order to create a more attractive, energy efficient, comfortable, affordable, safe, and sustainable built environment. After an overview on the economic and societal relevance of the construction industry, the chapter focuses on its current labor productivity and safety issues, along with the new megatrends that are affecting the AECO sector in the third millennium. Energy and environmental impacts of buildings and cities are investigated illustrating the main strategies and policies to promote a more sustainable built environment and a new circular economy model for construction. An in depth presentation of the emerging paradigms of Zero Energy Building, Green Building, and Smart Building is also given, highlighting their main characteristics, performances and design strategies. Finally, the new revolutionary approach to the building process, so-called C4.0, is presented, showing the new opportunities and benefits offered by the new digital technologies for the whole AECO value chain and how these are giving rise to a new era for the industry, to increase its productivity and, at the same time, to address emergent global challenges such as resource shortage, climate change and increase of global population.

Chapter 2, *Holistic Building Design Approach*, provides an overview on the new holistic design approach necessary to face the new challenges of the 21st century architecture, illustrating the methods, strategies and tools to consider the environmental, social and economic impacts of design choices along the entire AECO value chain. Life cycle design principles in architecture are addressed, describing building life cycle design and building life cycle costing strategies and objectives. Climate and context adaptive design goals, tools and methods are investigated focusing on the context and climate analysis phases and on the new, strategic targets for building operational performance that concern functionality, well-being, efficiency and quality, including the emerging objectives of adaptability, smart readiness, resilience to climate change, and safe human interaction in response to global health issues. A thorough review of the main design strategies for the maximum environmental, social and economic sustainability of the built environment is also given, focusing on the optimization and on the best harmonization with the context of building geometry, envelope, systems and renewable energy sources. Finally, for a lower impact of the built environment, design for construction and deconstruction strategies are addressed.

Chapter 3, *Building Digital Revolution*, provides an overview of the digital revolution that is changing the AECO industry and leading to the C4.0 model, based on augmented digital design, connected and automated construction processes and smart building operations and maintenance. The key technology drivers—including building information modeling, cloud and edge computing, IoT, 5G networks, AI and machine learning, Big Data and advanced analytics, and nanotechnology—are described, highlighting their role in the digital transformation of the construction sector and the new opportunities brought in terms of higher productivity and building quality. A thorough analysis of C4.0 tools and methods is given, describing the applications and advantages in the whole value chain of the new “digital twin building life cycle” achievable with the full integration of all these digital technologies.

In Part II, *Building modeling and advanced digital design tools*, devoted to the digital innovation in the programming and design phase, the book presents the most advanced tools and methods to support the design activity—BIM, building performance simulations (BPS), HD surveys, parametric design, generative design, extended reality, digital fabrication—illustrating their main applications and advantages for the design process and its beneficial effects on the whole construction value chain.

Chapter 4, *Building Information Modeling*, focuses on the role of BIM in the digital transformation of the AECO sector, describing the methods, tools, and processes for its full integration in the construction industry. Technological basics of BIM and computational methods for the geometric and semantic modeling of buildings are discussed. Level of development of the building information model and BIM multidimensional applications are investigated. Main BIM software tools are described and the main applications of BIM along the value chain are presented along with its

interaction with the other digital disruptive technologies. BIM processes, workflow, skills and collaborative practices are summarized. Finally, the maturity levels of BIM, up to BIM Level 3, are discussed focusing on current issues pertaining standardization and interoperability.

Chapter 5, Building Performance Simulation Tools, provides an overview of the use of building performance simulation (BPS) along the whole building process, illustrating basic principles, metrics, applications and main software tools. Early-stage simulation, systems sizing, life cycle analysis, code compliance, traffic and pedestrian simulation, along with building energy prediction in the operational phase, are investigated. The chapter also faces the issues of BPS data and accuracy, focusing on the innovative application of occupant behavior and weather models to better align the simulated results with the performance measured in the real conditions of use. An overview of the integration of BPS with BIM is also given, showing the advantages of parametric design in building simulation process to quickly compare and evaluate numerous potential solutions. Finally, future trends on BPS regarding the development of statistical and machine learning algorithm-based tools to predict the future behavior of buildings in the first stages of design are also described.

Chapter 6, Advanced Digital Design Tools and Methods, provides an overview of the most advanced digital tools and methods to support the design activity, illustrating their main applications and advantages for the design process and its beneficial effects on the following construction and operational phases. An in depth description of advanced survey systems and techniques is given, focusing on innovative data acquisition technologies such as aerial mapping, Geographic Information Systems (GIS), 3D photo reconstruction and LiDAR scanning for virtual migration of physical structures. New possibilities for enhanced design exploration and visualization through real time 3D rendering and extended reality (VR, AR and MR) are investigated, describing main applications, technologies and software tools. An in depth analysis of new possibilities offered by design automation, parametric design and generative design is given, illustrating applications, methods and software tools and their integration with building information modeling. Finally, an overview on design for digital fabrication methods is provided, showing the advantages in terms of higher geometrical complexity, precise material processing, and improved control of quality, time and costs.

In Part III, *Advanced materials, technologies, and building construction methods*, devoted to the digital innovation in the construction phase, the book presents a thorough review of the most advanced construction materials, building construction methods and techniques and site management tools for a new connected and automated construction model able to boost productivity, streamline operations and enhance quality and safety of works, and to improve energy and environmental efficiency of the built environment.

Chapter 7, Advanced Construction Materials, provides an overview on the most advanced construction materials available today on the market able to substantially increase the productivity of the sector, to ensure more safe and comfortable buildings, and to improve energy and environmental efficiency of the built environment. After a review on nanomaterials, smart materials and bio-based materials for architecture, an in depth presentation of some of the most innovative building products is given, illustrating their properties, their main applications, their role in digital fabrication and the benefits achieved along the entire building process. Advanced products treated in this chapter include: advanced concrete, engineered mass timber, high performance insulators, dynamic windows, smart coatings, and mimetic photovoltaics.

Chapter 8, Advanced Building Construction Methods, focuses on the emerging advanced building construction methods and techniques, oriented to improving quality, safety, and productivity of the construction industry. New advancements in prefabrication and modular construction, off-site and on-site construction automation, robotics, and additive manufacturing in construction are illustrated providing a review of the emerging trends, technologies and strategies, and showing current barriers, challenges and opportunities for their wider adoption in the building industry. Single task robots, biomorphic robots, exoskeletons, autonomous vehicles, and robotic on-site factories are investigated showing their main applications in construction. A holistic overview of different additive manufacturing processes, technologies and materials for the construction industry is given, which includes some of the 3D-printed demonstration projects at the building scale completed to date. Current status of technology, limitations, and advantages with reference to materials, systems, and construction processes are explained.

Chapter 9, Advanced Site Management Tools and Methods, focuses on advanced site management tools for a new connected construction model able to boost productivity, streamline operations and enhance safety and quality of works. New cloud-based construction management software are illustrated focusing on their integration with the BIM model for virtual design and construction (4D BIM and 5D BIM) and with AI for risk assessment and predictive analysis, and management and schedule optimization. The use of drones in construction is thoroughly investigated illustrating their main applications and advantages in project management. IoT and technologies for the digital connection of construction machines, equipment, materials, and employees, are presented, describing how these can monitor in a continuous

and integrated way productivity and reliability of both personnel and resources (connected construction sites). Wearable devices such as helmets, jackets or boots are also shown. The use of VR, AR, and MR in construction is described in detail, showing the advantages for site planning, design verification and training. Finally, recent advancements in digital twins of the construction site and in the use of blockchain for smart contracts are also addressed.

Finally, Part IV, *Smart building operation and management*, devoted to the operational and maintenance phase of buildings, provides an in-depth analysis on how digitalization and innovative technologies and systems can transform the way that infrastructure, real estate and other built assets can be operated and maintained in order to provide a more comfortable, energy efficient, sustainable, cost-effective, and smart built environment.

Chapter 10, Building Automation Systems, focuses on the deployment of advanced automation systems to make buildings and homes smarter. After an overview of the architecture, components and services of building automation systems (BAS), their topology, connected services, control strategies and advanced human interfaces are described in depth. The role of IoT for smart buildings is investigated and main connectible services (energy, HVAC, lighting, water, facades) are illustrated, showing applications and advantages for operation, costs and energy saving and indoor comfort. Within BAS, particular attention is given to the new, AI-empowered advanced control strategies based on Model Predictive Control (MPC) and reinforced learning. Finally, home automation is investigated, describing Smart home technologies and services up to the new concept of connected home.

Chapter 11, Advanced Facility Management, illustrates the most advanced building facility management tools and methods, focusing on facility operation & maintenance (O&M) activities. After an overview on main building maintenance policies and strategies, the chapter describes computer aided facilities management software (CAFM) for planning, managing, reporting and tracking maintenance operations with particular reference to their integration with BIM (FM-enabled BIM), illustrating applications and advantages. The use of IoT and machine learning is investigated, illustrating the new concept of building predictive maintenance for early fault detection, fault identification, health assessment of equipment, as well as to predict accurately the future state of systems. Applications of extended reality (VR, AR, and MR) technology in building and systems maintenance are described, showing advantages in supporting technical maintenance tasks, as well as improving the management of maintenance operations and supporting strategic decision making. Finally, the new Digital twin technology, which promises to revolutionize the way buildings are managed and maintained, is investigated.

Chapter 12, Smart Buildings and Smart Cities, investigates the AECO digital transformation at the urban scale, focusing on smart cities (SCs) and smart energy buildings. The SC concept is deeply illustrated focusing on the pivotal role of AI and urban Big data in enhancing different SC services and in helping decision makers plan for any improvement. Within the SC model, the innovative use of Digital twin is investigated showing its potential to transform urban landscapes and to address climate change issues improving the resilience of cities. In the path towards a net zero carbon future, the transformation of the energy system through smart energy infrastructure is thoroughly illustrated, describing technologies and strategies for a clean electrification of transport and building services and a full integration of e-mobility and renewable energies. At the urban scale, smart grids, smart meters, and microgrid technologies are described, also illustrating the role of green hydrogen in decarbonization. Finally, at the building scale, integration of renewable energies, electric storage, vehicle-to-building (V2B), and demand response technologies are investigated.

Part I

Challenges and opportunities for a new construction industry

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Toward a new building era

1.1 Construction industry: economic and societal relevance

The construction sector is a key pillar of the global economy, as it accounted for 13% of global GDP in 2018, with a global turnover of \$10 trillion, estimated to rise to \$12.9 trillion by 2022 and \$14 trillion by 2025, and an added value of \$3.6 trillion. It currently employs 7% of the world's working population, equal to 180 million people (Ecorys, 2016; FIEC, 2020; IFC, 2018; McKinsey, 2017a; McKinsey, 2020a; WEF, 2016).

The construction industry's value chain is very extensive and includes service businesses, suppliers and contractors across seven segments: development, construction and engineering, construction machinery, basic materials, finishing components, mayor systems equipment, and maintenance (see Table 1.1) (McKinsey, 2020a). The construction industry, with its broader ecosystem, is responsible of all the buildings, infrastructure, and industrial structures on which all economies and people's daily lives are founded. Indeed, all businesses rely on the construction industry to provide and maintain their accommodation, plants and infrastructure, determining where and how everyone gets to live, work, and use any service. Therefore, the built environment heavily influences quality of life of nearly the entire population of the world. The construction sector is also the largest global consumer of raw materials and primary energy, with a 40% share, and the built environment accounts for 40% of the world's total carbon dioxide emissions from related fuel combustion (IEA, 2019a; McKinsey, 2017a; UNEP, 2020a; WEF, 2016).

TABLE 1.1 Construction and building technology value chain (McKinsey, 2020a).

Sectors	Products and services
Development	• Real estate advisory and development • Real estate investment trusts • Building operators and lessors
Construction and engineering	• Construction and engineering • Specialty contracting
Construction machinery	• Earthmoving equipment • Material-handling equipment • Concrete and road construction machinery
Basic materials	• Cement, concrete, aggregates • Steel, including bars and pipes • Timber, plywood, glass, clay, and others
Finishing components	• Building envelope • Building interior • Supporting materials
Mayor systems equipment	• Power equipment • Plumbing • Building automation systems • Cooling and heating equipment • Lighting • Fire and security • Elevators and escalators
Maintenance	• Facility management • Energy management

1.1.1 Labor productivity and safety

Despite its global importance, productivity of the construction workforce has grown only 1% per year over the past two decades, much less than the 2.8% growth of the total world economy and then the 3.6% increase in productivity in the manufacturing industry (see Fig. 1.1) (McKinsey, 2017a; WEF, 2016). In construction, overall earnings before interest and taxes (EBIT) are only around 5%, despite the presence of significant risk in the industry, and time and cost overruns are the norm with just a quarter of construction projects in the last three years coming within 10% of their original deadlines (McKinsey, 2020a).

Other productivity barriers are due to lack of information and communication in the industry, causing up to 30% of the work performed by construction companies being actually corrective rework and 35% of construction professionals' time (over 14 hour/week) being spent on nonproductive activities including looking for project information, conflict resolution and dealing with mistakes and rework (Autodesk, 2021a). The industry's productivity challenges cut across all geographies and economies. If productivity of construction could reach the values of other economic sectors, the industry's value added could rise by \$1.6 trillion a year, enough to meet about half of the world's annual infrastructure needs or to boost global GDP by 2% (McKinsey, 2020a).

This low productivity is due to a combination of factors, some linked to the nature and characteristics of the building process, others linked to the characteristics and dynamics of the industry, others due to the behavior of companies in the sector, others linked to forces of external origin (McKinsey, 2017a; WEF, 2016).

Compared to other industrial processes, the construction process itself is characterized by complexities of a much different nature and order. A multiplicity of figures are involved in a contemporary and independent way in the process; activities of both industrial and artisanal nature, which require different quality control criteria, must coexist and collaborate; every single product is closely interdependent from the others, from its installation and from the related services, making it difficult to assess performance contributions and subtractions at the end of the construction process; each final product of a construction process is uniquely linked to specific production and contextual conditions, making the quality controls traditionally used for serial production inapplicable. Furthermore, construction works take place in a range of climates and geographies, on sites exposed to unpredictable conditions, including geological and topographical complexities and prevailing weather patterns. Construction sites change and grow as they progress, for example, a site may move for miles over the course of infrastructure works. Every construction project initially requires the creation of an entirely new workspace from scratch, in which different types of trades share the same area, making workflow planning more challenging. Contractors usually work on constrained, often occupied spaces where unexpected complications are the norm and where it is hard to work at scale and with a high degree of standardization. Interventions in dense urban environments have constraints on standard working hours because of the need to avoid noise nuisance and traffic disruption. Small lot sizes do not allow projects to be staged effectively in terms of storage and equipment, and transporting materials to the site often presents challenges. Each structure is typically built to highly specific owner requirements, while mass customization is often sufficient in industrial manufacturing. Moreover, in the building production process corrective actions are less effective than those that can be carried out in other industrial production sectors, so the quality of the work is strongly conditioned by the choices made in the preliminary stages.

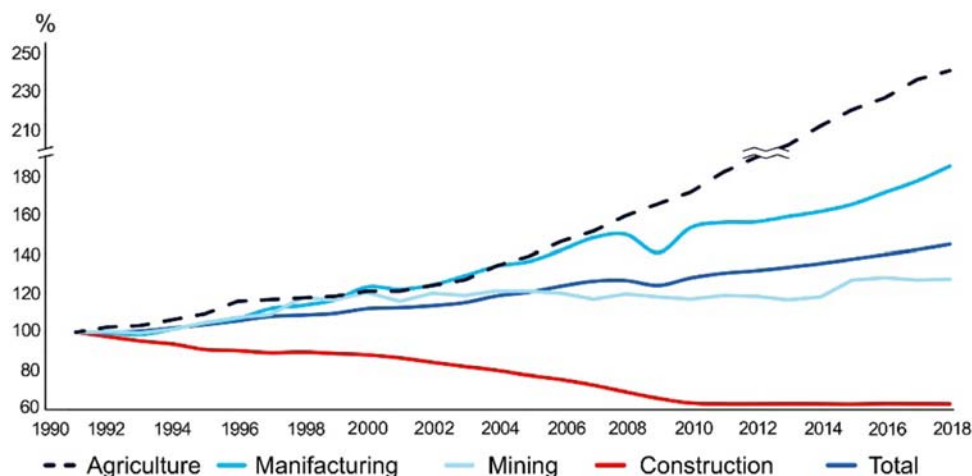


FIGURE 1.1 Productivity of different industry sectors. Redrawn from (McKinsey, 2020a).

As regards the characteristics of the sector, the construction industry is highly fragmented and mostly consists in a plethora of small- and medium-size enterprises (SME). This not only prevents players from attaining the size they need to achieve scale benefits leading to higher productivity, but also hinders coordination among different players, each with their own vested interests, making it harder to deliver a project on time and on budget. Such fragmentation also implies substantial information asymmetries among different players. One reason for this limit is that projects tend to be geographically dispersed and have bespoke requirements, which tends to compromise transparency on project costs or performance of contractors.

In Europe, firms with more than 250 employees (the upper limit considered in SME definition) account for less than 1% of all construction companies and contribute 21% to the sector's output, while 94% of firms have fewer than 10 full-time equivalent employees (micro enterprises) and contribute 39% to the total output of the sector (FIEC, 2020).

In the United States, among the 700,000 registered construction companies 80% have just 10 workers or fewer and only 2% have more than 100 employees. The top four firms in the United States construction sector control just 6% of the market, much lower than more centralized sectors such as retail (14%) and petrochemical refining (42%). Fragmentation is even more pronounced considering the top 20 firms, which account for only 8% of the market, compared with 18% and 94% in retail and petrochemicals, respectively (Autodesk, 2021b; BigRentz, 2020; BigRentz, 2021; McKinsey, 2017a).

In short, the construction industry is dominated by small, trade-based firms and subcontractors, often relatively unsophisticated, with few firms large enough to invest in R&D to pioneer and lead major innovations, and a general lack of competitive pressure. Small firms are often comfortable quietly going about their business in their local area instead of investing in expansion and diversification. This fragmentation has a significant impact on productivity also within the different construction works: smaller specialty trade segments and remodelers are the most highly fragmented and have the lowest productivity, whereas the construction of oil and gas pipelines is both highly consolidated and highly productive.

Moreover, factors such as fragmentation, geographical dispersion and uniqueness of each project also contribute to the industry being very opaque. In most countries and sectors, it is nearly impossible to find good benchmarking data on project cost or performance of contractors. In particular, small- and medium-sized clients often have to settle for a local firm based on word of mouth or professional recommendation, as expertise, pricing, and techniques are difficult to compare with those of their competitors. This further disincentivizes companies to improve their productivity as a source of competitive advantage.

In addition to these difficulties, the structure of contracts is one of the highest barriers to greater productivity in the construction industry. In fact, procurement criteria by public and private owners are usually misguided and focus on reducing initially offered prices and offloading risk. Combined with corruption or inexperience among buyers, this has encouraged an environment of misaligned contractual and incentive structures. If tendering is solely focused on cost, contractors tend toward incorrect behaviors, such as knowingly submitting bids that may not be feasible and may require costly rework, or toward overly risk-averse approaches in which the safest solution are played even when potentially game-changing innovations may be available. Conversely, contracts often fail to give adequate consideration to the inherent uncertainty of construction projects. This lack of flexibility severely limits risk taking, including trying new productivity techniques and materials. Finally, current contracting structures such as lump-sum and cost-reimbursable contracts do not share risk effectively, apportioning the majority of financial risk to a single party. This way, a concerted team effort to improve productivity and the project outcome will be more difficult, and the party holding the risk will tend to favor more conservative approaches over innovation.

The sector is also characterized by insufficiently skilled labor at both frontline and supervisory levels, leading to a mismatch between the demands of the construction sector and the capabilities of the available workforce. Around the world, the labor pool in the construction sector is mostly low- and medium-skilled, which makes implementing the changes necessary for achieving significant productivity improvements more challenging unless moving to full automation. This is due to the chronic lack of vocational and on-the-job training in the sector that would move workers from the low- to medium-skill category, which is exacerbated by the fact that only 23% of construction employees have graduated from secondary school, the lowest value of any job (McKinsey, 2017a). In Europe, construction is in last place for provision of continuous vocational training hours, at 5 hours/1000 worked, less than half of that of ICT and finance sectors (11 hours/1000) (McKinsey, 2017a). Skilled people are insufficient at the project-manager level as well: construction company owners are the least likely of any sector to have a technical or college degree, at 31% in the United States (McKinsey, 2017a).

The industry's skills problem is worsened by the progressive aging of the construction workforce, which hinders the adoption of more productive digital and other innovative construction techniques. The sector's share of employees over

45 years old increased from 32% to 50% between 1985 and 2010, leading to a workforce less likely to be receptive to the training necessary to implement the latest technology (McKinsey, 2017a). This is partly due to limited appeal of the construction industry among the latest generation of top-talent engineers and interdisciplinary managers who can run projects of substantial complexity, and they appear to prefer to use their talents elsewhere. In addition, in many countries, informal, mostly foreign-born labor makes up a significant part of the construction workforce. Informal labor may weaken incentives to invest in workers and their skills. These workers are primarily engaged in building construction, in which projects are on a smaller scale and subject to less scrutiny than civil and industrial projects. Without the same legal protections or contracts, they tend to be more transient and companies are more unlikely to provide training programs and other resources to improve their productivity.

Despite the low productivity and low-skilled workforce of the sector, in Europe wages have still typically risen, leading to a growth of unit labor costs (the amount of money paid for a unit of labor output or the increase in wages minus the increase in productivity) of 2.4% annually between 1995 and 2015, compared with 1.3% in manufacturing and only 0.3% in services (McKinsey, 2017a). A similar misalignment occurred in the United States as well: starting from the oil crisis of 1973, wages have been declining less than productivity (McKinsey, 2017a).

Nonetheless, even if the workforce were sufficiently skilled, construction companies today severely underinvest in the technology and digital tools needed to increase productivity. Spending on research and development in the construction industry is less than 1% of revenues, compared to 3.5%–4.5% for the automotive and aerospace sectors (McKinsey, 2016a). This is also true for IT spending, which accounts for less than 1% of construction revenue, although numerous new software solutions for the industry have been developed.

According to McKinsey's digitization index, construction is among the least digitized sectors in the world, coming in second to last in the United States, ahead of only agriculture, and in last position in Europe (McKinsey, 2017a). The index finds that there are particular deficiencies in the sector's ability to use digital tools to facilitate stakeholder interactions and in the rate of growth in digital tools available to the frontline labor force, as well as weak investment in ICT. In Germany, for instance, the construction sector invested in digital assets only 0.7% of its gross value added per year between 1991 and 2007, whereas financial intermediation invested 4.3%, manufacturing 1.8%, and the average of all industries was 2.3%. The same occurs the United States construction sector, where 1.5% of gross value added was invested compared with 5.7% in financial intermediation, 3.3% in manufacturing, and the all-sector average of 3.6% (McKinsey, 2017a). In fact, there is a robust correlation between the level of digitization in a sector and its productivity growth over the past 10 years, with several proven examples of companies in construction and in other sectors using digital technologies to achieve remarkable productivity gains. However, while the mining industry has embraced digital innovations to improve productivity and find new ways to manage variability, and aerospace industry productivity has risen by up to 10 times after companies adopted computer-aided 3D modeling in the 1970s, the construction industry has yet to adopt an integrated platform that spans project planning, design, construction, operations, and maintenance and still relies on bespoke software tools. In addition, project owners and contractors often use different platforms that do not sync with one another.

Examples of productivity benefits enabled by the use of digital technologies include a tunnel project in the United States that involved almost 600 vendors, in which the contractor put in place a single platform solution for bidding, tendering, and contract management. This saved the team more than 20 hours of staff time per week, cut down the time to generate reports by 75%, and sped up document transmittals by 90%. Similarly, automated workflows for reviews and approvals on a \$5 billion rail project saved more than \$110 million and greatly boosted productivity (McKinsey, 2017a).

Regarding, in turn, how business is operated in construction, processes typically adopted often lack maturity, rigor and consistency, with companies putting greater emphasis on defining the final product than on planning the actual construction process. Construction teams are often unnecessarily complex, frequently spanning multiple organizations and geographies, and collaboration between project teams and stakeholders remains problematic and introduces cost, delays, reworks, and risk to projects. Specifically, there is little knowledge transfer from project to project and past lessons are often not leveraged, with projects continuing to rely heavily on the expertise of the individual project manager. Construction projects are weakly monitored, compared to manufacturing industries in which operations are continuously tracked and large quantities of data are collected in order to quickly identify the root causes of a problem, implement remedies immediately and efficiently and perform predictive risk analysis. The conventional construction process is generally sequential, reflecting the input of the project owner, designers, constructors with little cross-functional cooperation.

Project planning often remains uncoordinated between the office and the field and is often done only on paper. Contracts do not include incentives for risk sharing and innovation; performance management is inadequate and supply chain practices are still unsophisticated.

Inadequate attention to design and engineering leads to project delays, cost overruns, and frequent change orders that directly affect the ability of a constructor to deliver a functional asset to its owner on time and on budget. Avoidable disruptions to the construction process include amendments to designs after constructability reviews; errors or omissions in the original design due to inadequate understanding of the owner's needs, drawing conflicts; reworks because of initial errors; lack of clarity among parties on a project's objectives, execution, or intended outcomes; variations of processes or plans based on a review of the design, technological advances, or value engineering.

Time and cost overruns are mainly caused by both insufficient attention to design at an early stage and the inability to execute projects effectively. Much closer attention shall be devoted to effective project management and execution of projects, as poor communication, lack of front-end loading and collaborative planning processes often lead to high levels of change orders during the life cycle of projects. This drags down productivity by forcing downtime and reworks and disrupting schedules. Transition from planning to construction is particularly delicate, as it often goes poorly and jeopardizes the entire project execution.

Furthermore, additional factors such as land fragmentation, highly varied building codes, and fragmentation among owners, contractors, and materials suppliers entail low level of standardization and require to offer different solutions to every customer, preventing economies of scale on both design and construction practices.

Finally, as regards external forces, these mainly concern extensive regulation, land fragmentation, the volatile nature of public investment, and informality and potential for corruption that may distort the market. Indeed, construction is one of the world's most highly regulated sectors: in the United States the sector is subject to seven times the number of laws directly or indirectly affecting its activities compared to agriculture or mining (McKinsey, 2017a). Some of these regulations have not been updated for decades, but it can be politically challenging to amend them. Rather than the sheer amount of regulation, the confusing and arduous bureaucratic processes through which it is administered cause delays and compromise coordination among owners, construction firms, and regulators. This uncertainty unnecessarily lengthens the time span of the project, as months can pass before approvals, and further dissuades firms from investing adequately in equipment that might not be used as planned.

In particular, building permits and approvals are the most challenging form of regulation to manage, with a global average permitting time of 160 days, with some countries requiring more than two years to navigate the process (McKinsey, 2017a). Furthermore, the process of issuing building permits is typically administered at local level—that is, by municipalities—which are often understaffed or underequipped and may display significant variations of efficiency even within the same nation or region. The adoption of streamlined building permit systems that leverage digital infrastructure is underway in several countries worldwide. Almost all EU countries have their permits system digitalized, with five (Germany, Estonia, Netherlands, Austria, and Finland) already coupling BIM with their permit systems to have a fully automated process with 3D models, and Estonia conducting preliminary analysis of AI adoption in the field of environmental permits, charges, and supervision (ECSO, 2021). Land acquisition is another area hindered by extensive regulation and processes, in addition to outdated zoning and fragmented land ownership, which makes it very difficult for developers to assemble land quickly and build on a large scale.

Moreover, as the public sector is a major purchaser of construction services, companies in the sector are vastly affected by public demand and public procurement processes, which is usually extremely strict in terms of requirements. This lack of flexibility makes it challenging for firms to adopt innovative and productivity improving approaches. Government construction works also tend to be volatile, or cyclical at best, discouraging companies from investing and retaining qualified staff.

Another important challenge that characterizes the construction sector is that of the health and safety of workers, which itself affect overall productivity and costs. Indeed, construction is one of the world's most dangerous industries, with 2.3 million deaths due to work-related accidents or diseases every year (ILO, 2019).

Construction workers account for more than 45% of all fatal work injuries annually and nonfatal injury rates are 71% higher in construction than in any other industry. One in every 10 construction workers is injured each year, and there is a 1 in 200 chance that a construction worker will die from a work-related incident over a 45-year career. In particular, about 58.6% of all on the job fatalities in construction is due to falls, electrocution, being struck by an object, and being crushed (so-called “Fatal Four” hazards). Falls alone account for 33.5% of all construction deaths (United States Bureau of Labour Statistics; Occupational safety and health administration OSHA).

Therefore, the construction industry sees a 71% higher spend on workers' compensation than all manufacturing industries combined, and accounts for 15% of overall workers' compensation costs. In 2018, work-related injuries have caused the loss of 103,000,000 production days for construction companies. This is partly due to a significant gap in the industry regarding safety training: construction companies spend on average 3.6% of their budgets on injuries, but only 2.6% on safety training. However, indirect costs for injuries in the construction industry can be as much as 17

times more than direct costs and construction companies can save up to \$6 in indirect costs for every \$1 invested in direct costs by evading an injury in the workplace (ILO, 2019).

As it turns out, safety, both physical and psychological, is fundamental to the success of construction projects and construction firms: companies with the greatest commitment to safety are also the ones with most sustainable success. This approach requires regular training, relevant safety programs, and a cultural commitment to safety at both organizational and individual levels (ECSO, 2020).

Poor training or lack thereof puts individual employees, teams, and the company itself at risk. Safety training is needed both during the on-boarding process and on a regular basis to protect workers themselves and avoid hurting others. From this point of view, extended reality (XR) and virtual reality (VR) in particular is proving very useful to allow effective and convenient safety training to workers: the immersivity provided is on par with on-field training and allows much better understanding and impression of the risks and safety procedures, without any of the expense, hazards and schedule conflicts normally associated (see Section 9.4.1). At the same time, the integration of digital and robotic technologies in the construction site can greatly reduce risks and hazards conventionally associated with construction. Prefabrication and modular construction methods allow to move fabrication and assembly activities in much safer and more comfortable factories, instead of exposed and insecure construction yards (see Section 8.1). The construction site itself can be equipped with diffused IoT sensors and wearable devices to keep track of workers' health status and prevent dangerous situations such as being run over by a truck (see Sections 9.3 and 9.5). AI and machine learning can leverage data produced on-site by sensors and cameras to detect accidents, conduct risk analysis and identify dangerous situations to be addressed on a timely and safe manner (see Section 9.6). Lastly, automation and robotization in construction allow to replace or help workers in most strenuous or dangerous activities, such as using autonomous/teleoperated robots to work in hazardous environment or exoskeletons to support manual tasks (see Section 8.2), as well as drones for inspections at heights (see Section 9.2).

1.1.2 New century megatrends for construction

The construction industry of XXI century is currently affected by four main overarching trends, that are deeply reshaping the construction and building technology sector as well as the built environment itself: sustainability, demographic trends, increasingly digital connectivity, and global health issues (WEF, 2016).

Concerning sustainability, the challenge of climate change and the need for a new circular economy (CE) model require materials manufacturing and construction processes and built assets that are more efficient in the use of resources and with less impact on the environment in terms of emissions and waste. The industry must also address the growing concerns over natural hazards (notably, flooding, hurricanes and earthquakes), and enhance resilience of buildings and cities. Therefore, there is a renewed urgency on devising risk-mitigating solutions, especially in urban areas with high population density.

From a desirable characteristic at the end of the nineties, the environmental, social and economical sustainability has become today a necessary requirement from both building codes and the market. Worldwide, the growing demand is for green buildings that are perfectly integrated into the surrounding environment, have efficient energy and resource consumption, use environmentally friendly materials and renewable energies, favor recycling and reuse, offer improved indoor comfort and air quality. These shall demonstrate environmental awareness in design, construction, and operation, by ensuring adaptability, resilience, recyclability of materials at the end of life, lower operating costs as well as increased asset value.

Available data increasingly confirm that such buildings can combine a lower environmental impact of their life cycle with healthier and more productive living and working condition for their occupants as well (UNEP, 2020a). Indeed, sustainable solutions such as better materials, improved airflow and daylighting, and the elimination of fossil fuels and harmful chemicals all contribute to a much higher appeal for building owners and developers, who will be able to pay less for energy and, at the same time, be more productive. According to the United States Green Building Council, employees in sustainable office buildings tend to be happier, healthier, and more productive than in conventional commercial structures. Coupled with the diffused pressure for Environmental, Social, and Corporate Governance (ESG) investment—that is, investors focused on environmental, social, and corporate governance that demand sustainable construction and operation plans—this has made greener projects extremely attractive for capital investment. Therefore, sustainability is becoming increasingly normalized in financial systems, with trillions of dollars of capital with sustainable requirements in play, leading to thoughtful site planning, embodied carbon, and aggressive climate benchmarks (UNEP, 2020a).

Traditional practices must adapt quickly to this growing demand for environmentally sensitive construction. These challenges require new approaches and consideration to closed-loop circular design and construction principles, and are

already causing substantial changes throughout the architecture, engineering, construction and operation (AECO) sector regarding materials, technologies, methods, techniques, work tools and skills required.

The second overarching trend concerns both the growth and the aging of the world's population. Urban dwellers, in particular, are expected to exceed 6 billion by 2045, with about 200,000 people moving to cities every day (United Nations Department of Economic and Social Affairs, 2018). This translates to an urgent need for a boost in affordable housing in urban areas, where space constraints complicate construction processes, and for infrastructure investment on services such as water supply and sanitation. Growing demand for new construction and the increasing density of existing urban centers contribute to driving up both size and complexity of projects, which in turn affect construction productivity. In this sense, the need for adaptive reuse and prefabricated/modular construction is increasing, as these solutions promise more affordability and better compatibility with sensitive contexts such as the contemporary megacities.

Another determinant demographic trend, particularly in developed countries, is the increasing age profile of population (WEF, 2016). In fact, the impact of the growing proportion of elderly people in the population on the construction industry is twofold: first, it creates a need to construct or adapt buildings to accommodate ageing and convalescent citizens; second, it reduces the available supply of a new generation of construction workers. This second issue is being partly addressed by the increasing automation and robotization in the industry, with new technologies taking over many of the tasks that formerly required low-skilled workers. Such new technologies, however, require a highly skilled workforce themselves, and the construction industry is struggling to secure the requisite digital talent.

The third overarching trend concerns the increase in digitalization and connectivity of both people and objects through the Internet of Things (IoT), which is leading to the growth in the market for building automation (building management systems, heat, ventilation and air conditioning (HVAC) controls, fire detection and controls, security systems, and lighting controls) coupled with increased expectations of end-user experiences that are more seamless and personalized, for instance optimizing workspace environments for temperature, ventilation, and lighting. The transition of the industry and economy toward a fully digital society is also directly affecting the fruition of the built environment: mobile computing, smart working and e-commerce are shifting demands and usage patterns, including occupancy levels of office spaces, volume and timing of private and public transport traffic, telecommunications infrastructure requirements, market shifts from physical stores to warehouses and fulfillment centers for home delivery.

At the same time, unprecedented levels of data, in both quantity and quality, are widely accessible for advanced analytics to gain accurate insights and knowledge on a wide range of subjects in the AECO sectors (IEA, 2019b). Occupancy levels, usage patterns, energy performance, water consumption, passenger journeys, labor and supply on the construction site, and many other data allow owners, contractors and their project partners to make better, more informed decisions about a building process to lower costs, improve existing capacity without compromising end-user experience, or enhance it with new capabilities.

Moreover, the increasing integration of IoT into the built environment and the data produced therein allows accurate prediction of future demand patterns at a granular level. Stored and analyzed, this wealth of historical data can be fed back into new projects to enable future assets to be better designed to enhance performance. By closing of the information loop, companies can open new business opportunities. Developers can leverage data on population demographics, economic growth, and wealth levels to achieve a deeper level of insight into future demand patterns and configure their asset accordingly, focusing on specific opportunities and investing with greater confidence.

This expanded potential for data analysis, furthermore, shifts traditional decision making on development and investments: as buildings become more complex and risks increase accordingly, the focus shifts on how to achieve the end outcomes rather than on mere price or value. Predicting how the proposed development will connect with other systems, physical or otherwise, will be essential to determine if the project is financially sustainable. Data analysis can help taking decisions concerning if, what, where and how to invest and build. Such improved awareness on the use of building assets and their performance across their lifecycle, should support contractors in diversified ventures such as Real-Estate-as-a-Service (ECSSO, 2021; JRC, 2019).

The fourth trend, finally, is that one triggered in 2020 by the COVID-19 world pandemic which has initiated profound changes in the real estate and construction market as well as in employment, extremely accelerating the process of digitization of society at large and the need for change in all industries, and in the construction sector in particular (McKinsey, 2020b).

The new, unprecedented needs required by the pandemic emergency have rapidly changed safety codes and rules of the built environment (concerning routes, spaces, filters, standards), life and work models (social distancing, remote working), market demand for the various building types (office spaces, remote education, health care, distribution of local facilities, etc.) and the need for new digital infrastructures (WEF, 2021a).

At the same time, construction companies had to quickly adapt to the new rules and methods of work imposed on the construction site for safety (e.g., how many workers can be on a site and how physically close they can work, or health and stress management issues), which require wider adoption of new connected technology (including smart wearables), remote collaboration solutions and digital workflows. According to JLL's State of Construction Tech report (JLL, 2020), in 2020 the rate of construction tech adoption reached in a single year what normally would have occurred in a three-year span, with positive effects on productivity, pruning of inefficiencies, attraction of younger workers, and safer jobsites.

The convergence of these four overarching trends with the pressing need of the sector to increase its productivity, reduce safety risks and address the labor shortage issues, along with the new availability of advanced materials and innovative physical and digital technologies, have finally started to move the AECO sector toward a new digital era, bringing important changes in both the value chain and the characteristics of the built environment.

1.2 Energy and environmental impact of buildings

1.2.1 State of planet: time to act

At the beginning of the third decade of the 21st century, the world is at a turning point for a transition to a more sustainable and climate responsible economy. The next decade will be decisive to act and turn the tide on climate change by reaching a zero emissions economy.

In 2020, despite the economic slowdown caused by the COVID-19 pandemic and the economic recession that is estimated to have reduced carbon emissions by about 5% respect to the previous year (IEA, 2020a), levels of the carbon dioxide in atmosphere continued to rise. The global surface average for carbon dioxide (CO_2), calculated from measurements collected at National Oceanic and Atmospheric Administration (NOAA)'s remote sampling locations, rose by 2.6 parts per million (ppm) reaching the value record of 412.5 ppm compared to 354 ppm of 1990, 310 of 1958 and values between 180 and 280 ppm in the preindustrial era (see Fig. 1.2).

This rate of increase was the fifth highest in NOAA's 63-year record, following 1987, 1998, 2015, and 2016. Since 2000, the global CO_2 average has grown by 43.5 ppm, an increase of 12% compared to a growth of 8.5% (+29 ppm) in the previous 20 years (1980–2000). Moreover, atmospheric carbon dioxide measured at NOAA's Mauna Loa Atmospheric Baseline Observatory peaked for 2021 in May at a monthly average of 419 ppm, the highest level since accurate measurements began 63 years ago. The atmospheric burden of CO_2 is now comparable to where it was during

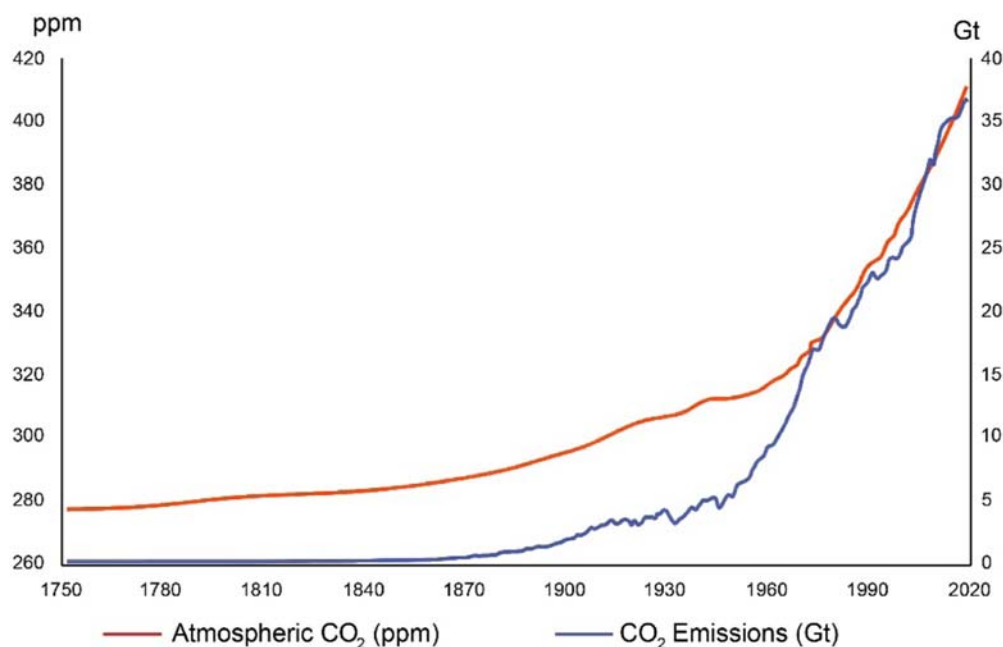


FIGURE 1.2 Carbon dioxide in atmosphere (ppm) and annual emissions in Gt (1750–2019). Redrawn from (NOAA, 2021).

the Mid-Pliocene Warm Period, around 3.6 million years ago, when concentrations of carbon dioxide ranged from about 380 to 450 ppm. During that time, sea level was about 24 m higher than today, the average temperature was 4°C higher than in preindustrial times, and studies indicate large forests occupied areas of the Arctic that are now tundra (NOAA, 2021).

The increase in CO₂ concentration in the atmosphere is due to anthropogenic emissions of carbon dioxide resulting from the use of fossil fuels which, starting from the industrial era, have been constantly increasing, reaching the value of 33.4 Gt in 2019 (38.0 Gt if we consider in addition to emissions from fuel combustion also those deriving from industrial processes and product use) (JRC, 2020a) equal to over 140% more than in 1970. From 1990 to 2019, the average annual growth rate was 2.1%.

Overall, despite major improvements in energy efficiency and the rising adoption of renewable energy sources, the combination of growth in energy demand and heavy reliance on fossil fuels have led to large increases in global CO₂ emissions.

Between the middle of the 20th century and the first decade of the 21st, global energy-related CO₂ emissions—that is, emissions from the combustion of fossil energy in transformation processes such as power generation and direct end uses—increased steadily, except during periods of major economic disruption, such as the oil crisis in 1973 and the global financial crisis in 2008–09. Although CO₂ emissions from fossil fuel combustion partially leveled off between 2014 and 2016 as a result of a sudden slowdown in coal use in Asia (largely due to energy efficiency gains) and a surge in nonhydro renewables generation worldwide, they edged up in 2017 and held steady at around 33 Gt in 2018 and 2019 (BP, 2020; IEA, 2019c; IEA, 2020b; JR2020c; IEA, 2020d; IEA, 2021a).

Coal remains by far the biggest contributor to global energy-related CO₂ emissions as it is the most carbon-intensive fossil fuel and the second-largest energy source worldwide. In 2019, coal accounted for 45% of total CO₂ emissions, followed by oil (34%) and natural gas (22%). Apart from a brief hiatus in the 2000s, the share of coal in the global energy mix has been declining in recent decades, while oil has been broadly flat and gas has been rising steadily. Indeed, coal is considered the single leading cause of global warming: CO₂ emitted from coal combustion is responsible for more than 0.3°C of the 1°C increase in global average annual surface temperatures above preindustrial levels (BP, 2020; IEA, 2019c; IEA, 2020b; JR2020c; IEA, 2020d; IEA, 2021a).

In recent years, the consumption of natural gas, which emits less CO₂ than coal and oil per unit of energy, has been rising more rapidly than coal, lowering the average carbon intensity of global energy use. Other contributions to carbon intensity of energy come from increased use of renewables, mainly in power generation in China, Europe and United States, from the continuing use of nuclear power and from diffused gains in energy efficiency. In the power sector, the global average carbon intensity of electricity generated in 2019 was 470 g of CO₂/kWh, 12% lower than in 2000. Cumulative emissions savings related to increased contribution of renewables in power generation since 2000 are estimated at 16 Gt (BP, 2020; IEA, 2019c; IEA, 2020b; IEA, 2020c; IEA, 2020d; IEA, 2021a).

Nonetheless, CO₂ emission trends vary greatly across countries and regions. In the advanced economies increases in CO₂ emissions generally have slowed since 2000 and, in some cases, started to decline due to dampening of primary energy demand, a shift to clean energy sources and gains in energy efficiency. Between 2000 and 2019, CO₂ emissions from energy dropped by 18% in Europe, 17% in the United States and 13% in Japan. By contrast, CO₂ emissions in the emerging economies have risen briskly, albeit at a slower pace in the last few years. Emissions between 2000 and 2019 tripled in China and more than doubled in other emerging economies in Asia, making them the principal driver of global CO₂ emissions growth for the past two decades, although per capita emissions remain substantially lower than levels in advanced economies. China alone contributed just under two-thirds of the increase in global emissions between 2000 and 2019: other emerging economies in Asia accounted for another 25%. China's emissions skyrocketed in the decade up to 2013—the result of an unprecedented surge in power generation capacity and industrial output, largely powered by coal. With 9.8 Gt of emissions in 2019, China accounted for 30% of global CO₂ emissions—up from just 14% in 2000. However, as the Chinese economy matures there are signs of a slowdown in emissions growth, mirroring what happened in most advanced economies in the 2000s. China's CO₂ emissions fell between 2013 and 2016 due to lower emissions from industry and the power sector, though they rebounded thereafter (BP, 2020; IEA, 2019c; IEA, 2020b; IEA, 2020c; IEA, 2020d; IEA, 2021a).

Due to the COVID-19 pandemic, in 2020 global energy demand decreased by 4% and CO₂ emissions declined by 5.8%, or almost 2 Gt CO₂, the largest ever decline and almost five times greater than the 2009 decline that followed the global financial crisis (see Fig. 1.3) (IEA, 2021a). According to data released by the International Renewable Energy Agency (IRENA, 2021a), that same year the world added a record new renewable energy capacity of more than 260 GW (+10.3%), exceeding expansion in 2019 by close to 50%. At the end of 2020, global renewable generation capacity amounted to 2799 GW. Solar energy continued to lead capacity expansion, with an increase of

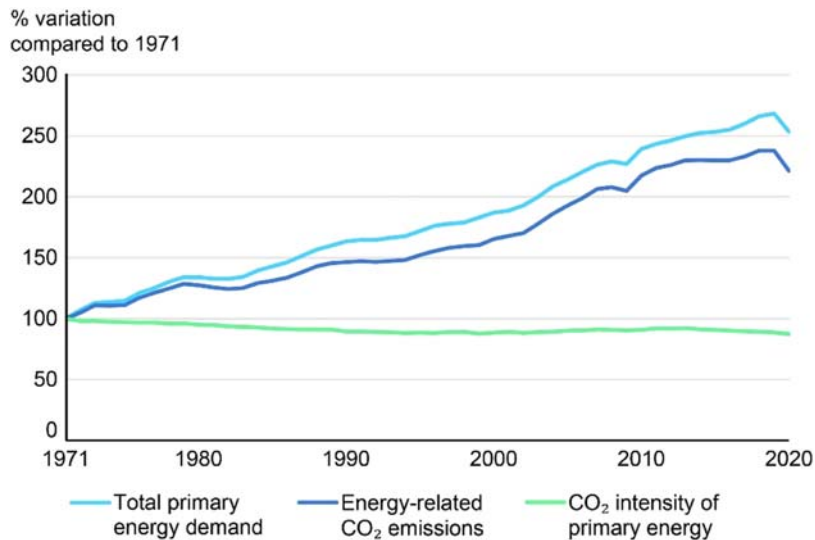


FIGURE 1.3 Global primary energy demand and energy related CO₂ emissions 1971–2020 . Redrawn from (IEA, 2021b).

127 GW (+22%), followed closely by wind energy with 111 GW (+18%). Accordingly, the share of renewables in global electricity generation jumped to 29% in 2020, up from 27% in 2019 (IEA, 2020d, 2021b).

Despite the increase in renewable and decline in energy demand in 2020, global energy related CO₂ emissions remained at 31.5 Gt. According to IEA, in 2021 global energy-related CO₂ emissions are projected to rebound and grow by 4.8% as demand for coal, oil and gas recovers with the economy growing by 4.6%. The increase of over 1500 Mt CO₂ would be the largest single increase since the carbon intensive economic recovery from the global financial crisis more than a decade ago, leaving global emissions in 2021 around 400 Mt CO₂, or 1.2%, below the 2019 peak (IEA, 2021a).

The increase in CO₂ emissions is directly linked to the growth in global energy demand, in turn linked to the GDP and population that have both risen sharply since the beginning of the 19th century (IEA, 2021c). Total primary energy supply worldwide reached 14,400 million tons of oil equivalent (Mtoe) in 2019, 45% higher than in 2000 and an estimated 16-fold higher than in 1900. GDP has increased by 160% and by 80% on a per capita basis since 1990. The number of people in the world swelled from around 1 billion in 1800 to roughly 7.8 billion in 2020. Population growth accelerated in the first half of the 20th century to peak at around 2% per year in the late 1960s but since has slowed to an estimated 1.1% in 2019 (UN DESA, 2019). Population is projected to increase by around 750 million by 2030 and by nearly 2 billion people by 2050 in line with the median variant of the United Nations (UN) projections (UN DESA, 2019).

Nonetheless, energy use has generally increased more slowly than GDP due to a combination of structural economic shifts, saturation effects and efficiency gains. Between 2000 and 2019, energy demand increased by around 0.6% for each 1% rise in global GDP, meaning that energy intensity—that is, energy consumption per unit of GDP—has been steadily declining (see Fig. 1.4). In 2019, the world needed 20% less energy to produce one dollar of economic output than it did in 2000.

Progressive shifts in the world economy centers have been mirrored by the global energy market. Most of the increase in economic activity and energy needs up to the 1970s occurred in Europe and North America. Afterwards, the economic rise of Asia has been the main driver of energy demand growth, particularly in recent years. Advanced economies accounted for 38% of global primary energy demand in 2019 compared with 63% in 1971, whereas emerging economies in Asia today account for 36% of global energy demand compared with less than 15% at the beginning of the 1970s (IEA, 2021b).

Despite the growing contributions of renewables and the steady progress in making energy use more efficient, world energy supply is still dominated by fossil fuels. Nonetheless, the key energy-related UN sustainable development goals (SDGs) may still be met by adopting the cleanest and most efficient technologies that are currently available without delay, and by developing new technologies.

According to IEA (IEA, 2021b), global energy demand is set to increase by 4.6% in 2021, more than offsetting the 4% contraction in 2020 and pushing demand 0.5% above 2019 levels. Almost 70% of the projected increase in global energy demand is in emerging markets and developing economies, where demand is set to rise to 3.4% above 2019 levels. Conversely, energy use in advanced economies is on course to be 3% below preCOVID levels. Demand for all

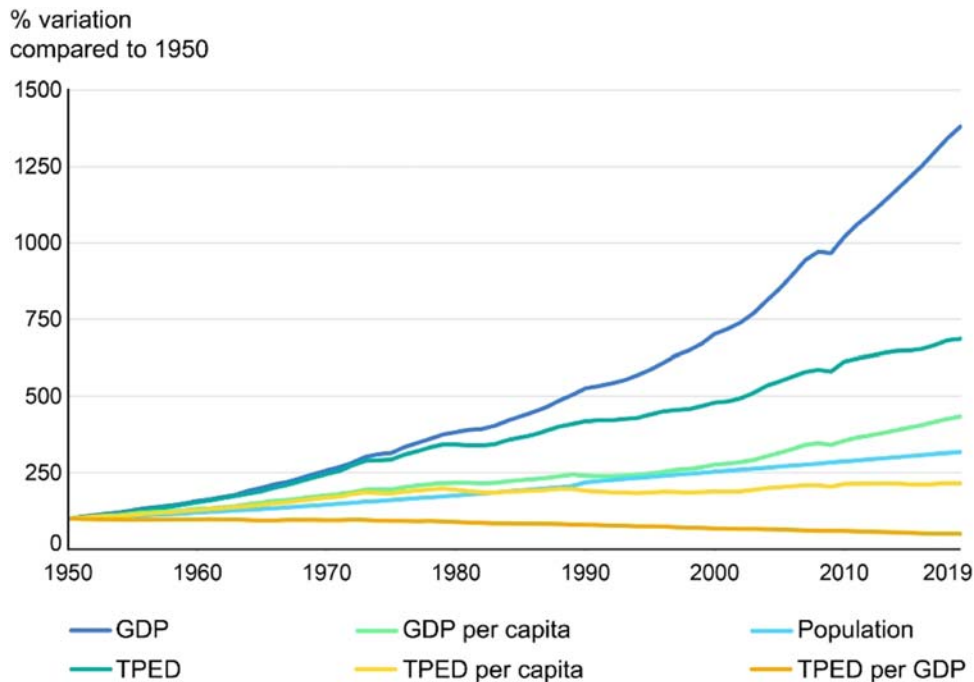


FIGURE 1.4 Global total primary energy demand (TPED), population and GDP, 1950–2019. Redrawn from (IEA, 2021b).

fossil fuels is set to grow significantly in 2021, with coal demand alone projected to increase by 60% more than all renewables combined.

Parallel to the increase in CO₂ concentration in the earth's atmosphere, the last 50 years have seen a significant and progressive change in the climate in terms of increased average temperature of air and seas, variations in the rainfall regime and in the number of extreme climatic events, that have led to the progressive melting of the ice surfaces, the rise of sea level of about 20 centimeters and its progressive acidification, as well as the desertification of numerous areas of the planet (IPCC, 2021, WMO (World Meteorological Organization), 2021).

According to NOAA, the global annual temperature has increased at an average rate of 0.08°C per decade since 1880 and over twice that rate (+0.18°C) since 1981. The decadal global land and ocean surface average temperature anomaly for 2011–2020 was the warmest on record for the globe, with a surface global temperature of +0.82°C above the 20th century average, surpassing the previous decadal record (2001–10) value of +0.62°C (see Fig. 1.5). The year 2020 was the second warmest year in the 141-year record, with a global land and ocean surface temperature departure from average of +0.98°C, only 0.02°C lower than the record high value of +1.00°C set in 2016. NASA scientists, who conducted a separate but similar analysis, have determined that 2020 ties 2016 as the warmest year on record, sharing the first-place spot. Scientists from Copernicus also have 2020 tying with 2016 as the warmest year on record, while the United Kingdom Met Office ranked 2020 as the second-warmest year on record.

All 10 warmest years in the 1880–2020 record have occurred after 2005, while the seven warmest have occurred since 2014. The year 2020 marks the 44th consecutive year (since 1977) with global land and ocean temperatures, at least nominally, above the 20th century average. At the current rate, global temperatures are on track to rise 2.6°C by 2050 or as much as 3.2°C by the end of the century. To meet the 1.5°C—or even the 2°C—maximum target called for in the Paris Agreement, greenhouse gas (GHG) emissions should decrease by 7.6% each year starting in 2020 (see Fig. 1.6). If world governments do not act swiftly and resolutely, the effects of climate change will be even worse than the 2020 pandemic, with an estimated reduction of the global economic production between 11% and 14% by 2050 (JRC, 2021a; UNEP, 2020b).

Both governments and businesses should use the opportunities arising from the COVID-19 crisis to accelerate the transition needed to achieve the Paris Agreement and the Sendai Framework for Disaster Risk Reduction 2015–30, redefine their relationship with the environment, and make systemic shifts and transformational changes to become low-GHG emission and climate-resilient economies and societies. The fight against climate change and the creation of a new clean economy can become a great opportunity for global growth and for the creation of millions of jobs. An opportunity that can be favored precisely by the unprecedented funds allocated to defeat the consequences of the pandemic. In April 2021, the Council and the Parliament of the European Union reached the agreement to be climate

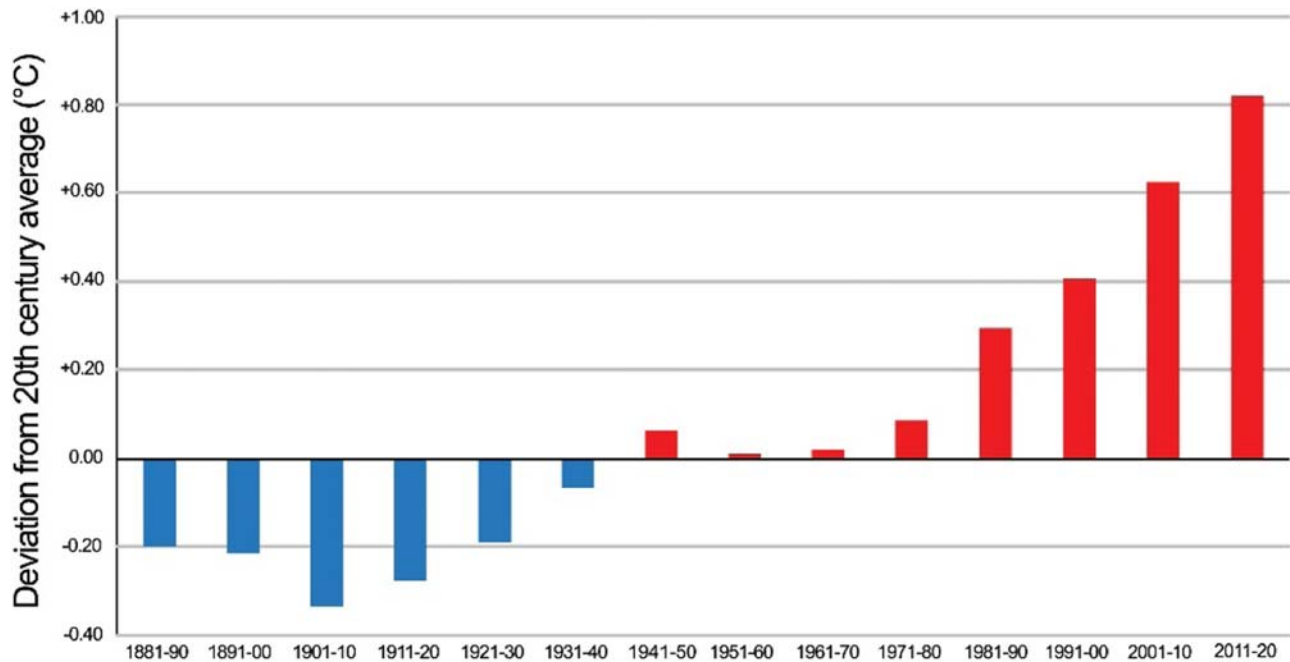


FIGURE 1.5 Annual global (land and ocean) temperature anomaly relative to the period 1901–2000. Source: Redrawn from (NOAA, 2021).

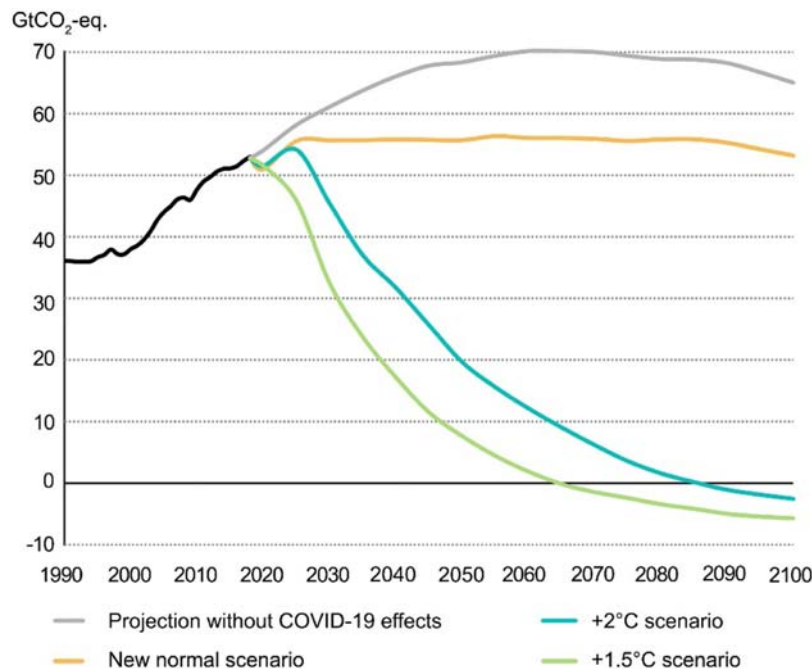


FIGURE 1.6 Greenhouse gases reduction scenarios to meet Paris Agreement targets. Redrawn from (JRC, 2021a).

neutral by 2050 and fixed a collective target of net reductions in GHGs emissions of “at least 55%” by 2030 compared to the 1990 values, and the United States of America announced the ambitious goal to double the planned cut in GHGs, reducing them by 50%–52% by 2030, with the final target to be a zero-emission economy by 2050. China also announced their will to reach the zero emissions target by 2060.

In this picture, decarbonizing the buildings and the construction sector, responsible of almost 40% of energy-and process-related emissions, is critical to achieve the Paris Agreement commitment and the UN SDGs for 2030. In fact, the building sector is not on track with the level of climate action necessary and is one of the slowest to act on addressing its climate impact. Although this industry is responsible for 38% of global energy-related CO₂ emissions, which

further increased in 2019, decarbonization efforts are yet to pick up. To meet the goal of reducing emissions to levels in line with the Paris Agreement by 2030, a threefold strategy is necessary: improved energy efficiency in building operations, increased resource efficiency to reduce impacts from materials and greater decarbonization of the energy system. An opportunity to kickstart the industry in the right direction is constituted by postpandemic recovery plans, which can be effective tools to slow climate change while speeding up economic recovery and providing jobs. According to the International Energy Agency, 9–30 jobs would be created for every million dollars invested in energy efficiency measures in buildings—helping to restore job losses suffered because of the pandemic slowdown. Yet, systematic investments are still lacking. For every dollar spent on energy efficiency in buildings, 37 dollars are spent on conventional buildings and construction. To help reverse this trend, governments should also step-up net-zero commitments for the sector when they submit their updated Nationally Determined Contribution (NDCs) under the Paris Agreement, including buildings and construction in their longer-term climate strategies and supporting regulation to spur uptake of net-zero emissions buildings. This means prioritizing performance based, mandatory building energy codes alongside widespread certification measures, and working closely with subnational governments to facilitate adoption and implementation.

In 2018, IPCC stated that following a 1.5°C consistent pathway would require an 80%–90% reduction of building emissions by 2050, entirely fossil-free and near-zero energy new constructions by 2020, and a raise in the energy retrofit rate of existing buildings to 5% per year in OECD countries (IPCC, 2019).

As the objective to reach near-zero energy in new construction was not reached by 2020, staying under a +1.5°C global temperature increase is already no longer possible. However, staying under 2°C is currently still achievable, but the longer the sector waits to make a transition the more abrupt this transition will be.

Transformative change in buildings is possible, and the capabilities to create a new generation of buildings and energy are at hand (GlobalABC/IEA/UNEP, 2020). The techniques to achieve climate neutrality in the building sector by 2050–60 are already available. At costs equal or close to those of traditional buildings, it is possible with today's technology to align buildings with the highest standards of health, comfort, well-being and sustainability, including improving energy productivity and reducing carbon dioxide emissions. The energy required by buildings can be reduced to a level that can be supplied largely, perhaps exclusively, by noncarbon-based energy. This new approach requires a holistic, systemic approach to building design, delivery and operation and a new paradigm that envisions buildings as energy producers and not solely or primarily as energy sinks. The principles required for an era of truly sustainable buildings emerge from building science, materials science, digital science, information and communication technology and more. They reflect lessons learned and best practices of building owners, designers, engineers, builders, managers, policy makers, and more. The goal is to shift the building industry paradigm from fragmented and serial to holistic and integrated.

In parallel with climate mitigation actions, aimed at limiting the magnitude or rate of global warming by directly addressing the causes of climate change, it is necessary to carry out climate adaptation strategies in order to anticipate, reduce, and avoid the impacts of climate change by making current systems less vulnerable and more resilient.

The built environment is particularly at risk from climate change, and so are the people living and working within buildings (WMO, 2021). All actors along the buildings and construction value chain, including governments, are responsible to address this situation, as climate risks pose a real threat to the lives and economic activities of people. Buildings as long-term assets should be resilient to climate change, and also to other future risks such as pandemics and potential behavior changes.

The number of extreme weather events has increased dramatically in the past 20 years with China (577) and the United States (467) that recorded the highest number of disaster events from 2000 to 2019, followed by India (321), the Philippines (304) and Indonesia (278). Globally, 7348 major disaster events were recorded, claiming 1.23 million lives, affecting 4.2 billion people and causing \$2.97 trillion in economic losses during the two-decade period. Drought, floods, earthquakes, tsunamis, wildfires, and extreme temperature fluctuations were among the events causing major damage taking a heavy human and economic toll worldwide and are likely to wreak further havoc since this upward trend is continuing (UNDRR, 2020).

Among the 100 fastest growing cities in the world, 84 are at an extreme risk from climate change. By 2050, over 800 million people will be vulnerable to sea-level rise and coastal flooding if no effective actions are taken. Other risks include heatwaves, droughts, a rise in average temperatures, coastal erosion, storms, forest fires, floods, landslides, rainfall patterns, soil movements, and thawing permafrost (WMO, 2021).

Climate risks have an impact on both the structure of a building and the economic activities taking place within. Besides physical damages and economic operational losses, extreme events can reduce a property's value by 5% to as much as 20% (Global Alliance for Buildings and Construction & OID, 2021).

Cities, urban infrastructure, and buildings occupy a central place in climate change resilience strategies. Indeed, social, and economic mechanisms rely on the smooth functioning of this triplet, which itself is highly dependent on environmental conditions. Investing in buildings adaptation and the financing of resilient urban infrastructure is therefore crucial to prevent further problems related to climate change.

Adaptation to climate change is recognized as a global issue, and climate change has also been integrated in standard risk management at the international level (UNSDR, 2015). For instance, Article 7 of the Paris Agreement establishes that adapting to climate change is as important as mitigating it. Yet, most countries do not have explicit measures and policies in place to improve the adaptation of buildings to climate change. If such policies are not established, adaptation may remain inaccessible to most of the global population: increased adaptation expenditure in the Risk Based Capital sector in fact currently favors populations that are already relatively privileged, while poorer people find it difficult to pay for the necessary adaptation investments, making the informal sector (slum areas or substandard and unsafe housing) even more vulnerable (Global Alliance for Buildings and Construction & OID, 2021).

Similarly, specific measures must be implemented to protect the most vulnerable populations in the case of a lack of ownership title and insurance. The adaptation of the built environment to climate change, in addition to issuing regulations, requires developing a culture of risk and improving resilience and needs to be interconnected with disaster management, whether linked to climate-related events or not. Similarly, the adaptation of the cultural sector and of listed buildings is an issue that must be considered since world heritage may also be affected by climate change.

Finally, energy production and use do not just affect climate change: fuel combustion is the leading source of air pollution caused by human activity, which has an enormous impact on public health. Around 90% people in the world breathe polluted air every day, leading to more than 5 million premature deaths each year, largely as a result of increased mortality from stroke, heart disease, chronic obstructive pulmonary disease, lung cancer and acute respiratory infections. Such death toll is higher than deaths from HIV/AIDS, tuberculosis and road injuries combined (3.7 million deaths). Outdoor (ambient) pollution accounts for 3 million premature deaths and around 2.5 million also die prematurely from indoor air pollution from combustion of fuel for cooking and heating. The biggest impact is in emerging economies, where more than 2.6 billion people still do not have access to clean cooking (Manisalidis, Stavropoulou, Stavropoulos, & Bezirtzoglou, 2020; United Nations, 2020).

1.2.2 Buildings as a key part of the energy and environmental system

The construction industry is one of the world priority action areas for the achievement of a smart, sustainable and inclusive growth and for a transition to a resource-efficient and low-carbon economy. In 2019, building construction and operations accounted for the largest share of global final energy consumption (35%) and energy-related CO₂ emissions (38%) (see Fig. 1.7). Global final energy consumption for buildings operation was approximately 130 EJ (3100 Mtoe), equal to 30% of total final consumption (of which 22% of residential buildings and 8% for nonresidential), and a further 21 EJ (5% of total demand) for construction, for an industry total of 149 EJ (3500 Mtoe) (UNEP, 2020a).

Buildings consume energy for heating, cooling and interiors ventilation, for domestic hot water production, for lighting appliances and for electrical equipment, for people transport and for food cooking, using electricity (42%), gas (30%) and biomass (24%) as main energy carriers (see Fig. 1.8). The incidence of each of the above items on total consumption varies depending on the type of building, its year of construction and the climate zone in which it is located. Today, space heating is the largest energy end use in the buildings sector, consuming more than 1000 Mtoe annually on a global basis. It represents more than a third of energy demand in buildings, three-quarters of which is consumed in

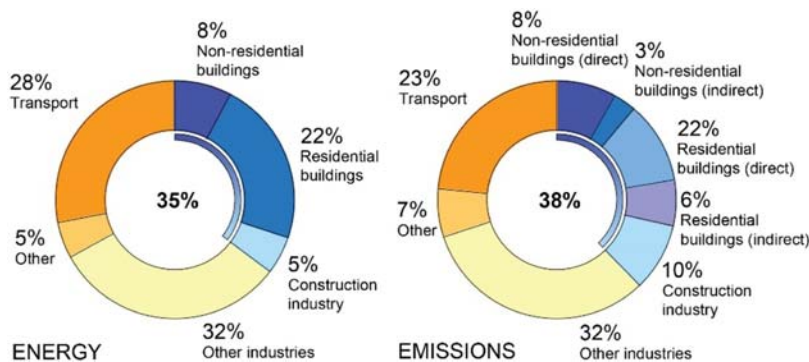


FIGURE 1.7 Role of building industry in global energy demand and CO₂ emissions. Redrawn from (UNEP (United Nations Environment Programme), 2020a).

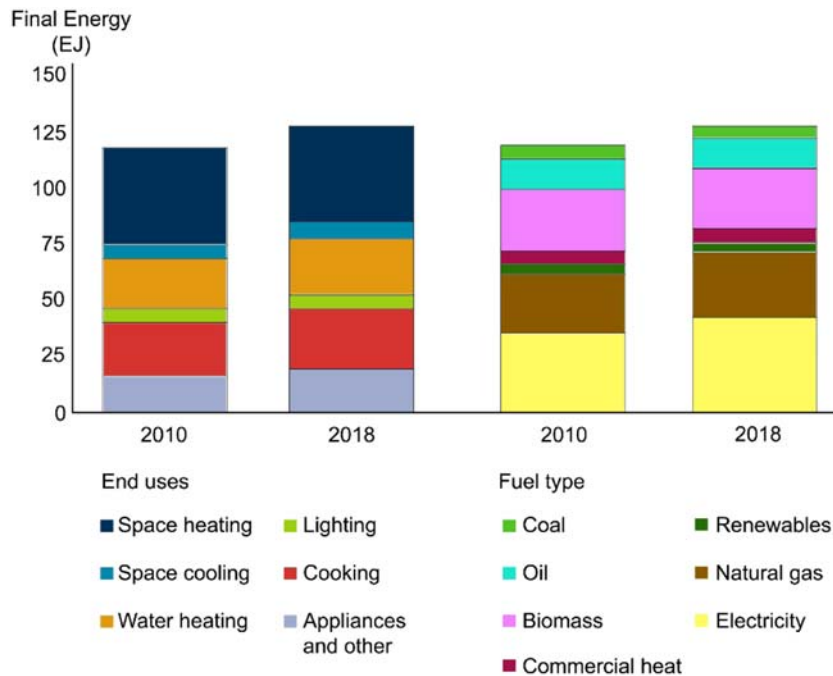


FIGURE 1.8 Final energy consumption of buildings and fuel type share. Redrawn from (IEA, 2021c; IEA, 2019d).

TABLE 1.2 IEA buildings operation and construction CO₂ emissions estimates 2019 (UNEP, 2020a).

Building life cycle	2019 (MtCO ₂)	Share
Buildings use phase	9953	28% of total energy related emissions
Coal	496	9% Direct emissions
Oil	939	
Natural gas	1663	
Electricity and heat	6855	1% indirect emissions
Buildings construction	130	10% indirect buildings and construction value chain emissions
Construction energy use	130	
Material manufacturing	3430	
Cement-and-steel manufacturing for construction	2038	
Other	1391	
Building and construction value chain	13512	38% of total energy related emissions

the United States, the European Union, China, and Russia. Water heating, cooking, and lighting and appliances are responsible for about 20%, 20% and 14% of consumption respectively. Space cooling, which today only accounts for 6% of energy use in the buildings sector, is by far the fastest growing end use worldwide as more and more buildings are being equipped with air conditioners.

In the same year, direct emissions from fossil fuel combustion in buildings for space conditioning, water heating, cooking and other service applications amounted to about 3 GtCO₂ worldwide (9% of global emissions) (see Table 1.2). Indirect emissions from the consumption of electricity and heat by electrical and electronic devices used in buildings (e.g., air conditioners, heat pumps, household appliances and lighting) account for 9.8 GtCO₂ (19%), for a total value of 28%. Producing the materials and constructing buildings involves an additional 3.5 GtCO₂ of energy- and process-related CO₂ emissions in the industry sector (10%), mostly from cement and steel manufacturing (UNEP, 2020a).

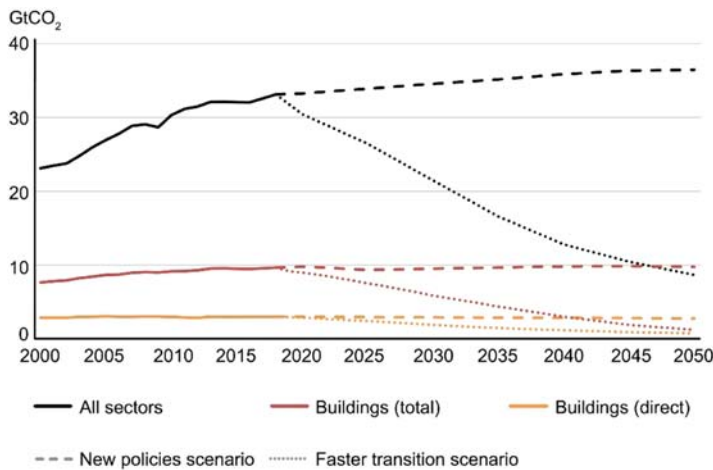


FIGURE 1.9 Direct and indirect emissions from buildings in the fastest transition scenario to 2050. Redrawn from (IEA, 2019a; UNEP (United Nations Environment Programme), 2020a).

Across the globe, buildings energy use remains a significant proportion of overall energy demand. In 2019, buildings accounted for 57% of total final energy consumption in Africa, and 32% of total process-related CO₂ emissions. In China, India and Southeast Asia nations, energy consumption in buildings accounted for 26% of total final energy consumption and 24% total process and energy-related CO₂. Buildings accounted for 24% of total final energy consumption in Central and South America, and 21% of total process-related CO₂ emissions.

To achieve a net-zero carbon building stock by 2050, the IEA estimates that direct building CO₂ emissions would need to decrease by 50% and indirect emissions for power generation in the building sector should decline by 60% by 2030. Building sector emissions should fall by around 6% per year from 2020 to 2030 (see Fig. 1.9).

Although the global commitment to improving the energy efficiency of buildings has been greatly increasing over the past two decades, energy use in the buildings sector and global energy-related emissions have risen steadily since 2000 with an average annual growth rate of about 1.5%, leading to an overall increase of over 30% in the period 2000–19 (+54% compared to 1990). In 2019, while the total final energy consumption of the global buildings sector remained at the same level compared to the previous year, CO₂ emissions from the operation of buildings have increased by 4.4% reaching the record value of 10.1 GtCO₂. Against this trend, the reduction scenario should envisage a decrease in emissions of at least 2.5% per year on average between now and 2030.

The increase in emissions that occurred in the last decades has been mainly due to the indirect emissions following the increased consumption of electricity (still primarily sourced from fossil fuels, such as coal and natural gas), which since 2010 has increased more than 20%, constituting the main energy source of buildings in 2019 (42%). In fact, whereas direct emissions remained stable around 3 Gt, indirect emissions increased by over 42%, from 4.9 Gt in 2000 to 7.0 Gt in 2019. Moreover, electricity consumption by household appliances continues to increase, reaching over 3000 TWh in 2019 and accounting for 15% of global final electricity demand, or one-quarter of electricity used in buildings. Demand is driven by rising ownership of connected plug-load devices, especially in developing countries that are becoming wealthier.

The buildings sector now represents more than 55% of global final electricity consumption and, given the increasing dependence of buildings on electricity, it is therefore strategic to decarbonize the power sector as quickly as possible. In fact, in the last 20 years, electricity demand in buildings globally grew more than five times faster than improvements in power sector carbon intensity.

Diffused improvements in last years in building envelopes (e.g., better insulation and windows) and in the performance of building energy systems (HVAC and lighting) and components (e.g., cooking equipment) could not offset rapidly growing floor area and rising demand for energy services. In particular, constructed floor space in buildings worldwide has increased by about 65% since 2000, reaching nearly 245 billion m² in 2019 (see Fig. 1.10)

Yet, average energy use per m² (energy intensity) has declined by only around 25%. Global total final energy intensity for buildings has been decreasing at an annual rate of (–)0.5% from 330 to 320 kWh/m² in the period 2015–19, meaning advances in energy efficiency have only partially offset floor area growth. From 2010 to 2018, changes in buildings sector final energy intensity show that the greatest improvements (i.e., reductions) were in global average space heating (–20%) and lighting (–17%) (see Fig. 1.11).

Conversely, as floor area has been expanding rapidly in hot countries, energy intensity for cooling increased more than 8% in the same period. In 2019, space cooling was responsible for emissions of about 1 GtCO₂ and nearly 8.5% of total final electricity consumption.

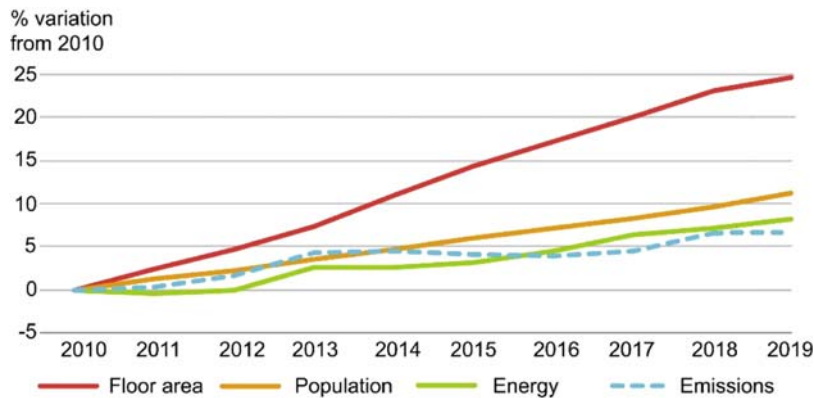


FIGURE 1.10 Changes in floor area, population, building sector energy use and energy-related emissions globally, 2010–19. Redrawn from (IEA, 2021c; IEA, 2019d).

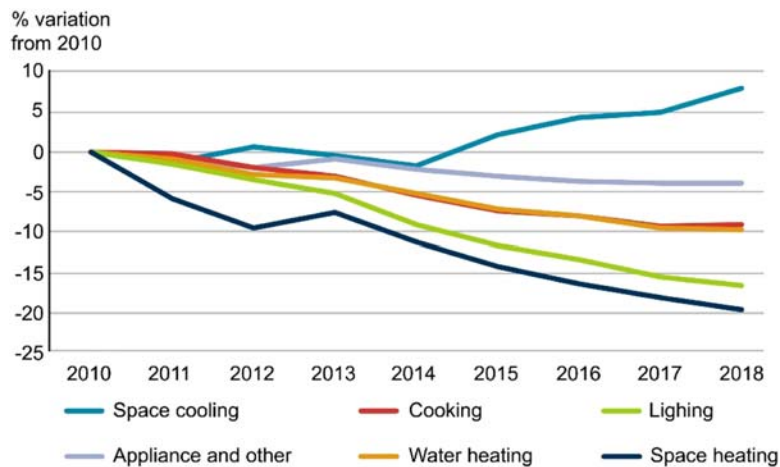


FIGURE 1.11 Global buildings sector final intensity energy use changes by end use, 2010–18. Redrawn from (IEA, 2019d).

These data indicate untapped energy efficiency potential, as global building energy code evolution is not keeping pace with rapid floor area expansion in emerging economies, while renovation rates in developed countries still stagnate. Similarly, the marginal increase in direct emissions suggests that renewables, heat pumps, efficient electric technologies and district heating are not replacing fossil fuel-based assets (including boilers, furnaces and cook stoves) on an average global level. Greater investments in efficiency and passive design strategies are needed to limit demand and reduce energy intensity.

Particular attention shall be given to energy needs for space cooling, which rose more than 33% during 2010–18 and are expected to rise threefold over the coming 30 years (IEA, 2018), especially in hot and tropical countries and in residential buildings, accounting for over 20% of potential global electricity demand growth. Global sales of AC systems per year have nearly quadrupled since 1990 and the global stock of air conditioners in buildings is expected to grow to 5.6 billion by 2050. Approximately 2.8 billion people live in places with average daily temperatures above 25°C all year and only 8% of them are estimated as having AC yet (GlobalABC/IEA/UNEP, 2020). Such trend is set to intensify, driven by rising incomes, the expected doubling of building floor area by 2060 (GlobalABC/IEA/UNEP, 2020), and a warming planet with higher temperatures and more frequent heat waves.

Going forward, addressing cooling demands will be a critical challenge due to the vast amount of buildings being constructed around the world with little adaptive capacity to the surrounding climate. Without proper thermal breaks, shading, ventilation, insulation or thermal mass, poorly designed buildings can be prone to overheating and require an excessive amount of energy for mechanical cooling. Better building designs can reduce or even avoid the energy demand for space cooling, resorting to climate-adapted building envelopes, clear exterior colors, solar control windows, natural ventilation, orientation and vegetation which offer large possibilities to reduce the energy demand for cooling (see Section 2.3).

Concerning, finally, emissions from the production of buildings materials and their construction, these are largely driven by cement and steel manufacturing processes, and their growth in use is a major driver of building related embodied carbon emissions (IEA and WBCSD, 2018; IEA, 2020e).

Building design and types, such as high-rise towers, have resulted in increased demand for steel and cement, though such buildings may have a longer lifespan as a result. Globally, the buildings construction sector accounts for approximately 50% of the demand for cement and 30% of steel. These factors show the importance of extending the lifetime of buildings, optimizing their use and replacing them with materials that have lower embodied carbon (see [Chapter 7](#)).

In this sense, the use of modern methods of construction, such as prefabricated, offsite and modular construction, constitutes one of the major innovation areas for energy-efficient building construction (see [Section 8.1](#)). The global value of modular building construction in 2019 was estimated at US\$70 million to US\$110 billion. The construction industry continues to invest in advanced design and manufacturing facilities for increasing bespoke building production for a range of building types, including multifamily, education and hospital buildings. In 2019, for example, the United Kingdom announced that GBP 2.5 billion (US\$3.2 billion) of its Home Building Fund was allocated to modern methods of construction and that an additional GBP 170 million (US\$222 million) was being spent on research and development ([MarketsandMarkets, 2020](#)). However, the shift to modular construction has so far been led by heating dominated regions, such as the Baltic Region, Europe, North America and Northern China.

1.2.3 Sustainable buildings and construction policies

In order to achieve the objectives set by the sustainable development scenario (SDS) and climate targets, it is urgent for all countries to focus on how to make buildings more energy-efficient, less carbon-intensive over their full life-cycle, and more sustainable. Therefore, the commitment of all nations to these themes must be greatly increased in the next decade with the triple objective of significantly reducing the energy consumption of existing buildings, of ensuring that all new buildings are characterized by high energy efficiency, and of prioritizing renewable energy, instead of fossil fuels, to meet the energy needs of both new and existing buildings. The ultimate objective is to reduce the energy required by buildings to a level that can be supplied largely, or exclusively, by noncarbon based energy.

Several analyses show that this decarbonization of the sector can be achieved at costs equal or close to those of traditional buildings and that it is possible, with today's technology, to transform buildings to align with the highest standards of health, comfort, well-being and sustainability, including improving energy productivity and reducing carbon dioxide emissions. Nonetheless, this requires clear pathways to be developed and implemented to accelerate the needed transition for buildings to achieve net zero carbon by 2050, including progressive building code implementation, market regulation, and supporting investment in energy renovation for existing buildings.

In order to separate aggregate building energy use from its historical drivers, several energy policy measures are to act together. These include improved building energy codes for both new constructions and existing buildings undergoing retrofit, improved standards and labels for appliances, whole building rating, labeling and disclosure programmes, educational programmes and capacity building as well as improved data availability and quality to allow for informed policy design and implementation ([GlobalABC/IEA/UNEP, 2020](#); [IRENA, 2019a, 2019b](#); [UNEP, 2020a](#); [Global Alliance for Buildings and Construction & OID, 2021](#)).

To support the decarbonization of both new and existing buildings, policies and regulations shall cover the entire building life cycle, including the design, development, operation and decommissioning stages, and also extend beyond site boundaries through neighborhood planning and clean energy supply. Greater collaboration is a key to accelerate this action, involving a range of stakeholders including policy makers, urban planners, architects, construction companies, materials suppliers, utility companies, developers and investors. Governments and industry consortia should promote the adoption of existing efficient building construction and operation techniques and low-cost technologies that can improve building performance and lower embodied carbon, as well as opportunities for capacity building on topics like embedding CE concepts into building design through life-cycle assessment, data collection for efficiency improvement, reuse of construction materials, and phasing out materials with the highest global warming potential, such as some HVAC refrigerants.

Regarding new constructions, to achieve sustainable, carbon-neutral, efficient and resilient new buildings in the next decades, a series of key actions concerning design, construction and operation of build assets will be needed. First, governments should promote building designs that adapt to local climatic conditions as well as to urban forms and construction practices, and that integrate passive strategies such as natural ventilation and passive cooling. In addition, a life-cycle approach to buildings—that includes the construction, operation and decommission phases—shall be encouraged through the greater use of sustainable materials, coupled with improved building design and neighborhood and urban planning measures for building construction and renovation. Furthermore, the integration of simulation and optimization tools into building design should be promoted so that technology synergies can be achieved already during the planning phase. Designers, engineers and installers shall be adequately trained to facilitate adoption of the best building design practices.

Particularly important is the need to develop and enforce in the coming decade mandatory building energy codes that strive for near-zero energy and net-zero emissions in new constructions in as many countries as possible. Codes should set or refer to guidelines for locally adapted and bioclimatic design principles, and include requirements for resilience and adaptation, requirements regarding the embodied carbon of materials, clean energy, and urban planning strategies. Conversely, monitoring frameworks for compliance checking, accessible tools and extensive capacity building are required to enable and facilitate compliance within all sectors of the construction industry, including the informal and the social housing sector. Rating systems and benchmarks shall be developed to evaluate building energy performance and ensure they are accessible and disclosed to facilitate comparison. Finally, regular energy performance auditing shall be promoted to ensure systems are being maintained and operated efficiently and make full use of advanced energy management systems and smart controls.

As of 2019, however, only one third of world countries have mandatory or voluntary building energy codes or are currently developing them, and around 45% of those only cover just part of the buildings sector (e.g., residential or non-residential). Only in 2018, more than 5 billion m² in the world have been built without mandatory performance requirements, and between now and 2050 more than two-thirds of new buildings constructed are expected to be built in countries lacking building energy codes. Swift action is therefore needed to enlarge and strengthen mandatory building energy codes in order to regulate the coming expansion of the building sector, improving the thermal comfort of buildings without significantly raising energy demand and resultant emissions (UNEP, 2020a).

Although developing countries will need to accommodate 2.4 billion new urban residents by 2050, more than 50% of the current global building stock is expected to remain in use in that timeframe, a figure that reaches or exceeds 75% in OECD countries. It is apparent that the reduction of energy consumption and carbon emissions associated with buildings cannot prescind from a deep and rapid energy upgrading of the existing building stock (deep energy renovation, DERs, with a minimum reduction of energy consumption of 50%–60% compared to prerenovation levels), therefore the promotion of large-scale building refurbishment should be a key policy priority in the upcoming decade.

In 10 years, buildings must look remarkably different and become the microcosms of a more resilient, greener and digitalized society, operating in a circular system by reducing energy needs, waste generation and emissions at every point and by reusing what is needed. Their roofs and walls should increase the green surface of cities and improve the urban climate and biodiversity, or host integrated renewable energy sources to cover most of the building's needs. Within their walls, buildings should host smart and digitalized appliances, providing real time data on how, when and where energy is consumed. Recharging electric vehicles (EVs) in residential and office buildings shall be a common experience complementing publicly accessible charging infrastructure. Many more citizens will be prosumers, producing electricity for self-consumption or even selling it back to the grid. District approaches will unite people and communities. Cities will become greener and better connected with nature.

An effective energy upgrade of the existing building stock goes through the increase of the rate, quality and effectiveness of building renovation, as the current annual renovation rate is only 1%–2% with average energy intensity reductions of generally less than 15%. Across the EU, deep renovations that reduce energy consumption by at least 60% are carried out only in 0.2% of the building stock per year and in some regions, energy renovation rates are virtually absent. At this rate, driving the building sector to net-zero carbon emissions would require centuries. Major commitment on all regulatory, economic/financial, technological, and cultural fronts is therefore required in order to increase minimum standards, reduce renovation costs, minimize disturbance for occupants and address specific barriers including socio-economic ones and those linked to the building ownership structure. Effective retrofit solutions need to be demonstrated and widely replicated in order to help increasing the renovation rate of the building stock from less than 1% per year today to at least 2.5% per year by 2030 in advanced economies and 2% per year in emerging and developing economies, which would translate to around 30 million dwellings retrofitted every year on average to 2030 (ECSSO, 2018; GlobalABC/IEA/UNEP, 2020; JRC, 2020b; Global Alliance for Buildings and Construction & OID, 2021).

Overall, the target of full decarbonization of energy use in the construction sector entails comprehensive zero-carbon-ready building codes to be implemented in all countries before 2030. Such zero-carbon-ready buildings must be both highly energy efficient and either use renewable energy directly, or use an energy supply that will be fully decarbonized by 2050, such as electricity or district heat, allowing them to become zero-carbon by 2050 without any further changes to the building or its equipment (see Table 1.3). Moreover, zero-carbon-ready buildings should adjust to users' needs and maximize the efficient and smart use of energy, materials and space to facilitate the decarbonization of other sectors.

To be effective, zero-carbon-ready building energy codes should regulate building operations as well as technical performance. They should account for how passive design features, building envelope improvements and high energy

TABLE 1.3 Key milestones in transforming global buildings sector.

Category	2020	2030	2050
Share of existing buildings retrofitted to the zero-carbon-ready level	<1%	20%	>85%
Share of zero-carbon-ready new buildings	5%	100%	100%

performance equipment lower energy demand, reducing both the operating cost of buildings and the costs of decarbonizing the energy supply. The integration of locally available renewable resources—solar thermal, PV and geothermal systems—and of thermal or battery energy storage should be promoted to reduce the need for utility-scale energy supply. Buildings must become a flexible resource for the energy infrastructure, using connectivity and automation to manage building electricity demand and the operation of energy storage devices, including V2B capable EVs. Lastly, zero-carbon-ready building energy codes should cover lifecycle emissions of building materials and components (embodied carbon emissions): for instance, material efficiency strategies can cut cement and steel demand in the buildings sector by more than a third relative to baseline trends, and embodied emissions can be further reduced by more robust uptake of biosourced and innovative construction materials.

An improvement of energy performance of buildings, along with reducing carbon emissions, would also yield important benefits to building owners and occupants, such as improved durability, reduced maintenance, greater comfort, lower costs, higher property values, increased habitable space, increased productivity, and improved health and safety. Renovation can in fact open up numerous possibilities and generate far-reaching social, environmental and economic benefits. With the same intervention, buildings can be made healthier, greener, interconnected with the neighborhood, more accessible, resilient to extreme natural events, equipped with recharging points for EVs, and can provide essential, privacy-compliant data for smart city planning and services. Deep renovation can reduce pressure for green-field construction, helping preserve nature, biodiversity, and agricultural land.

The COVID-19 crisis in 2020 has also brought into sharper focus our buildings, their role in our lives and their fragilities. Throughout the pandemic, for instance, the home has been the focal point of daily life for millions of people, acting as an office for those teleworking, or a nursery or classroom for children and pupils. Private business and offices had to readjust to social distancing. Schools had to adapt to distance learning and reduced social interactions. Hospital infrastructure has been under severe strain. These effects have created new demands on our buildings and their energy and resource profile, further adding to the need to renovate them deeply and on a massive scale. In this picture, renovation offers a unique opportunity to rethink, redesign and modernize our buildings to make them fit for a greener and digital society and sustain economic recovery.

Renovation is held back by barriers at different points throughout the value chain—from the initial decision to engage in renovation, to financing and completion of the project. When considering a renovation, benefits from energy savings might be difficult to measure and monetize or poorly explained and understood, especially by the end-users. From this point of view, in addition to the energy performance certification (EPC) of buildings, innovative tools such as the new building renovation passport (BRP) and digital building logbooks (DBL) recently introduced by the European Union are particularly important in encouraging energy redevelopment.

Quantitative building energy labeling, such as the EPC, can be used to benchmark building envelope and system characteristics on a scale of less to more efficient and should become widespread in existing buildings as well as new buildings. Clear labeling promotes information sharing and awareness for consumers and investors, and should increasingly disclose the embodied and operational carbon of buildings. As EPCs are necessary to guide occupants' choices, it is needed to reinforce and strengthen their quality and introduce a more standardized format for digital use and improved accessibility, supported by newer smart technologies. In 2019, roughly 85 countries out of 195 in the world had building energy certification: 40 had mandatory EPC policies; 20 had widespread voluntary certification policies or programs; and the remainder had only a handful of voluntary projects. In the European Union, for instance, energy certification is mandatory for new buildings and for existing building in case of mayor renovation, sell or rent contracts. However, the current national EPC scheme has been found to provide too general recommendation for improving the energy efficiency without specific information and to omit completely indicators related to thermal and visual comfort or air quality that are the most important benefit of the building renovation (Sesana and Salvalai, 2018). Reliability, consistency and comparability of EPCs, also across nations, should be improved so that they become a trusted market tool to assess performance and quality of buildings. New features could be added to EPC to

incorporate, for example, indicators on comfort, smart readiness or air pollution. For its European Union Circular Economy Action Plan, the European Commission launched in 2021 “Level(s),” a voluntary reporting framework for the buildings sector, in addition to EPCs, that encourages lifecycle thinking at the whole-building level (see Section 1.5.2).

Along with EPCs, BRPs, currently being implemented or tested in at least Germany, France and the region of Flanders in Belgium, can be used to track information about the building, its materials, systems, energy use, renovations and other relevant information to improve decision-making processes. Basic information includes floor plans, activity information, past retrofit or refurbishment works, and monthly energy consumption and peak demand. The BRP can include a separate element, a storage logbook where the building’s features and information (e.g., stability, durability, water, installations, humidity, maintenance requirement, etc.) can be collected and regularly updated, becoming a proper repository of information and data related to a specific building. The logbook could also include other sets of information related to each individual building, such as the financing options available in the area for renovation projects (e.g., green loans, incentives, tax credits) as well as energy bills, equipment maintenance recommendations, insurance and property obligations. All this information could be inventoried in a digital register, the DBL, available to property owners. Depending on the type of DBL or its intended use, owners could grant access to some information to public authorities (e.g., municipality, property tax office), building professionals and craftsmen, and make some information publicly available, while keeping other data private or restricted. In its most sophisticated form, the DBL could also be used as an interactive tool to monitor and compare real energy consumption with the designed one both at individual building and portfolio level, sending alerts when unusual consumption patterns or flaws in technical installations are detected. It could also be linked to market actors (such as building professionals, craftsmen or financial institutions) to provide information regarding certified contractors and installers, facilitate invoicing and simplify the process for subsidies or loans repayment. Indeed, the availability of clearer, dynamic and easily accessible information on buildings data is the basis for developing synergies between the construction value chain, building owners, the financial sector and local authorities, and digitalization enables more systematic data collection and management to be mainstreamed across the entire lifecycle of buildings.

To promote building energy renovation, governments should introduce policy interventions that route market to improve access to financing and de-risk clean-energy investment, including measures such as tax exemptions, grants, loans, auctions and obligations. The finance sector, banks and investors, shall be involved to create a common classification scheme and a robust evidence base for such investments. For instance, standardizing verification procedures would reduce the uncertainties surrounding energy-savings evaluations and help investors understand the benefits of building investments and their replicability, making investment more attractive. Incentives such as increased scope or special permits can also be significant enablers of the refurbishment and retrofit of existing buildings. Finance tools particularly relevant to building renovation may include dedicated credit lines, risk-sharing warranties, green bonds, preferential taxes, grants and rebates, energy performance/energy service contracts, procurement purchase and lease, on-bill/tax repayment, community finance and crowdfunding.

One notable example is the Energiesprong program, an innovative initiative which seeks to make zero-energy-building retrofits affordable by leveraging private financing that can be repaid through energy savings in public buildings. Started in 2010, it is now active in five countries—France, Germany, the Netherlands, Italy, and the United Kingdom.

Other actions include the EU revision of the European Performance of Buildings Directive in June 2018, to accelerate the renovation of existing buildings. In 2019, the World Green Building Council network in Europe launched the BUILD UPON² project to align ongoing building renovation efforts and deliver a report. Another interesting project is Individual Building Renovation Roadmaps (iBROAD), which is developing a tool to outline building renovation plans at the individual building level.

In addition to advantages to buildings users and residents, energy renovation can also bring multiple benefits to governments such as reduced societal health costs, improved air quality, an improved tax base and lower budget variation, higher GDP and enhanced energy security. Utility companies benefit as well from cost and operational benefits due to reduced customer turnover, reduced emissions and reduced system capacity constraints.

Moreover, the pursuit of energy efficiency can also bring major benefits to the construction industry. Renovation works are labor-intensive, create jobs and investments rooted in local supply chains, can generate demand for high energy and resource-efficient equipment and bring long-term value to properties. Construction jobs would mostly be local, while manufacturing jobs in the wider industrial sector would be created by increased demand for building materials and equipment such as insulation, efficient glazing, and HVAC systems. In the EU, during the 2008 financial crisis, an average of 18 jobs were created for €1 million invested in energy renovation of buildings. By 2030, an

additional 160,000 green jobs in the EU construction sector are expected through the “Renovation Wave,” the EU plan that aims to at least double renovation rates within 10 years to increase energy and resource efficiency, achieving 35 million interventions by 2030. This can be very valuable for a sector where more than 90% of the operators are SMEs, hard hit by the economic impact of the COVID-19 crisis.

Governments play an important role in unlocking this opportunity, especially in the current contingency caused by the COVID-19 pandemic. While this crisis brings many challenges, it also presents the conditions for a paradigm shift: by systematically including building decarbonization measures into recovery packages, they can dramatically increase renovation rates, channel investment into zero-carbon buildings, create jobs, and increase real estate value. In 2020, numerous countries have implemented stimulus programs that target the building sector, which are being collected by the Platform for Redesign 2020, a UNFCCC initiative led by the Japanese government that showcases information on policies and actions taken by national governments to contribute to a sustainable and resilient recovery from COVID-19. Governments can also support industry-led initiatives such as the Advancing Net Zero project by the World Green Buildings Council, which calls on businesses, organizations, cities, states and regions to reach net-zero-carbon operating emissions by 2030 and to advocate for 100% sector decarbonization by 2050.

To tackle emissions and reduce energy intensities in the buildings and construction sector, governments, companies and private citizens must raise adequate investments in efficiency to offset growth and to unlock the benefits associated with zero emission, efficient and resilient buildings. Spending for energy efficient buildings has shown an increase in 2019 for the first time in the past three years, with investment in building energy efficiency across global markets increasing to US\$152 billion, an increase of 3% from 2018 (UNEP, 2020a). This increase is driven by both the increase in construction industry investment activity across the global market, with a rise of 4.9% from 2018 levels, and a continued effort in policies, especially among European countries and in China to direct greater investment in building energy performance (UNEP, 2020a). However, this still constitutes a small proportion of the US\$5.8 trillion spent in the global building and construction sector. It is evident that energy efficiency investment growth is not keeping pace with the construction of buildings globally, leading to little change in final energy use in global buildings stock. It is therefore imperative that post COVID-19 recovery plans clearly seek to have energy efficiency investment growth outperform floor area growth to gain net reductions in final energy use (UNEP, 2020a). Supporting sustainable buildings requires an increase in annual investment to an average of US\$27 billion over the next decade (GlobalABC/IEA/UNEP, 2020).

An enabling policy framework for investment and finance is thus critical to rally and effectively channel finance to investments in the low-emissions buildings and construction sector. This includes support for low-carbon technologies, removing fossil fuel subsidies, building capacity among policy makers and financial institutions, and establishing effective retail channels.

Yet, there are positive signs across the investment sector that building decarbonization and energy efficiency are taking hold in investment strategies, with finance institutions and property companies realizing the strong growth potential and investment opportunities available with sustainable building investment. For instance, 90% of the 1005 real estate investors that reported to The Global ESG Benchmark for Real Assets (GRESB) in 2019 align their projects with green building rating standards for construction and operations. Indeed, green buildings represent one of the biggest global investment opportunities of the next decade, which is estimated by the International Finance Corporation (IFC) to be \$24.7 trillion by 2030 (GlobalABC/IEA/UNEP, 2020).

Due to the world pandemic, in 2020 activity in construction fell by 15.7% and energy efficiency investments dropped by 12% compared to the previous year. Even if a recovery is expected, there is likely to be a lasting impact on the sector. An important opportunity for the path toward the decarbonization of buildings is the updating of the NDCs prepared by each country to reduce national emissions and adapt to the impacts of climate change under the Paris Agreement. Although most countries (136 on 184) mention buildings in their NDCs, few of those detail explicit actions to address emissions within the buildings sector. In the next round of NDCs, covering 2020–25, further focus is needed on actions to mitigate building emissions through switching to low-carbon and renewable energy sources, and greater attention should be paid to low-carbon building materials, building envelope improvements, nature-based solutions, and equipment and system efficiency (IEA, 2021b; UNEP, 2020a; United Nations Environment Programme, 2018).

1.3 Low-carbon and sustainable cities

As UN Secretary-General António Guterres said, “Cities are where the climate battle will largely be won or lost,” and urban dwelling will constitute the main focus of most future planning and policy making efforts. Today, nearly 55% of the world population already live in urban areas (up from 43% in 1990 and equal to around 4.2 billion people), and it is

expected that this number will increase up to 66% by 2050 (<https://ec.europa.eu/digital-single-market/en/smart-cities-smart-living>). Moreover, there are currently 30 megacities with a population of over 10 million, up from only two in 1950, and by the year 2030 these are expected to rise to 43 (UN DESA, 2019).

Globally, urbanized areas contribute almost 80% of the world's GDP (McKinsey, 2016b) and account for 75% of global energy consumption and for almost 70% of GHGs emissions with transportation, buildings, infrastructure and construction representing more than 50% of total emissions (REN21, 2021).

In addition, cities are responsible for global energy use that does not actually take place within urban boundaries as well. They contribute indirectly to energy use and to GHG emissions through their supply chains, which include construction materials (concrete, steel, etc.), everyday goods (food, clothing, electronics, etc.) and other products consumed in cities but produced beyond their borders. Cities cover 3,629,312 km², or 2.8% of global land area (REN21, 2021). In 2016, they generated 2 billion tons of solid waste, with 3.4 billion tons projected by 2050, with the associated health concerns, environmental issues and economic losses as well, as cities could reuse these resources. Since the turn of the 21st century, the impacts of climate change have been increasingly affecting cities globally. More frequent and severe weather events, such as flooding, windstorms, heat waves and droughts, have crippled and even paralyzed urban areas. More than 75% of cities worldwide are already exposed to severe climate change risks, as demonstrated by the wildfires in Australia and the western United States in 2020. In the United States alone, flooding will cause \$136 billion worth of property damage by 2045, forcing 280,000 Americans to adapt or relocate. Groundwater depletion, fires, food shortages, sea-level rise, spikes in energy use due to extreme temperatures also affect city infrastructure and the livelihoods and health of residents. More than 90% of the world's urban areas are located along coastlines, where rising sea levels and storms threaten inhabitants and infrastructure with flooding and strong winds. Furthermore over 1 billion people live in urban slums and informal settlements which are particularly vulnerable to climate impacts, as situated along waterfronts and riverbanks that are prone to flooding. The economic resources that the worldwide cities have addressed to adaptation measures to climate changes like protective barriers against floods, more resilient infrastructures and better draining systems are already relevant (around the 0.22% of GDP for developed countries and 0.15% for the cities of developing countries).

As cities expand, so does their demand for services but also the pressure on resources, as well as problems such as traffic congestion, air and noise pollution, or waste production. In particular, current mobility systems based on fossil fuels and individual vehicles, besides being responsible for above 25% of polluting emissions, are increasingly unsuitable to the needs of urban areas, making movements difficult especially during rush hours, with journey speeds around 7–8 km/hour (the same speeds recorded in 1700) and making urban transport account for around 40% of total transport-related CO₂ emissions globally. Conversely, 12.6 million people die because of environmental pollution every year, equal to one fourth of the total deaths. Air, water and soil pollution, chemical exposure, climate changes and ultra-violet radiation are contributing to the increase of over 100 illnesses and health damages. On a global level, air pollution is the fourth risk factor for deaths, and the main environmental risk factor for lungs and heart diseases, causing the death of over 5.5 million people every year.

An estimated nine out of 10 people worldwide regularly encountered polluted air in 2018. In 2016, as much as 91% of the global urban population was exposed to air pollution—measured in the form of fine particulate matter (PM_{2.5})—and more than half of the urban population faced PM_{2.5} levels at least 2.5 times above the safety standard of the World Health Organization. Exposure to polluted air has been linked to mental illnesses such as depression and bipolar disorder as well, and socially disadvantaged groups are often exposed to disproportionate levels of pollution as they are usually closer to fossil fuel power plants and transport routes. Air pollution has a high economic cost. In 2015, death and illness caused by air pollution cost an estimated USD 1.8 trillion in OECD countries and US\$3 trillion among the so-called BRIICS countries (Brazil, Russia, India, Indonesia, China, and South Africa). In Beijing, the economic costs related to hospital admissions and premature death due to respiratory diseases, reduced lung function and chronic bronchitis from particulate air pollution amounted to 10%–13% of the city's GDP in 2008–12. India, Latvia and Russia lose more than 10% of GDP annually because of costs associated with air pollution, and Latin America and the Caribbean lose around 2% of their GDP annually to these costs as well.

In cities with rapidly growing informal settlements and slums, often located in the periphery of urban areas, many inhabitants lack access to basic services, including modern energy sources and city infrastructure such as sanitation and public transport. In 2019, 176 million people in urban areas still did not have access to electricity, and 2.6 billion people worldwide lacked access to clean cooking.

In this scenario, over the next 10 years the urbanization process must necessarily coincide with the diffused decarbonization of the global energy system. To accelerate the transition toward net zero carbon cities, it is primarily necessary to promote energy efficiency, renewable energy, clean electrification, smart energy infrastructure and smart mobility

(IRENA, 2020a; IRENA, 2021b; WEF, 2021b). A combination of technologies and actions is needed to keep the economy and society on track toward a 1.5°C climate pathway, in particular:

- stabilization of energy demand through increased energy efficiency and CE measures, while maintaining economic growth;
- decarbonization of power systems using renewables to meet growing supply needs;
- electrification of end-use sectors, with the increased use of electricity in buildings, industry and transport;
- expanded production and use of hydrogen, synthetic fuels and feedstocks to pursue indirect electrification;
- targeted use of sustainably sourced biomass, particularly in place of high-energy-density fuels or in gas grids;
- carbon capture usage and storage technologies deployment mainly for process emissions in industry and hydrogen production, and bioenergy with carbon capture and storage technologies deployment in cement and power and cogeneration plants.

The future urban energy systems must be integrated and based on high levels of renewables and on more robust, digitized, flexible and resilient networks. Distributed energy generation should be promoted, along with an integrated approach to develop future urban infrastructure by coupling the power, buildings, transport, heating and industry sectors to achieve higher system efficiency and enhance climate resilience.

Urban renewable energy technologies include solar energy (solar photovoltaic, solar thermal heating, solar thermal cooling), urban wind turbines, bioenergy and waste-to-energy, geothermal energy, and district thermal energy networks. Introducing and expanding the use of renewables in urban energy systems, especially via distributed solutions, reduces emissions and can also reduce the risk of sudden, large blackouts and increase the overall reliability of supply. In the next future, ongoing cost reductions for renewable power generation will make electricity an attractive low-cost energy source to fuel the transport sector and for clean hydrogen production (Green hydrogen) (IRENA, 2020b). Green hydrogen, in particular, can support decarbonization of several sectors where it is proving difficult to meaningfully reduce emissions such as intensive and long-haul transport, and chemicals, iron and steel industries (see Section 12.2.4). In addition, it has the potential to create a virtuous cycle for renewables-based electricity grids, as hydrogen can provide much-needed flexibility to power systems, acting as a buffer to nondispatchable renewable generation such as photovoltaics and wind power, and has a potential role for seasonal balancing of renewable generation by storing large amounts of hydrogen for months or even years.

The technical, economic and societal challenges consist in scaling up renewable technologies and building or upgrading grids to accommodate this additional electrification, both of which will require substantial investment. In fact, the power infrastructure and associated policies and regulations were designed decades ago for a centralized system and are proving unsuited for an increasingly decentralized and digitalized system based on high volumes of renewables.

To date, renewable-based decentralized energy systems have been deployed increasingly in and around cities in many countries, supported by a mix of enabling technologies, such as energy storage (including electricity and thermal storage), smart charging for EVs, renewable power-to-heat and renewable power-to-hydrogen, digital technologies and intelligent energy management in both grids and buildings. As this trend continues and accelerates, innovative business models are also emerging, such as energy-as-a-service, aggregators, peer-to-peer electricity trading, community-ownership models, and pay-as-you-go, also enabled by coupling different sectors such as buildings, transport and industry (IRENA, 2019c).

Clean electrification consists in moving the biggest energy-using sectors in cities—buildings and mobility—to the electricity vector, enabling a systemic efficiency concept and supporting the adoption of renewables. Several technologies are available to electrify cities backed by renewables: transport, heating and cooling, lighting and home appliances can all run on clean electricity. Multiple sectors that were either independent or only narrowly interactive before can be fully integrated throughout the grid: for instance, electrified buildings and transport can interact as resources for each other in new ways, exchanging energy as needed. Space heating from fuel generators can be converted to electric heat pumps that are about four times more efficient than traditional fossil fuel technologies and provide cooling power as well, thus simplifying grid and systems infrastructure. In addition, innovative ways to operate power systems in cities will help make the energy transition based on renewables a reality, with distribution system operators playing a vital role. For example, advanced weather forecasting tools for solar and wind power generation can help integrate these renewable resources in today's power systems (IRENA, 2019c; IRENA, 2021b, 2021c).

Clean electrification strategies shall be complemented by energy efficiency measures as well. By reducing initial demand, for instance by insulating buildings and using district heating and cooling, the required build-out of electricity infrastructure is also reduced. CE strategies will also play an increasingly important role in coming decades, contributing to reductions in energy consumption and use of resources. New urban paradigms are also emerging, as more

compact and connected cities are showing significant economic and environmental benefits and tend to be more productive and innovative. In fact, 10% higher urban population density is linked to a 1.1% increase in patents filing and a 1.9% increase in gross value added, according to a study from the Coalition for Urban Transitions. Higher urban density usually entails more efficient energy and land use, reducing the overall carbon footprint of citizens and improving air quality—for instance, networks in single family districts suffer from a 20%–30% distribution loss compared to 5%–10% in higher density neighborhoods. Concepts like the “20-minute neighborhood” in Melbourne and the “15-minute city” in Paris are redesigning urban districts to better provide communities with equitable access to all amenities and services, such as education, health, basic supplies, etc., within a short distance from home, fostering local interactions and supporting small businesses (WEF, 2021b).

In fact, street redesigns and infrastructure investments that prioritize mobility alternatives can positively affect lower-income communities in particular, that tend to be transit-dependent. In addition to reducing (and preventing) emissions, more intelligent urban forms can enhance economic productivity and increase cities’ tax bases by reversing the trend of suburbs cannibalizing tax revenue and burdening cities with debt associated with roads and public utility expansions. This also helps to preserve ecosystems and agricultural land on the urban periphery.

Advanced digital and communication technologies can optimize freight transport as well, for example, as efficiency enhancements in traffic control reduce the overall energy consumed by freight. Technology shifts can also lead to the improvement and relocation of industrial processes, for instance shifting steel production from traditional carbon and energy-intensive methods to green hydrogen methods. Electric arc furnaces could enable a wider relocation of the iron and steel sector to places where relatively low-cost and abundant renewable electricity sources are available.

Parallel to technology development and adoption, policy and regulatory frameworks and market design should be updated to facilitate the shift to low-carbon and climate-resilient cities, as well as the creation of local jobs. In the last decade, many municipal governments have scaled up energy efficiency measures and the use of renewables in the power, heating and cooling, and transport sectors, driven by the need to reduce air pollution, mitigate climate change, enhance resilience, ensure a stable and secure energy supply, reduce expenses and managing costs, alleviate poverty and support local economic development.

By the end of 2020, at least 834 cities in 72 countries, covering 558 million people, have adopted a renewable energy target in at least one sector, and more than 1 billion people—around a quarter of the global urban population—live in a city with a renewable energy target and/or policy (for a total of over 1300 cities) (REN21, 2021).

These cities have a combined total of 1088 targets, including 653 targets for 100% renewable energy use either in municipal operations or city-wide. Around 800 cities committed to net-zero emissions, with the number of such net-zero targets increasing roughly eightfold from 2019, and at least 799 municipal governments have in place regulatory policies, fiscal and financial incentives as well as indirect support policies to enable the uptake of renewables in buildings and transport city-wide. By the end of 2020, 53 cities in 10 countries had either introduced or planned a ban or restriction on the use of natural gas, oil or coal in buildings for space and water heating purposes, up from only a handful of countries in 2015. In addition, several municipal governments are facilitating the integration of renewables into their district energy networks, often in cooperation with public or private partners (REN21, 2021).

Local governments have been forming global and regional networks to increase their advocacy capacity and increase their weight in the climate, sustainable development and energy debates. Collectively, these networks have played an important role in encouraging cities to adopt renewable energy targets and implement local climate action, and they have offered a platform for effective information and resource exchange and inspiration. Main initiatives, which involve several thousand cities around the world, include: Global Covenant of Mayors for Climate & Energy, ICLEI—Local Governments for Sustainability, C40 Cities network, Carbon Neutral Cities Alliance, Sierra Club’s Ready for 100, United States Climate Mayors, the United States Conference of Mayors Climate Protection Agreement, Inter-American Development Bank’s Cities Network in Latin America and the Caribbean, ASEAN Smart City Network, Race to Zero (UNFCC), CC35 (Mayors for Climate) (REN21, 2021).

Within their development programs oriented toward decarbonization, cities are promoting sustainable urban mobility by shifting fleets to renewable fuels and reducing overall road transport through improvements in land use, increased walkability and cyclability, and the promotion of public transport and shared mobility. In the 2030 Agenda for Sustainable Development, sustainable transport is at the center of several SDGs and targets, especially those related to food security, health, energy, economic growth, infrastructure, and cities and human settlements. In particular, electric mobility is constantly growing and will play a decisive role both in reducing urban emissions, and in the possibility of sharing the EV batteries with the grid by accumulating renewable energy or supplying energy when needed (V2B). Smart charging infrastructure should provide an intelligent interface that enables charging cycles that are adaptable to both the conditions of the power system and the needs of vehicle users.

After a decade of rapid growth, in 2020 the global electric car stock hit the 10 million mark, a 43% increase over 2019, and representing a 1% share of overall stock. In 2020, battery electric vehicles (BEVs) accounted for two-thirds of new electric car registrations and two-thirds of the stock. China, with 4.5 million electric cars, has the largest fleet, though in 2020 Europe had the largest annual increase to reach 3.2 million. About 3 million new electric cars were registered in 2020 and worldwide about 370 electric car models were available in 2020, a 40% increase from 2019 (IEA, 2020f).

Numerous factors are contributing to the success of EVs. Several governments provide fiscal incentives that buffer electric car purchases from the downturn in car markets. In several countries and cities, EV charging infrastructure has become mandatory in new buildings, providing a critical entry point for higher uptake of renewables in transport, especially if combined with renewable electricity policies. The growing numbers of low-emission zones and of bans/restrictions on certain fuels or vehicles—in place in 249 and 14 cities, respectively, as of late 2020—are also favoring EV adoption. A few cities have developed local strategies for the production and use of renewable hydrogen in fleets. Electrification already covers all modes of urban transport, including buses, cars, vans, bikes as well as trucks and ferries. Heavy-duty transport such as buses and trucks can use biofuel blends and renewable hydrogen.

Regardless of the sectors involved and the technologies used, a sound process and the right tools for urban energy system planning are needed to establish effective local power generation and meet renewable targets. Sustainable urban energy system plans must be integrated into urban programming as early as possible, as urban forms, functionalities and zoning have significant impacts on energy demand and increasingly also on energy production, particularly with the proliferation of distributed energy sources and prosumers. Collaborative, holistic planning will be crucial to the green transformation of cities. City governments and urban planners should switch from planning around individual assets and sectors toward integrated systems, sharing expertise among professional disciplines and industries. Mayors shall engage multisectoral businesses, civil society and academic stakeholders, including leaders from design, engineering, real estate, construction, utilities, finance, to identify and execute integrated solutions that address multiple issues.

Public and private developers have to collaborate with architects, urban planners, public transport agencies, engineers, contractors, and utility providers throughout the design and building process to deliver the integration needed for a net carbon zero objective. Digital solutions must be embedded into this integrated value chain to enable a more efficient, connected, data-rich, and human-centered design. Digital technologies such as building information modeling (BIM) and digital twins can enable greater flow of information between stakeholders in the value chain throughout the full lifecycle of the building or infrastructure asset, resulting in less waste and improved energy and material efficiency.

1.4 Built environment and circular economy

The world has seen unprecedented economic development the last decades. This global economic growth has been underpinned by strong increases in the use of material resources, as these are used in almost all parts of the economy, not least in construction, the energy sector, and manufacturing. Globally, the use of material resources grew from 27 billion tons (Gt) in 1970 to 89 Gt in 2017 (see Fig. 1.12). Since 1971, global demand for steel has increased by three times, cement by nearly seven times, primary aluminum by nearly six times and plastics by over 10 times. Material consumption growth has coincided with population and economic development. In the same period, global population doubled, while global GDP grew nearly fivefold. Such development has surpassed the planetary capabilities of the Earth, as the current production and consumption system would require an equivalent of 1.7 Earths to replenish the resources consumed and absorb the pollution generated (Earth Overshoot Day). Humanity has become a dominant force in shaping the face of Earth (Krausmann et al., 2009; Smil, 2013; Zalasiewicz, Waters, Williams, & Summerhayes, 2018).

Every year the Earth Overshoot Day (EOD), that is, the day of the year when humanity comes to fully consume the resources (Humanity's Ecological Footprint) that the planet is able to generate annually (Planet's Biocapacity), occurs earlier: July 29 in 2021, September 22 in 2000, December 30 in 1970. If the current trend is maintained, in 2050 humanity is estimated to consume more than double what the Earth is able to produce yearly (Global Footprint Network). Moreover, the human-made mass, so-called “anthropogenic mass”, has recently doubled roughly every 20 years and in 2020 surpassed all global living biomass which currently equals approximately 1.1 teratons. The amount of plastic that has ever been produced (over 8 billion tons) currently doubles the combined mass of all of Earth's animals (4 billion tons) (Elhacham, Ben-Uri, & Grozovski, 2020).

Between 2017 and 2060, the world's population is projected to further grow from 7.5 to 10.2 billion people and the global average GDP per capita, pushed by the advancement in living standards in all countries, is projected to triple and to reach the current level of OECD countries. In the absence of new policies, global materials use would rise more than

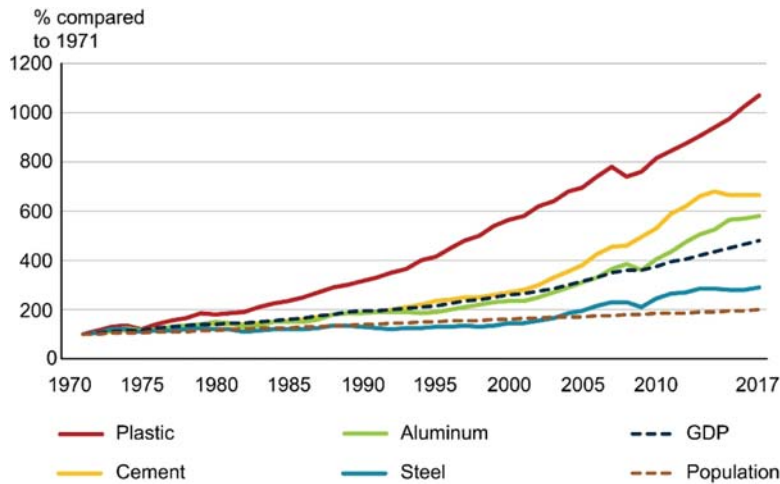


FIGURE 1.12 Demand growth for key materials, GDP and population. Redrawn from (IEA, 2019e).

85% and reach 167 Gt in 2060, and increase reflected in all major categories of materials: metallic ores (9—20 Gt), nonmetallic minerals (44—86 Gt), biomass (22—37 Gt) and fossil fuels (15—24 Gt) (IEA, 2019e).

The projected increase in materials use implies a significant increase in a wide range of environmental impacts, including acidification, climate change, eutrophication, land use, as well as water, human and terrestrial ecotoxicity.

Materials extraction and use have in fact important environmental implications. These include the pollution of local water sources, ecosystem disruption from mining facilities, the emissions of gases that contribute to climate change and air pollution, and environmental degradation from waste landfilling and incineration. All these environmental damages in turn entail economic consequences, as they affect human health, ecosystem services, labor productivity, capital and crop yields, among others. Conversely, materials are essential for production processes and their availability is also fundamental for sustained economic growth (OECD, 2018). OECD studies show that while absolute scarcity is not a major problem for most materials, risks to the security of supply of economically important materials can well damage economic prospects (OECD, 2018).

For these reasons, materials use, their economic drivers and their environmental consequences are central components of several UN SDGs. The topic of materials use is represented most prominently in SDG 12, which aims to “ensure sustainable consumption and production patterns,” explicitly targeting sustainable management and efficient use of natural resources (United Nations, 2020).

Most global environmental impacts are projected to at least double (OECD, 2018). Despite ongoing improvements in efficiency, and thus gradually declining environmental impacts per unit of production, declining ore grades and the increased scale of extraction and production of materials are expected to significantly worsen environmental impacts until 2060. Materials use also has significant consequences for climate change as most GHG emissions stem from materials-management sectors. These come from the combustion of fossil fuels for energy, from agriculture, from manufacturing and from construction. The increased extraction and use of materials contribute to a global increase in GHG emissions, even if their contribution to overall emissions is projected to decrease relative to emissions not related to material management. Total emissions are projected to reach 75 Gt CO₂-eq. by 2060, of which materials management would constitute approximately 50 Gt CO₂-eq. The targets set by the Paris Agreement, including the NDCs and the “well below two degrees” objective, would not be met in the central baseline scenario. Therefore, additional policy efforts are required to meet these goals, such as including policies aimed at reducing GHG emissions in a comprehensive resource management policy package. The waste streams generated by current production and consumption patterns are also projected to increase. As a consequence, the future challenges linked to materials use affect waste management as well as the environment.

These issues have led to increasing policy interest in promoting a transition to a more circular and resource efficient economy, with the goal to avoid the irreversible damages that may be incurred by consuming resources at a rate that exceeds the Earth’s capacity to replenish them, in terms of biodiversity, air, soil, water and climate. CE roadmaps have been established in China in 2013, in the European Union in 2015, in Finland, France, the Netherlands, and Scotland in 2016, as well as in Slovenia and Portugal in 2017. Similar frameworks targeted at resource efficiency are also in place in Japan (Fundamental Law for Establishing a Sound Material-Cycle) and the United States (The Sustainable Materials Management Program Strategic Plan).

1.4.1 Circular economy paradigm

The CE paradigm encourages to rethink and redesign the manufacturing, usage and disposal patterns of products and services in an economy. The concept of CE presents a sustainable alternative to the usual linear model of take-make-use-dispose, replacing it with make-use-reuse-remake-recycle. By definition, CE is an economic system that is based on business models which replace the “end-of-life” concept with reducing, alternatively reusing, recycling and recovering materials in production/distribution and consumption processes.

The CE framework weaves together opportunities related to innovation, competitiveness, productivity, wage upgradation and industrial strategy together with environmental, socio-economic and climate objectives. According to the Ellen MacArthur Foundation, CE has a “trillion-dollar opportunity with huge potential for innovation, job creation, and economic growth” across the globe, given that the resource productivity is an underexploited source of possible future wealth and competitiveness (Ellen MacArthur Foundation, 2015). According to Accenture, \$4.5 trillion could be saved globally by a shift toward CE and reusing what is usually cast away and wasted. Better-informed reuse and recycling operations, committed to reducing carbon emissions, would help developers find creative and cost-saving ways to reuse materials from the built environment.

In this context, the importance of promoting a CE model for the construction sector, which is the most resource-intensive industry, is clearly evident (Norouzi, Ch’afar, Cabeza, Jiménez, & Boer, 2021).

Between 40% and 50% of the resources extracted for global materials are used for housing, service buildings and infrastructure. The sector consumes over 4 Gt of cement per year (equally divided between buildings and infrastructures), over 700 Mt of steel (equal to over 60% of world consumption), over 20 Mt of aluminum (corresponding to over 27% of world consumption), over 40 Mt of flat glass (about 80% of global consumption), over 75 Mt of plastic (PVC, PUR, PE-HD, corresponding to about 20% of global consumption), over 30 Gt of sand, about 0.9 billion m³ of wood products, along with adhesives, coatings, paints, varnishes and many others (ECSO, 2018; ECSO, 2019; IEA, 2019e; International Bank for Reconstruction and Development, 2018; OECD, 2018).

The manufacture and use of materials for buildings construction and renovation represented 11% of the global overall energy- and process-related carbon dioxide (CO₂) emissions, a quantity greater than the overall CO₂ emissions of the European Union. Specifically, more than half of emissions related to buildings materials stem from steel and cement, as they are used in large quantities and are still usually produced through carbon-intensive routes (see Table 1.4). Aluminum, glass, insulation, plastics and other materials (e.g., other petrochemical products and copper) are secondary contributors. Steel and cement alone accounted for around 1.8 GtCO₂ in 2017, or approximately 15% of total buildings-related emissions, which includes direct emissions from fossil fuel use in buildings and indirect emissions from upstream electricity, heat, steel and cement production. Total cement production is responsible for around 7% of global CO₂ emissions, with steel contributing 7%–9% of the global total, of which around half can be attributed to buildings and construction (IEA, 2019e; OECD, 2018). At the same time, annual material losses in construction and demolition (C&D) are rising, and result in end-of-life materials, or waste materials, equivalent to nearly 40% of mass when extracted. In the EU, current C&D waste accounts for approximately 25%–30% of the total waste generated and consists of numerous materials, including concrete, bricks, gypsum, tiles, ceramics, wood, glass, metals, plastic, solvents, asbestos, and excavated soil (ECSO, 2019). Although many of these can be recycled, today only a third is recovered and reused, causing the irredeemable loss of valuable minerals, metals and organic materials. With such quantities involved, even small improvements in the way the construction industry works can have significant impacts on sustainability (WEF, 2016).

Material demand in buildings is mostly dictated by their framing, height, construction practices and prescriptions by buildings codes. In particular, framing significantly affects the material intensity of a building, that is, the amount of material used per m² of floor space. While timber-frame buildings typically require less than 50 kg/m² of cement per of floor space; reinforced concrete structures typically require 200–300 kg/m² of cement. 60–90 kg/m² of steel is generally used in concrete or steel building structures. The use of load-bearing masonry can reduce steel use intensity by half, and timber framing reduces it even further. Increased material use in buildings is also due to global market shifts: the share of reinforced concrete buildings reached over 50% in 2017, which is an increase of more than 15% since 1990, largely caused by construction development in China and other emerging markets (IEA, 2019e).

Building’s height is another strong driver of global material demand, as the number of stories affects structural material quantities and increases material intensities per m² of livable area. As a reference, buildings with 6–10 stories typically use 35% more structural materials per m² than buildings with five and fewer stories. For more than 20 stories buildings, steel use intensity can be four times higher than low-rise structures with similar framing (IEA, 2019e). According to the Council on Tall Buildings and Urban Habitat, over the past 15 years, particularly as buildings

TABLE 1.4 Main use of metallic materials in construction.

Use in construction	Ferrous		Nonferrous			
	Steel	Cast iron	Copper	Aluminum	Zinc-titanium	Lead
Structural frames	■			■		
Concrete rebar	■					
Roof cladding	■		■	■	■	■
External façade cladding	■		■	■	■	■
Internal façade cladding			■			
Window frames				■		
Shading systems				■		
Gutters, flashing, downpipes			■		■	
Water distribution pipes	■		■			
Gas distribution pipes	■	■	■			
Drainpipes	■	■				■
Heating system pipes	■		■			
Heat exchangers			■			
Electrical wires			■			
Soundproofing panels						■
Vapor barriers				■		
Pipes casing						■
Radiation protection						■
Radiators		■		■		
Kitchen sinks	■					
Water taps	■					
Cables	■					
Door handles, locks			■			

construction boomed in China, the total floor space of buildings of more than 30 stories has more than quadrupled (IEA, 2019e). This trend has significantly contributed to material demand growth.

Floor area in the buildings sector worldwide is expected to increase 75% between 2020 and 2050, of which 80% is in emerging markets and developing economies. Globally, an additional floor area equivalent to the surface of the city of Paris is expected every week through to 2050, with a consequent increase in the consumption of materials, production of waste and polluting and climate altering emissions (IEA, 2021b).

It is therefore necessary to act swiftly to promote a circular model in the construction sector as well, capable of achieving the climate change mitigation goals set in the Paris Agreement and of UN's SDGs for 2030 aimed at ensuring sustainable consumption and production patterns (goal 12), build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation (goal 9), make cities and human settlements inclusive, safe, resilient and sustainable (goal 11) and take urgent action to combat climate change and its impacts (goal 13) (United Nations, 2020).

1.4.2 A circular model for construction

To promote CE in the construction sector, it is necessary to improve both the life cycle of materials and components and that of buildings, through a combination of material efficiency strategies and of technology shifts. Enabling

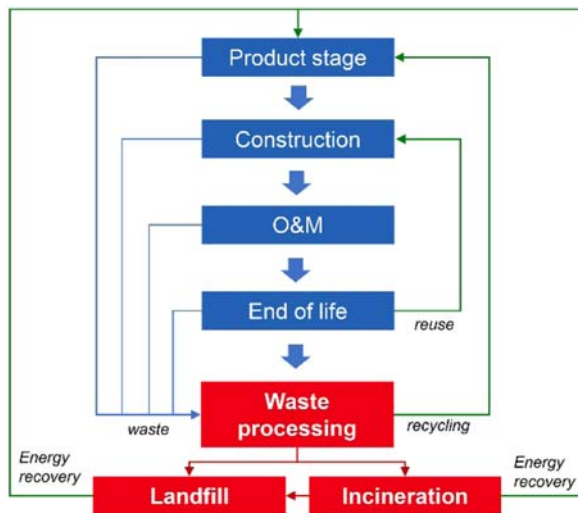


FIGURE 1.13 Circular model for construction.

frameworks are needed to reduce business risks and other barriers, and to create market support for adopting more resource efficient construction materials, technologies and practices, including standards, policy and regulation that will support CE practices. These may include codes of practice, quality protocols, performance-based technical standards, harmonized classification of primary and secondary resources, certification procedures for reuse of structures, components and materials; regulation to enable construction materials recovery and industrial symbiosis, while maintaining environmental protection (ARUP, 2018; Charef and Emmitt, 2021; ECSO, 2019; Ghaffar, Burman, & Braimah, 2020; Hart, Adams, Gieseckam, Tingley, & Pomponi, 2019; Mhatre, Panchal, Singh, & Bibyan, 2021).

The strategic objective is to decouple economic growth from the combination of demand for materials and the environmental impact of materials lifecycle (Benachio, Freitas, & Tavares, 2020; Gallego-Schmid, Chen, Sharmina, & Mendoza, 2020; Ghaffar et al., 2020; Mhatre, Gedam, & Unnikrishnan, 2021).

As regards the life cycle of building materials and components, it is necessary to improve the energy and environmental efficiency of the production process by reducing the quantity of material used per unit of product, favoring renewable and recycled materials, increasing production efficiency and recovery of processing scraps, reducing water consumption, reducing atmospheric emissions, improving the energy efficiency of the process, switching to lower-carbon fuels (e.g., gas instead of coal, electrification of processes, use of hydrogen), increasing the use renewable energy and introducing certified company systems for the management of the environment (ISO 14001) and energy (ISO 50001). The use of recycled materials for the creation of new building products, in addition to reducing the overall consumption of virgin raw materials and the production of waste sent to landfill, determines a reduction in energy consumption and environmental impacts in the extraction and processing phase of the raw material (see Fig. 1.13) (WEF, 2016; UNEP (United Nations Environment Programme), 2020a). In the case of aluminum, for example, energy consumption is reduced by 95%, going from 14 kWh/kg of primary processing to 0.7 kWh/kg in the case of treatment of recycled material.

Strategies for greater sustainability of building products must also concern the procurement of raw materials, the distribution of the product by minimizing packaging, the phase of use by increasing its durability, and the end-of-life by using recyclable materials that allow easy separation of components (see Table 1.5).

It is also important to favor the adoption of product labels on materials and components such as Environmental Product Declaration and Health Product Declaration, which provide information on their sustainability, including their embodied energy and carbon, in ways that can be used in a life-cycle assessment of products or buildings: this in turn increases the capacity for people to make better design, purchase and operational decisions.

Concerning buildings, instead, the strategies to promote CE require a life cycle thinking design approach, with the the following aims:

- to select the materials and products with a lower environmental footprint (bio-based materials, recycled materials, low-carbon materials, bricks made from recovered building materials, recycled concrete, concrete mixes that reduce carbon impact, etc.), coming from low-carbon supply chains and possibly locally sourced to reduce the impacts due to transport and embodied carbon (see Section 7.3);

TABLE 1.5 Eco design strategies.

Strategies	Actions
Design for resource conservation and for low-impact materials	Renewable raw materials Reduction/replacement of hazardous materials Protection of the territory and biodiversity Use of natural techniques
Design for cleaner production	Reduction of materials content Reduction of energy consumption Use of recycled materials Recovery of processing wastes Improvement of production efficiency Reduction/replacement of hazardous materials Use of renewable materials Use of lower carbon fuels Use of energy produced from renewable sources Reduction of matter and energy emissions Reduction of accident risks Adoption of an ISO 14001 or ISO 50001 management system
Design for efficient distribution	Avoidance of packaging Minimization of materials Make the packaging an integral part of the product Provision of a second use of the packaging Use of recycled and recyclable materials for packaging Minimization of consumption for transport Design of compact, concentrated products to be assembled in place Lighter packaging materials
Design for green use and maintenance	Improvement of the efficiency of the product during use Reduction of impacts on health and the environment during use Increased durability Increased longevity Additional functions Simplicity of disassembly and maintenance Instruction for use and maintenance
Design for reuse, remanufacture, disassembly, recycling, safe disposal	Use of recyclable materials Use of low complexity materials Ease of disassembly Recovery of components by remanufacturing Efficiency of the recovery/disposal process

- to reduce the materials use intensity through design optimization choices on shape, right-sizing and light weighting of components and structures, reducing cement content in concrete and using high performing materials that provide the required performance with reduced quantities (nanoporous insulators, PCMs, nanostructured concrete and steel—see [Section 7.4](#));
- to reduce the maintenance needs and prolong the operating life by employing advanced materials and products with enhanced durability and self-cleaning/self healing capabilities;
- to favor the recovery and reuse of materials through adaptive reuse and selective demolition of existing buildings;
- to optimize building and elemental service life, encouraging a medium to long term focus on the design life of major building elements, as well as their associated maintenance and replacement cycles (design for durability and maintenance);
- to extend the service life of the building as a whole, either by facilitating the continuation of the intended use or through possible future changes in use—with a focus on replacement and refurbishment (design for adaptability);
- to facilitate the future circular use of building elements, components and parts, with a focus on producing less waste and on the potential for their reuse, or high-quality recycling of major building elements following deconstruction by improving the component design and using different construction methods to avoid down-cycling (design for deconstruction).

- to provide more efficient building construction methods and techniques such as prefabrication and modular construction, off-site and on-site construction automation, robotics and additive manufacturing able to ensure cleaner production by preventing the production of waste while increasing efficiencies in the uses of energy, water, and resources (see [Chapter 8](#)).

Particular attention must also be given to the management of the construction site using Lean construction methods, designing and implementing of site waste management plans and procedures to ensure the achievement of maximum potential to reuse and recycle wastes, and leveraging digital systems to track materials and prevent their excessive use (see [Chapter 9](#)).

In this picture, the progressive adoption of digital technologies in the whole building sector can be leveraged as a key enabler for the deployment of the CE strategies depicted above. The digital transition of all architecture, engineering, construction and operation tasks is already providing unprecedented insights over the whole life-cycle of the building and its components. The use of integrated building design and construction processes, including BIM and life cycle assessment (LCA) tools, allows in fact the designer to take into account and track the environmental impact of every project decision from a life-cycle point of view. Advanced survey methods that include LiDAR scanning, drone photogrammetry and 3D photo reconstruction allow the best assessment of the site's potential for reuse and recycle of existing structures (see [Section 6.1](#)). Any choice regarding building shape, technical elements and systems can be optimized by the use of building performance simulation (BPS) tools (see [Chapter 5](#)) and parametric and generative design methods (see [Section 6.4](#)), which can moreover produce detailed construction specifications that are directly fed to digital fabrication tools (3D printers, CNC machines) able to produce exactly what is needed, eliminating material wastes from both processing and from components oversized due to limited customization of standard products. Once delivered, each building can also keep a digital twin to be continuously and automatically updated with all data concerning its components and materials, their maintenance and renovations, which, along with the building's Material Passport (MP) and BRP, can provide all information needed to drive informed retrofit, adaptive reuse or selective demolition interventions (see [Section 11.4](#)).

1.5 Climate positive and smart buildings

To address the convergence of these health, social, economic and environmental planetary emergencies, the future cities, buildings and infrastructure must be based on four main pillars: livability, sustainability, resilience and affordability. In such vision, buildings will provide comfort, be equipped for the most unprecedented events, support human and planetary health, and be affordable and accessible for all of society ([WEF, 2021a](#)).

First of all, the future built environment shall be thoroughly livable, that is, designed for people of all ages and abilities. Habitats should enable a rich, culturally vibrant existence, with real estate developing in tandem with the needs of citizens to ensure the best interactions between spaces and occupants. Moreover, buildings should be fully sustainable, that is, optimized for lower environmental impacts in every aspect from construction to operations. Cities and buildings should be resilient, that is, capable of adapting and mitigating the effects of unforeseen natural and man-made events, such as climate, financial, social and health crises. Finally, real estate should be affordable as the availability of housing, transportation and essential services is essential to the overall health of society. Such affordability includes both financial accessibility (affordable rents, low barriers to home ownership) and the promotion of standards in terms of space, health, location and access to basic services.

The new needs for comfort, health, energy efficiency, environmental sustainability and resilience required of the architecture of the new millennium have led in the last two decades to the definition of new and more performing building standards, which can be summarized in the three paradigms of zero energy building (ZEB), green building and smart building.

The first, "ZEB", emphasizes the very high energy performance of the building in its operational phase and the ability to meet its energy needs with the use of renewable energy produced on site or nearby. The second, "green building," emphasizes the building's ability to offer maximum comfort to users while ensuring the lowest energy and environmental impact throughout its entire life cycle. The third, "Smart or intelligent building," adds to the requirements of energy efficiency and environmental sustainability those of intelligent interaction with the context and with users.

All three models respond to the need to move toward a net-zero carbon economy through a building industry based on knowledge and innovation, more resource-efficient, greener and more competitive, with a high employment rate and favorable to social and territorial cohesion.

Smart buildings, in particular, thanks to extensive connectivity and digitalization and the integration of AI instruments, can play a leading role in transforming the world energy market, by transforming it into a more decentralized,

renewable-based, interconnected and variable system that maximizes efficiency and ensures that all resources are used in an optimal way, all while enabling a better living and working environment for their occupants. The digital technologies that characterize smart buildings can not only increase their inherent energy efficiency in performing the expected activities, but also underpin new possibilities of managing that same energy. This potential is today increasingly valuable because the world's energy systems are undergoing a radical transformation. As decarbonization has become a priority for the built environment, intermittent renewable energy sources (wind power, photovoltaics) are being increasingly integrated into the grid, the electrification of energy consumption is increasing, and “prosumers” (users that both consume and produce energy) are emerging as new important actors in the energy supply. In this context, demand-side flexibility is increasingly important to ensure that grid-side energy systems run as efficiently as possible and that energy is supplied when it is effectively needed, and is consumed only when it is available. Furthermore, by digitally connecting buildings, vehicles and equipment, system operators are able to accurately quantify and predict the impacts of energy efficient technologies and behaviors in lowering and shifting energy demand, to provide transparent measurements, and contribute to grid decarbonization.

Therefore, technology adoption represents one of the most important enablers in the transition to a new era for real-estate. Cities are already generating enormous amounts of data that can be harvested to inform operating, maintenance and investment decisions. An interconnected network of smart buildings that operate together shall be rolled out to create scale and efficiencies. This future vision requires extensive upskill and competences throughout the industry as well as an expanded talent pool. Industry and governments should establish the right leader teams and appoint them with capabilities to head the transformation around sustainability, resilience, and technology. Data privacy and security must also be a top priority to ensure occupants and owners are protected.

1.5.1 Zero energy buildings

The term “ZEB” is intended to generally indicate a category of buildings with very high energy performance in the operational phase, characterized by a very low or almost zero annual energy requirement, entirely or very significantly covered by renewable energy, produced on-site or nearby (BPIE, 2011; ECOFYS, 2013).

The energy performance of a building is usually determined based on the amount of annual primary energy actually consumed, or that is expected to be required to meet the different energy needs with a standard use of the building, such as winter and summer conditioning, domestic hot water production, ventilation and, for the tertiary sector, lighting, lifts and escalators systems (energy and transport services). Global energy performance, as well as that of individual energy and transport services of the building, is generally measured by performance indexes ($EP_{gl,tot}$) expressed in total annual primary energy per area unit (kWh/m^2_{yr}).

The concept of ZEB was introduced in the early 2000s and has since gained popularity world-wide to promote the important objectives of achieving the balance between needs and self-sufficiency for a building under service conditions (D'Agostino and Mazzarella, 2019; EU, 2010; IPEEC Building Energy Efficiency Taskgroup, 2018).

According to the definition, the transition from a reference conventional building toward a zero-energy building should follow two main strategies, the reduction of the energy demand ($EP_{gl,tot}$) using energy saving techniques, and the increase of energy supply from renewable energy taken from the grid or produced on site or nearby ($EP_{gl,ren}$). Design and construction of a ZEB require therefore a comprehensive approach to promote rational use of energy by reducing energy requirements (energy sufficiency), installing high efficiency systems (energy efficiency) and using renewable energy sources (clean energy) through an optimal balance of passive (thus affecting mainly the architectural, morphological and building technology variables) and active measures (concerning the operation of technological systems), in order to achieve the best comfort conditions, a proper use of resources and reduced impacts on the receptor ecosystem.

Because buildings are normally connected to an external network (grid-connected) for the supply of energy (electricity and gas), and in view of the discontinuous nature of renewable energy sources (available only for certain times of the day), what is actually equal to zero is not the consumption of nonrenewable primary energy, but the balance between primary energy taken from the grid and the self-produced one. Therefore, they are more commonly, and correctly, referred to as “net ZEBs”: the excess energy produced by the system is fed into the electricity distribution grid, which in turn provides the users with the energy required in the case of insufficient self-production in unfavorable times (at night or in conditions of poor wind or sunlight). Buildings in which renewable energy production covers to a very significant extent the energy needs, although without achieving zero net consumption of nonrenewable energy, are referred to as “nearly zero energy buildings” (NZEB); when instead the production of renewable energy actually exceeds the needs of the building, they are called Net Plus Energy Buildings or Net Positive Energy Buildings. For

TABLE 1.6 Benchmarks for net zero-energy building performance according to European climate zones.

Climate zone	Office buildings			Single family house		
	EP _{gl,tot} (kWh/m ² yr)	EP _{gl,ren} (kWh/m ² yr)	EP _{gl,nren} (kWh/m ² yr)	EP _{gl,tot} (kWh/m ² yr)	EP _{gl,ren} (kWh/m ² yr)	EP _{gl,nren} (kWh/m ² yr)
Mediterranean	80–90	60	20–30	50–65	50	0–15
Oceanic	85–100	45	40–55	50–65	35	25–30
Continental	85–100	45	40–55	50–70	30	20–40
Nordic	85–100	30	55–70	65–90	25	40–65

these buildings, the difference between the energy demand (EP_{gl,tot}) and renewable energy supplied (EP_{gl,ren}), normally calculated to support classifying buildings as Nearly Zero, Zero or Positive energy, is almost equal to zero or negative (Mehrdad Shirinbakhsh, 2021).

In 2016, the European Commission published possible benchmarks by climate zone for NZEB performance of office buildings and single family houses, providing yearly reference values per unit of floor area for global primary energy consumption (EP_{gl,tot}), renewable energy produced on-site (EP_{gl,ren}) and nonrenewable primary energy demand or net primary energy demand (EP_{gl,nren}) from which the energy performance rating, the energy performance requirements and/or the certificate are normally calculated (see Table 1.6) (Commission Recommendation EU, 2016).

Renewable energy can be produced by equipment located on the roof or integrated into the building envelope (generation on the building's footprint) or via systems on the ground (on-site generation from on-site renewables), it can be produced on site from external sources such as biomass (on-site generation from off-site renewables), or in the neighborhood as in the case of common facilities shared with a larger group of buildings (nearby generation). Finally, it can be produced off-site and bought from the network (off-site in the grid). Renewable energy produced anywhere in the grid has the advantage of allowing any building the opportunity of reaching zero CO₂ emissions, considering that buildings in cities would typically not be able to produce enough renewable energy, on-site or nearby, to reach zero CO₂ emissions. However, the definition of ZEB does not cover the cases, although positive in terms of globally reducing GHG emissions, of investments in plants powered by renewable energy sources located in other places (off-site generation) or the purchase of green energy (off-site supply).

If neither on-site nor off-site generation or purchase are viable options due to technical, financial, and/or legislative barriers, carbon offset solutions can be explored next. These should be used only to compensate for the carbon emissions generated by remaining consumption of noncarbon free energy. Such offsets should preferably be obtained by investing in energy efficiency or carbon-free renewable energy projects elsewhere, although preferably within the boundaries of the city. The emissions reduction benefits must be claimed through a credible mechanism such as carbon credits or a local carbon credit fund (WRI, 2019).

The energy performance of the building in terms of primary energy can either be measured only during the use phase (as is the most common case) or refer to a building's broader life cycle, thus including the phases of manufacture of materials (embodied energy), transportation and construction. The current definition of ZEB excludes energy consumption related to the production stages of materials and building systems (embodied energy), transport to the yard, construction and demolition of the building itself.

From an energy point of view, in fact, these phases currently have a modest relevance compared to consumption in the use phase of the building: on a 50 years scope, heating, cooling, lighting, hot water production account to more than 90% on the overall energy consumption throughout the entire life cycle of the building. Furthermore, due to a still insufficient results consistency from different LCA tools, it may be too early to require LCA information as part of a regulatory requirement.

Nevertheless, as energy consumption during the use phase decreases with increased energy efficiency, energy consumption for building maintenance of systems and equipment, for building construction and disposal as well as due to occupants behavior and usage patterns become more important and should be considered in the near future. In fact, life cycle analyses of energy consumption of existing low-energy buildings show that the influence of embodied energy on the overall lifetime energy in a NZEB is much higher than in an inefficient building. Similarly, usage patterns also become increasingly important as buildings become more efficient, as the way buildings are operated becomes a larger factor of overall energy consumption. In the case of low-energy buildings or buildings supplied by a

low-carbon-intensity grid, embodied emissions can indeed represent as much as 40%–60% of the life cycle carbon emissions. Therefore, as designers move toward more energy efficient buildings through energy sufficiency, energy efficiency and clean energy measures, policy makers shall look into additional aspects such as energy management, embodied energy and usage patterns to promote further energy savings. The reduction of embodied carbon should be considered before compensating for remaining emissions with carbon offset solutions, such as carbon credits, for instance by selecting low-carbon materials and cleaner fuels.

In the framework of a more circular economy, the future goal is to include into the net zero definition the embodied carbon arising from the materials, machinery, and equipment used in building construction, maintenance, and repair as well. This will lead to a “zero-carbon building” that produces on-site enough carbon-free renewable energy to meet its energy needs across its entire life cycle.

1.5.2 Green buildings

The term “green building” indicates a building which has a lower environmental impact compared to an identical building constructed in accordance with local regulations and current practice, as evaluated along its entire life cycle: from raw material extraction to products manufacturing and transport, to construction, management and maintenance of the building, until its final decommission. Environmental aspects taken into account in this assessment concern relations with the context, resources consumption, diffusion of pollutants into air, water and soil, waste production and indoor well-being (Khoshbakht, Gou, Lub, Xie, & Zhang, 2018). Therefore, the differences from a ZEB are on the one hand in the performance requirements, and on the other hand in which phase of the life cycle these requirements are assessed.

As regards the first aspect, in addition to the energy efficiency requirements that characterize ZEBs, a green building must in fact be able to provide its occupants with the optimum conditions of thermal, visual, acoustic, electromagnetic, and psychological comfort and indoor air quality through an efficient use of all resources (including water and material resources), a low level of emissions and the use of materials compatible with the environment, possibly locally sourced (zero km), which can guarantee both durability and reuse and recyclability of the construction components at the end of their operative life. In particular, acoustic comfort is often neglected in the design of ZEBs as it may conflict with optimal daylighting and natural ventilation design. In fact, recent post-occupancy evaluations of low-energy buildings show that they often score high for all categories of occupant satisfaction except for acoustic quality and privacy.

Concerning the second aspect, unlike ZEBs which energy performance is measured only in the operative phase of the building, the performance of a green building is measured along its entire life cycle (*from cradle to cradle*), including production (*from cradle to gate*), transport (*from gate to site*), construction and demolition phases (*from construction to cradle*), in order to reduce the net environmental unbalance between the benefits and burdens to the environment during the different phases of the building process.

Over the last 20 years, the concept of green building has arisen as the most important and progressive trend in the building industry, and it is being recognized as a long-term business opportunity. This is also shown by the significant increase in the number of green building technology patents deposited since the beginning of the new century, covering both constructional and architectural elements and equipment systems (renewable energy integration, energy efficient HVAC and lighting technology, etc.) (Jodidio, 2013). While design, construction and operation of buildings has steadily progressed, these forward steps are still minute when compared with the rate of change that is required to avoid the worst effects of climate change and other global environmental challenges. Nevertheless, the growth of green buildings is unmistakable and the Global Green Building Market is projected to grow at a CAGR of 13.2% from US\$247.26 billion in 2019 to US\$671.37 billion by 2027 (Green Building Market Size, 2020).

The environmental quality of a green building is normally attested by a process of performance evaluation and certification carried out by independent third parties and accredited according to the correspondence of specific requirements (green building rating systems, GBRS). The evaluation criteria concern aspects such as the building integration into the environment, the efficient use of resources, the atmospheric emissions, the environmental compatibility of materials, the quality of the indoor environment, the use of innovative technology solutions.

Criteria relating to building integration into the environment (Sustainable sites, location and transportation credits) tend to limit the impact generated by construction activities on the natural environment while respecting the balance of the ecosystem. They promote and reward aspects such as the reduction of emissions associated with transport, the protection of local ecosystems, the management of rainwater runoff, the reduction of the heat island effect and the reduction of light pollution.

Criteria relating to water management (water efficiency credits) normally approach environmental issues related to the use, management and disposal of water inside and outside buildings, monitoring the efficiency of flows and

pursuing the objective of reducing the consumption of drinking water for all those functions where it is not strictly necessary. The reduction in the consumption of drinking water also makes it possible to reduce the volumes of discharges from buildings resulting in a lower load on public networks and lower costs of public infrastructure for the administration and citizens.

Criteria on energy efficiency and atmospheric emissions (energy and atmosphere credits) aim to achieve increasing levels of energy performance beyond the code standards, to reduce environmental and economic impacts associated with excessive energy use and to encourage the reduction of GHG emissions by using renewable energy technologies and carbon mitigation initiatives. These criteria also reward participation in demand response technologies and programs that make energy generation and distribution systems more efficient, increase grid reliability, and reduce GHG emissions.

Criteria relating to materials and resources consider environmental issues related to the choice of materials for construction and the reduction and disposal of waste during both construction and demolition. The various credits incentivize the use of sustainable materials, as well as the reuse and recycling of materials, reducing the disposal of waste in landfills and incinerators. This way, an attempt is made to reduce the demand for virgin materials and to favor local materials to reduce the environmental impact.

A score is associated with each of the criteria and the overall final evaluation of the building is obtained from the weighted sum of the scores, which determines its performance class: sufficient, good, optimal, excellent. A certain set of criteria (so-called prerequisites) are compulsory for the pass grade and therefore mandatory to get certified at all.

GBRSs have become increasingly important in the current green building development, as they can help building owners and designers in baselining (by establishing initial performance targets), benchmarking (by allowing comparison with competitors or with alternative solutions) and decision-making processes. To date, several GBRSs have been developed around the world to evaluate the sustainability of buildings and more and more buildings can boast certified high environmental performance (see [Table 1.7](#)).

Most popular assessment and certification systems include, at the international level, the Leadership in Energy & Environmental Design (LEED) system, developed by the United States Green Building Council in 1996 and used since 2000, the Building Research Establishment Assessment Method (BREEAM), introduced in 1990 by the British Building Research Establishment (BRE) and now widely used in the UK and in Northern European countries, and the Living Building Challenge program, created in 2006 by the nonprofit International Living Future Institute, as well as the Excellence in Design for Greater Efficiencies (EDGE), a green building certification system for emerging markets, launched in 2014 by the International Finance Corporation (IFC)—a member of the World Bank Group—to make it faster, easier and more affordable to build and brand green buildings in over 170 emerging markets. Other national buildings environmental certification schemes include the CASBEE in Japan, Green Mark in Singapore, the UAE Estidama Pearl Rating System in UAE, the DGNB in Germany, the Green Star in Australia ([Awadh, 2017](#); [He, Kvan, & Liu, 2018](#); [Leskinen, Vimpari, & Junnila, 2020](#); [Pai and Elzarka, 2021](#); [Quirapas Franco, Pawar, & Wuc, 2021](#); [Sartori, Drogemuller, Omrani, & Lamari, 2021](#); [Shana and Hwang, 2018](#); [Zhang, Zhan, Wang, & Li, 2019](#); [Zhang et al. 2019](#)).

Some GBRSs are specifically suited for the building industry and the specific needs of the country where they were developed, whereas others can be applied worldwide. Most GBRSs offer specific versions in terms of building type, such as hotels, offices or schools, while few of them differentiate versions in terms of project stages such as design, construction, decoration, and operation. Some GBRSs, such as LEED, require documentation confirming that operational performance is monitored and reported after occupancy, others go further by requiring onsite performance verification to obtain (Living Building Challenge) or to maintain certification (WELL rating system).

Among more recent and noteworthy examples of buildings with environmental certification, Powerhouse Brattørkaia by Snoetta in Trondheim (see [Fig. 1.14](#)) is the biggest new energy-positive building in Norway, expected to generate more energy in its operational phase than it consumed through the production of building materials, construction, operation and disposal of the building. The building, certified BREEAM Outstanding, has been designed based on environmental requirements. For Powerhouse Brattørkaia, form follows environment, while optimal use of solar energy has determined the building's strongly characterized architecture. Photovoltaic systems and other sources of renewable energy, able to produce around 485,000 kWh/year, and an extremely low energy consumption allow the building to be energy-positive.

In January 2021, after 2 years of testing, the European commission launched the instrument Level(s), an assessment and reporting framework that provides a common language for sustainability performance of buildings throughout their entire life cycle ([JRC, 2021b](#)).

Level(s) promotes lifecycle thinking for buildings and provides a robust approach to measuring and supporting improvement from design to end of life, for both residential and office buildings. It can be used directly on building

TABLE 1.7 Main green building rating standards in the world.

Country	Name of GBRS	Scope of application	Agency/organization who published the standard	Starting year
Singapore	Green Mark	Buildings located in Singapore and internationally	Building Construction Authority (BCA)	2008
Philippines	Building for Ecologically Responsive Design Excellence (BERDE)	Buildings located in the Philippines	Philippine Green Building Council (an NGO in the Philippines, member of World Green Building Council and accredited by the Philippines Dept of Energy)	2018
China	Assessment Standard for Green Building (GB/T 50378)	Civil buildings located in China	Ministry of Housing and Urban- Rural Development of the People's Republic of China (MOHURD)	2006
Germany	DGNB certification system	Buildings and urban districts located in German or internationally	German Sustainable Building Council (DGNB)	2007
US	Leadership in Energy and Environmental Design (LEED)	Buildings located internationally and all building types	United States Green Building Council (USGBC)	1998
UK	Building Research Establishment Environmental Assessment Method (BREEAM)	Buildings located internationally and all building types	Building Research Establishment (BRE)	1990
Japan	Comprehensive Assessment System for Built Environment Efficiency (CASBEE)	Buildings located in Japan	Institute for Building Environment and Energy Conservation (IBEC)	2002
Australia	Green Star	Buildings located internationally	Green Building Council Australia (GBCA)	2003
UAE	Estidama Pearl Rating System	Buildings located in the Gulf region	Abu Dhabi Urban Planning Council (UPC)	2010
Qatar	Global Sustainability Assessment System (GSAS)	Buildings located in the Gulf region	Gulf Organization of Research and Development (GORD)	2009
Hong Kong	Building Environmental Assessment Method (BEAM)	Buildings located in Hong Kong	Hong Kong Green Building Council and the BEAM Society Limited	1996
India	Indian Green Building Council (IGBC)	Buildings located in India	Indian Green Building Council	2013
France	Haute Qualité Environnementale (HQE)	Buildings located internationally	Cerway–France	1997
Italy	Protocollo Itaca	Buildings located in Italy	Institute for Innovation and Transparency of Procurement and Environmental Compatibility (ITACA)	2004
US	Living Building Challenge	Buildings located internationally	International Living Future Institute (ILFI)	2006
US	Excellence in Design for Greater Efficiencies (EDGE)	Buildings located in emerging markets	International Finance Corporation (IFC)	2014

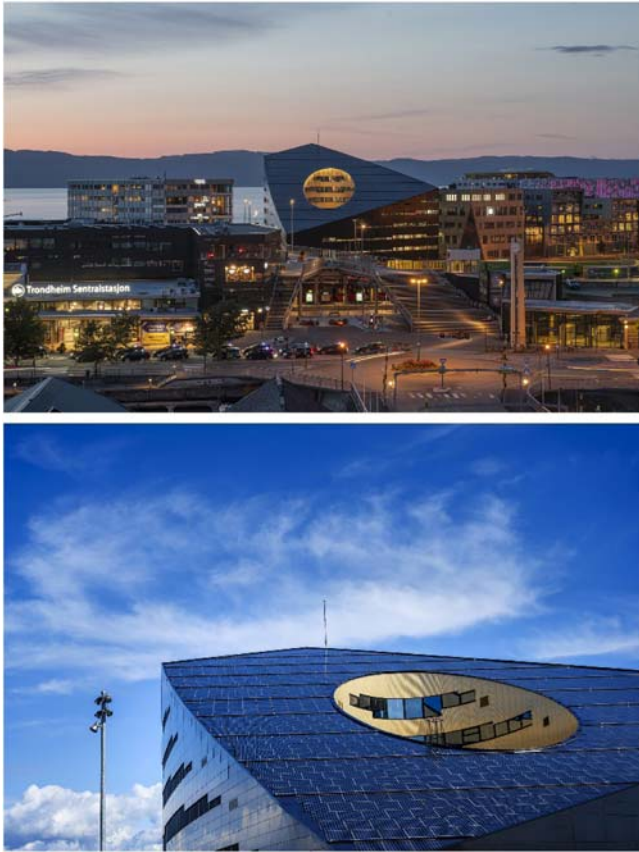


FIGURE 1.14 Powerhouse Brattørkaia, Trondheim. *Courtesy of Powerhouse.*

projects and portfolios, or as a basis for other initiatives, policies, schemes and actions to include life cycle thinking and circularity. It can be applied from the very earliest stages of conceptual design through to the projected end of life of the building.

The Level(s) common framework has been designed with three main project actors in mind and has the potential to offer a range of advantages: project design teams, including architects, engineers, quantity surveyors and specialist consultants; clients and investors, both public and private, including property owners, developers, managers and investors; public policy makers and procurers, at national, regional and local level.

The Level(s) common framework is based on six macroobjectives, which describe what the strategic priorities should be for the contribution of buildings to EU policy objectives in areas such as energy, material use and waste, water and indoor air quality (see [Table 1.8](#)).

A set of indicators and common metrics is provided for each of the macro-objectives for measuring environmental performance, health and comfort, life cycle cost and value, and potential risks to future performance (see [Table 1.9](#)).

The evaluation system is organized into three successive levels of technical detail corresponding respectively to the conceptual design (Level 1), to the detailed design and construction (Level 2), and to the as-built and in-use phase of the building (Level 3) to monitor how the building performs after completion and handover to the client. This articulation into levels allows to identify the relevant aspects to be taken into consideration for each phase of the construction process. Progressing through the levels also represents an increase in the accuracy and reliability of the reporting—the higher the level, the closer the reported results will be to reflecting the performance of the building as-built and in-use.

1.5.3 Smart buildings

The smart building represents the evolution of both the ZEB and the green building. In a smart building, the established characteristics of energy and environmental efficiency, evaluated along the entire life cycle, are integrated with those of flexibility, intelligence and resilience through a continuous interaction of the building in the formal and functional aspects with the context and with users. Smartness of a building refers in fact to the ability of a building or its systems

TABLE 1.8 Level(s) macro objectives (JRC, 2021b).

Macro-objectives	Scope and focus
1. GHG and air pollutant emissions along a building's life cycle	Minimize the total GHG emissions along a building's life cycle, from cradle to grave, with a focus on emissions from building operational energy use and embodied energy.
2. Resource efficient and circular material life cycles	Optimize the building design, engineering and form in order to support lean and circular flows, extend long-term material utility and reduce significant environmental impacts.
3. Efficient use of water resources	Make efficient use of water resources, particularly in areas of identified long-term or projected water stress.
4. Healthy and comfortable spaces	Create buildings that are comfortable, attractive and productive to live and work in, and which protect human health.
5. Adaptation and resilience to climate change	Futureproof building performance against projected future changes in the climate, in order to protect occupier health and comfort and to minimize long-term risks to property values and investments.
6. Optimized life cycle cost and value	Optimize the life cycle cost and value of buildings to reflect the potential for long-term performance improvement, inclusive of acquisition, operation, maintenance, refurbishment, disposal and end of life.

TABLE 1.9 Level(s) indicators of environmental performance (JRC, 2021b).

Macro-objectives	Indicators
1. GHG and air pollutant emissions along a building's life cycle	1.1 Use stage energy performance 1.2 Life cycle Global Warming Potential
2. Resource efficient and circular material life cycles	2.1 Bill of quantities, materials and lifespans 2.2 Construction & demolition waste and materials 2.3 Design for adaptability and renovation 2.4 Design for deconstruction, reuse and recycling
3. Efficient use of water resources	3.1 Use stage water consumption
4. Healthy and comfortable spaces	4.1 Indoor air quality 4.2 Time outside of thermal comfort range 4.3 Lighting and visual comfort 4.4 Acoustics and protection against noise
5. Adaptation and resilience to climate change	5.1 Protection of occupier health and thermal comfort 5.2 Increased risk of extreme weather events 5.3 Increased risk of flood events
6. Optimized life cycle cost and value	6.1 Life cycle costs 6.2 Value creation and risk exposure

to sense, interpret, communicate and proactively respond in an efficient manner to changing conditions in relation to the operation of technical building systems or the external environment (including energy grids) and to demands from building occupants (Casini, 2016).

The concept of smart buildings is not new, but it has evolved mainly due to the development of new technologies, which, when incorporated, enable more intelligent resources and processes, and expand the building's capacity to operate in more efficient, flexible, interactive and sustainable ways. Literature already includes several definitions of smart building, or intelligent building (Mofidi and Akbari, 2020), all of which broadly refer to the presence inside the building of more or less complex building automation systems (BASs), providing active systems and controls that allow the motorized action of specific subordinate functions and appliances (see Chapter 10). The BAS allows a continuous interaction with the environmental context (indoor microclimate parameters, outdoor climate, weather forecast), with the users and with the built environment (power grids, utilities, information from the web). It acquires data and information

useful for optimizing internal operation with advanced logics that include AI and machine learning algorithms, aiming at the utmost efficiency and effectiveness in the use of environmental and economic resources. In particular, a smart building shall feature four main functions: climate response, grid response, user response, and monitoring and supervision (Dakheel, Del Pero, Aste, & Leonforte, 2020).

Climate response refers to the buildings' capability to respond to external climate conditions (actual and predicted), according to which the BAS identifies the best operating profile. Smart buildings must be able to minimize their energy demand and generate renewable energy in order to cover their energy consumption. Advancements of IoT and control systems today make it easier to obtain climate and weather data. Sensors and actuators can be integrated in all relevant building components, such as the HVAC, lighting, and solar shading systems, to connect them to the BAS and enable continuous adjustment. For instance, HVAC setpoints will predictively adapt to weather changes and occupancy levels, and lighting fixtures will brighten and darken alongside ambient sunlight, dynamically maximizing energy savings (PEEB, 2019).

User response constitutes the capability of a building to enable a real-time interaction between users and technologies implemented. The user interacts with the BAS to automatically create optimal load operation schedules, different priorities and specify their comfort settings. Smart buildings emphasize user experience, providing occupants with greater personal control over their surroundings. Lighting systems identify occupants and adjust the intensity and color temperature to suit individual preferences. HVAC systems monitor and adjust for ideal air quality, removing the "sleep-inducing" effects of a poor climate, and respond to individuals as well, for instance automatically adjusting the temperature in conference rooms to the ideal average between attendees. Human-centric building control helps to improve productivity, creativity, and wellness of occupants. Lighting fixtures will adjust their color spectrum throughout the day to more closely mimic sunlight and support the circadian rhythm. Predictive awareness enables more effective and efficient mobility throughout a building, as well as use of space. Elevators steer occupants according to the next meeting in their calendar, prepositioning cars to minimize waiting. Conference-room availability can be tracked in real time, eliminating wrong bookings and making spaces available again if attendees do not show up. Flexible workspace assignments can take a range of variables into consideration when identifying an employee workstation for the day, including personal location preferences, meeting locations, and anticipated occupancy levels. And indoor positioning will enable employees and visitors to locate and rapidly route to shared spaces and assets. Hotels are further implementing connected-home-like applications in their rooms, with personalized lighting, climate, and entertainment control as well as occupancy awareness. Retail spaces are installing wayfinding capabilities that help shoppers to identify the location of items they are searching for and to suggest promotions along the way. Hospitals are leveraging asset tracking to identify the location of portable equipment in real time.

Grid response indicates the building's capacity to act/react to signals and information coming from utilities grid, with the aim to maximize the energy and economic efficiency (e.g., reducing grid overload, consuming energy when there is maximum availability thereof and the price is lower, etc.). As the introduction of distributed solar and energy storage is shifting buildings owners from energy consumers to energy prosumers, the focus of power management has been changing from mere demand reduction to dynamic source optimization, extending to building-to-building communication and smart-grid tie-in. The key components of a smart grid are renewable generation, advanced metering infrastructure, and data exchange (see Section 12.2). The smart grid emphasizes the interaction with the users through power consumption monitoring and dynamic pricing, including demand–response programs (see Section 12.3.4). Users in turn can deploy various demand-side management (DSM) strategies to adapt their priorities to the price variations or incentives. The complete integration of DSM requires communication systems and sensors, automated metering, intelligent devices and specialized processors.

Monitoring and supervision refers to the building's capability to carry out the real-time monitoring of the building operation or, rather, of both the status of its technical systems and the users' behavior. This has the double aim to enable all automated response features of BAS and to allow a more efficient operation by enabling predictive maintenance, real-time detection of faults, etc. (see Section 11.2). Moreover, monitoring and data analyses are essential for an appropriate commissioning and performance tracking, due to the performance gap between energy consumption predicted in the design phase and measured in actual operation.

A smart building can present different, increasing levels of development (maturity levels), from automated to self-cognitive capabilities, in relation to the systems and equipment managed, their degree of integration and interoperation, the functions performed and the level of autonomy (see Table 1.10) (JRC, 2020c; Powerhouse, 2019).

An automated building (Level 0) already meets the current, demanding code requirements for new buildings, as well as the basic expectations that the various stakeholders may have. It would be a robust and energy efficient building that does not expose occupants to any significant health-related risk. Building owners can expect good quality and low

TABLE 1.10 Maturity levels of smart buildings.

Smart building maturity level	Smart building features
Level 0 Automated building	The building is constructed according to current regulations and statutory requirements and features ordinary automated services.
Level 1 Smart ready building	The technical infrastructure of the building is already prepared to develop it to a higher smart level at a later point in time. Operation of the building is simplified by systems intercommunication and access to data.
Level 2 Smart standard building	The building communicates and interacts with its users, providing guidance and tips, and adapts to their preferences and usage patterns.
Level 3 Smart predictive building	The building monitors direct and indirect data from occupants and environment to predict and anticipate future operation and recommend actions accordingly. Each user receives customized information and guidance.
Level 4 Smart cognitive building	The building uses machine learning on historical and monitored data to improve its prediction models, operation and management. It communicates and interacts with other smart buildings and with the smart city.

lifecycle costs. Temperature, ventilation and lighting will be automatically controlled based on predefined levels and hours of operation, which will be the same for each user.

A smart ready building (Level 1) does not differ significantly from an automated building, as most of the changes entailed by this level are in the form of the preparation of additional infrastructure and systems in the building that may facilitate achievement of the higher levels. Building will feature futureproof technologies which simplify subsequent integration of new functions and lay the foundation for new services and enhanced user interaction. Owners can expect the building to hold up better value over time and reduce the risk of future change costs. Moreover, smart ready buildings will have a reduced environmental footprint, as this level places demands on better energy performance and smarter control of HVAC.

A smart standard building (Level 2) instead improves substantially over the two previous levels. Users' influence on indoor climate will be considerably increased and their experience simpler, as their surroundings are more geared for automatic adjustment to their preferences, for example by allowing entrance to zones based on biometric data. All technical solutions are comprehensive and thoroughly prepared so that the building, its digital twin and the integrated systems ensure more streamlined operations and greater adaptability over the lifecycle, carrying substantial value for the building owner. Tenants can have services personalized on their individual needs and adapt them as those change over time. Smart standard buildings are characterized by lower energy consumption for operation, reduced peak loads, increased robustness and additional security barriers.

A smart predictive building (Level 3) is able to leverage large volumes of input data to predict its future condition and anticipate its operation accordingly, with great benefits in terms of indoor comfort and energy and costs savings. The building will advise and guide the users based on their own preferences. Tenants and owners can expect the prediction models to provide even better energy efficiency in operations, and thus lower operating costs and environmental impact, thus raising property value. This will include communication with outside networks regarding energy needs and grid loads. Such building can be utilized more fully outside normal working hours, and thus contribute to increasing the quality of the surrounding area. Benefits for both the building owner and tenants also include valuable reputation improvement and enhanced attractiveness among employees and in the real estate market.

Finally, a smart cognitive building (Level 4) will exploit large volumes of historical data, AI and machine learning to improve its prediction models and systems and ensure the best user experience. This will improve the building's energy performance, reduce environmental impact and further improve indoor climate, although benefits in certain areas may be only marginal. Predictive operation and maintenance will enable the building to foresee incidents and events and act proactively, reducing disruption, downtime and repair costs. A smart cognitive building is able to develop and adapt itself to future needs, ensuring high economic and social value throughout the entire lifecycle. While some buildings will meet certain functional requirements at this level in just a few years, significant development work remains to achieve this level for all requirements.

All the advanced functionalities of the different level of smart buildings are underpinned by a profound step change in technological infrastructure (Monteiro Froufe et al., 2020).

Successful development and deployment of a smart building requires merging elements of connectivity, Big Data, machine learning, and mobile applications with traditional building hardware, and effectively connecting infrastructure together in a reliable, secure, and extensible manner. Ultimately, a smart building aims at being a real icon of the 21st century able to combine innovative design and technological solutions with the highest performance in terms of comfort, energy efficiency, social and environmental sustainability to keep up with the evolving needs of clients, users, and community. Building smartness is a result that starts from design and also involves construction methods and facility management, and today is finally enabled by the availability of new materials, of new technologies in the energy and information sector as well as of increasingly advanced IT tools able to support all building process.

Smart buildings with different maturity levels are a reality increasingly present in cities around the world. Among the more relevant examples is The Edge building in Amsterdam which is considered one of the most sustainable office buildings in the world with a BREEAM-NL rating of 98.36%. Constructed in partnership with Schneider Electric in 2018, it is equipped with solar panels and thermal energy storage to generate all the energy required for its own heating and cooling, with 70% less consumption than the average nonresidential building, and embraces circular, zero-waste design principles and smart digital infrastructure to optimize energy use. Other sustainability measures include the reuse of 50% of materials from the original building, a post office, including the natural stone from the original façade repurposed as flooring, and the top two floors constructed from wood, which can be disassembled for future reuse. The building combines real-time automated adjustment of HVAC and lighting, thanks to thousands of environmental sensors, with advanced building services to visitors and employees, such as a smartphone app to configure climate preferences and book and route to parking spaces, workstations and conference rooms, or tracking effective activity to divert cleaning robots toward areas that have been used most heavily that day.

The new Bee'ah Headquarters under construction in Sharjah, UAE (see [Fig. 1.15](#)) was designed by Zaha Hadid Architects to LEED Platinum standards and includes many active and passive energy efficiency measures including dynamic window control, daylight controls and high efficiency HVAC systems. The 7450 m² building will be 100% powered by on-site solar PV and outfitted with 1890 kWh capacity of battery storage. Data from all building systems will be stored in a central server to enable advanced data analytics and machine learning to continuously reduce environmental impact and improve occupant productivity.

Another example of smart building is the 2019 IKON innovation center in County Cavan, Ireland. It functions as a “living experiment,” for its owner, Kingspan insulating products manufacturer, providing engineers with the perfect real-world setting to measure the energy-saving properties of new materials. It was built using recycled and recyclable materials (such as recycled PET bottles for the building’s insulation) and utilizes daylighting, rainwater, solar panels, and other elements such as multiple sensors to create a sustainable and energy efficient workspace. Its centerpiece is an advanced digital twin, the world’s first to target Level 5 evolution (see [Section 11.4](#)) which is powered by IoT devices and video cameras to visualize building performance along with 3D BIM data, creating an “occupancy-aware” building. This way, the building’s BAS can anonymously gather data pegged to people, behavioral patterns, occupant movement, represented as skeleton visualizations, for behavioral analysis. By cross-analyzing human activity data against metrics



FIGURE 1.15 Bee'ah Headquarters, Sharjah, UAE. *Courtesy of Zaha Hadid Architects.*

such as energy consumption by room or floor, better occupant-simulation models can be created, which in turn could inform the creation of more energy-efficient buildings optimized for comfort, wellness, and productivity.

1.6 Toward a digital future for construction

At the beginning of the fourth industrial revolution, the advent of digitalization, innovative technologies and materials, and new construction techniques, have begun transforming the way that infrastructure, real estate and other built assets can be designed, constructed and operated in order to create a more attractive, energy efficient, comfortable, affordable, safe and sustainable built environment. Developments in AI, robotics, nanotechnology, 3D printing and biotechnology, have finally started to move the construction industry—traditionally reluctant to innovation and slow in adopting new technologies—toward a new era. Massive changes are occurring as a result of the possibilities created by Big Data and the IoT, along with the technological advances which are driving down the cost of sensors, data storage and computer services (Autodesk, 2016; Berger, 2018; Boston Consulting Group, 2016; ECSO, 2021; IEA, 2019b; McKinsey, 2017b; WEF, 2016; WEF, 2017a; 2017b).

From lifecycle BIM, generative design, XR and drones usage, smart and innovative building materials, techniques and technologies, to standardized, modularized or prefabricated products and components, and on-site fully autonomous robotic 3D printing, up to AI and machine learning, there are more and more successful cases showing the potential of a transformation of the construction industry in order to increase its productivity and, at the same time, to address emergent global challenges such as resource shortage, climate change and increase of global population.

By applying the right technologies in the right way, companies can not only reduce the asset's construction time and whole-life-cycle cost but also enhance the quality of processes and improve safety, working conditions, and sustainability. For instance, full-scale digitalization in nonresidential construction is expected to allow in 10 years global cost savings of \$0.7–1.2 trillion/year (13%–21%) on engineering and construction and \$0.3–0.5 trillion/year (10%–17%) in the operations phase (Boston Consulting Group, 2016).

Similar to what happened in the manufacturing industry with the Industry 4.0 paradigm (see Table 1.11) (Ghobakhloo, Fathi, Iranmanesh, Maroufkhani, & Morales, 2021; Marr, 2020), a new revolutionary approach to the building process, so-called Construction 4.0, can exploit the new possibilities offered by the digital revolution, bringing significant opportunities for the whole value chain, from the early design stage to the very end of an asset's life cycle, giving rise to a new era for the industry characterized from a new set of connected capabilities (Delicato, Al-Anbuky, & Kevin I-Kai Wang, 2020; Sawhney, Mike Riley, Javier, & Irizarry, 2020):

- *Connected Teams* bring every stakeholder together dynamically, in real time, across geographies and different disciplines, effectively replacing the industry's traditional, asymmetric approach to collaboration. This will also expand the pool and facilitate access to talent by the use of work-exchange hubs and crowdsourcing platforms;
- *Connected Insights* allow to figure out innovative and effective solutions to highly complex design problems, by connecting Big Data and smart algorithms to infinite computing power in the cloud to make the best possible design decisions for everything from buildings to commercial strategies;
- *Connected Outcomes* connect the digital and physical worlds seamlessly through reality capture, real time 3D and XR, allowing project teams to explore and refine options already within the real-world context in which they are planned to reside—physical, environmental, economic and social;
- *Connected Delivery* allows to transform the design for a building or infrastructure in a virtual environment into a finished real-world asset with the minimum number of variations, improvisation, cost, and supply-chain overheads, using industrial off-site construction and digital fabrication methods;

TABLE 1.11 Historical evolution of industry.

Industry paradigm	Years	Characteristics
Industry 1.0	1784–1869	Steam-based mechanical production
Industry 2.0	1870–1968	Electric-based mass production
Industry 3.0	1969–2013	Controller-based automation
Industry 4.0	2014–Present	Ubiquitous production and control

- *Connected Construction* allows to minimize risks and increase productivity in the construction site by deploying networked technologies to support project management, workers' safety and materials tracking to ensure delivery on time and on budget;
- *Connected Assets* digitally connect all aspects of real-world physical buildings and infrastructure allowing insights on how those assets perform, are utilized, and interact with the systems in which they reside to improve the built environment and to inform future work pipelines;
- *Connected Capital* streamlines funding of project proposals by mitigating construction risks, providing data-driven insights into the performance of proposed assets across their lifecycle, and enabling new sources of capital such as crowdfunding, and digital assessments of "remaining value" in existing built assets.

The Construction 4.0 framework is based on a confluence of trends and technologies, that bring the virtual and physical worlds together to create a truly networked world in which intelligent objects communicate and interact with each other (see [Table 1.12](#)). This mechanism allows to:

- digitally capture the built assets that already exist in our physical world with unprecedented speed, completeness and accuracy;
- use these data to inform design of new assets or to plan for the retrofit and rehabilitation of existing assets;
- employ both digital and physical technologies to deliver these assets once they are digitally captured and designed;
- use the same digital and physical technologies to support operation and facility management functions of the constructed asset.

The start of this revolution was made possible by the growing and concomitant development in the last 10 years of key enabling technologies (BIM, Cloud and edge computing, IoT, 5 G network, AI and machine learning, Big Data and advanced analytics and nanotechnology). These in turn kickstarted the diffusion of numerous other advanced (and still advancing) technologies, which are strongly interconnected and are driving the capabilities for much more efficient construction at scale. [ECSO \(2021; McKinsey 2017b; Qi, Razkenari, Costin, Kibert, & Fu, 2021\)](#) ([Fig. 1.16](#)).

These trends pertain better sensing technologies such as LiDAR, aerophotogrammetry and 3D photo reconstruction; new digital tools to support visualization (XR) and decision making (BPS, parametric and generative design); streamlining of construction with modular prefabrication, 3D printing, and robotized workforce; more accurate and abundant data coming in real-time from more sensors in both buildings and construction sites, to be gathered in digital twins; cloud-based systems to provide collaboration, data storage and computing power; and the increasing quality of insights and automation provided by AI and machine learning.

Individually, each of these already has the potential to drastically change one or more aspects of the industry. Collectively, the interaction between these technologies can evolve the whole sector to a whole new level and fundamentally disrupt the very way in which buildings and infrastructure assets are designed, built, and operated.

The combination of these technologies enables, in addition to a full collaboration between all actors of the building process, the adoption of a digital building life-cycle model that allows to create the digital virtual buildings first, followed by assembling the physical artifact and finally by commissioning the digital-physical building as a new tool for real estate and facility management. In particular, the Construction 4.0 approach allows to:

- virtually erect the building by simulating and monitoring its performance at all process stages from design, construction, management to decommissioning;
- automate the processes of design (via parametric/generative tools), construction (site automation) and building management (BAS, digital twin);
- analyze the operational data of the construction and management phases for predictive analysis, optimization and decision making.

BIM and cloud-based common data environment (CDE) are the cornerstones of the Construction 4.0 framework: BIM provides the modeling and simulation features that are a core component of this new approach, and CDE acts as a repository for storing, sharing and leveraging all data that relates to the construction project over its life cycle. Together, they constitute a single platform that helps promote:

- the integration of all phases of the project life cycle (vertical integration), the collaboration between all members of the project team (horizontal integration), as well as learning and knowledge management between projects (longitudinal integration);
- real-time connection between the physical and digital layers over the entire project life cycle to utilize technologies from both realms in an integrated manner.

TABLE 1.12 Main technologies and trends of Construction 4.0 framework.

Technologies and trends	Construction 4.0 functions	Section/Chapter
3D mapping and scanning	Point-cloud data collection	6.1
5 G	Fast and reliable mobile connectivity	3.1.4
Adaptive reuse	Reuse and reconvert existing structures	2.3.6
Additive manufacturing	Directly 3D print parts, products and buildings using the 3D model	8.3
Advanced materials	New or improved technical properties (structural or functional) or environmental features of materials and products	7
AI and ML	Classifying, predicting, image processing, data mining, computer vision, problem solving	3.1.5; 9.6; 10.4; 10.5
Automated construction processes	Use of construction robots, drones, autonomous vehicles, exoskeletons and robotic on-site factories	3.2.2; 8
Autonomous vehicles	Survey, security and operations in construction sites	8.2.4
Big Data and analytics	Trend analysis and business intelligence	3.1.6; 12.1.1
BIM	Modeling and simulation	3.1.1; 3.2; 4
Blockchain	Smart contracts, certified security, data records	9.1.5
Building automation system	Smart management of single services or whole building systems	10
Building energy storage	Storage of electrical energy produced onsite by renewables	12.3.2
Building integrated renewable energy	Architectural integration of the renewable energy sources in the building envelope	7.5.6; 12.3.1
Building performance simulation	Performance driven design and management of buildings	5
Cloud and edge computing	Enable convenient, on-demand network access to a shared pool of configurable computing resources	3.1.2
Common data environment	Collect, manage and share project models and documentation	4.6.2; 9.1
Connected construction site	Assembly of parts and products in a location aware environment	3.2.2; 9.3; 9.5
Data driven design	Informed decision making based on data analytics and simulation	3.2.1
Demand response	Energy demand side flexibility to grid requirements	12.3.4
Design for deconstruction	Ensure the full recyclability of buildings materials at the end-of-life	2.3.6
Design for digital manufacturing	Directly manufacture parts, products and buildings using 3D models	6.5
Digital construction management	Use of ICT and CDE for management of construction activities	3.2.2; 9.1
Digital twin	Use of a real time digital replica of a built asset for its management or maintenance	3.2; 11.4; 12.1.2
Exoskeletons	Enhance human labor safety and productivity	8.2.3
Extended reality (VR/AR/Mr)	Immersive and context aware visualization for design, construction and management	6.3; 9.4; 11.3
Generative design	Multiobjective design optimization	6.4

(Continued)

TABLE 1.12 (Continued)

Technologies and trends	Construction 4.0 functions	Section/Chapter
Geographic information system (GIS)	Multidimensional geographic and spatial analysis	6.1.2
Green buildings	Design buildings with lower environmental footprint over the entire life-cycle	1.5.2
HD survey systems	Accurate virtualization of real assets	6.1
IoT	Connectivity of things, people and data	3.1.3; 9.5; 10.2.3
Machine vision	Recognize and identify objects, people and actions from video and images	9.6; 10.5
Mobile Internet	Application of mobile devices in the construction site	3.1.2
Modular construction	Extensive prefabrication of the whole building structure	8.1
Nanotechnology	New or improved technical properties (structural or functional) or environmental features of materials and products	3.1.7; 7.2
Parametric design	Design automation	6.4
Predictive maintenance	Data driven optimization of the maintenance of systems and appliances	11.2
Prefabrication and off-site construction	Use of industrial manufacturing to produce parts and products	8.1
Real time 3D visualization	Enhanced 3D model visualization	6.3
Robots in construction	Transport, assembly, production and maintenance	8.2
Smart buildings	Design of connected buildings with very high energy, environmental and comfort performance supported by building automation	1.5.3; 10; 12.3
Smart cities	Knowledge based city management, administration and services	12
Smart grids	Flexible and intelligent management of electrical energy flows	12.2
Smart Home	Design of connected homes with extensive sensing and automation features	10.6
Smart objects	Connection to other objects and to the web for data analytics and operation	9.3.2; 10.6
UAVs	Collection of aerial images and 3D scans	9.2
Vehicle to building (V2B)	Shared EV energy with smart cities and smart buildings	12.3.3
Virtual design in construction (VDC)	Use of 4D and 5D BIM, XR, and digital twin for construction simulation and management	9.1.2
Virtual assistant	Enhance human interface with digital services	10.5
Wearable technology	Collect location, vital stats and movement information	9.3
Zero energy buildings	Design of buildings with very high energy performance with a low energy demand entirely met by on-site renewables	1.5.1

Architects and engineers will use BIM as a single, encompassing design platform to create the digital twin of a building, which will be used by manufacturers and contractors as the single source of truth to prepare building components and execute construction. Both on-site and in off-site factories, robots and automated machine tools will fabricate precisely the building components based on the design information from BIM, and managers will also use BIM data to ensure the construction proceeds as designed. Workers will use XR to fully understand the design intent from the BIM and to get support information, such as dimensions, processes, and tool instructions to perform their work. This way, the finished construction product will be the precise realization of the digital twin.

More generally, Construction 4.0 leverages the pervasive digitalization of the whole building process to bridge the operative gap that still separates the virtual and physical instances of the built environment (see [Table 1.13](#)). The

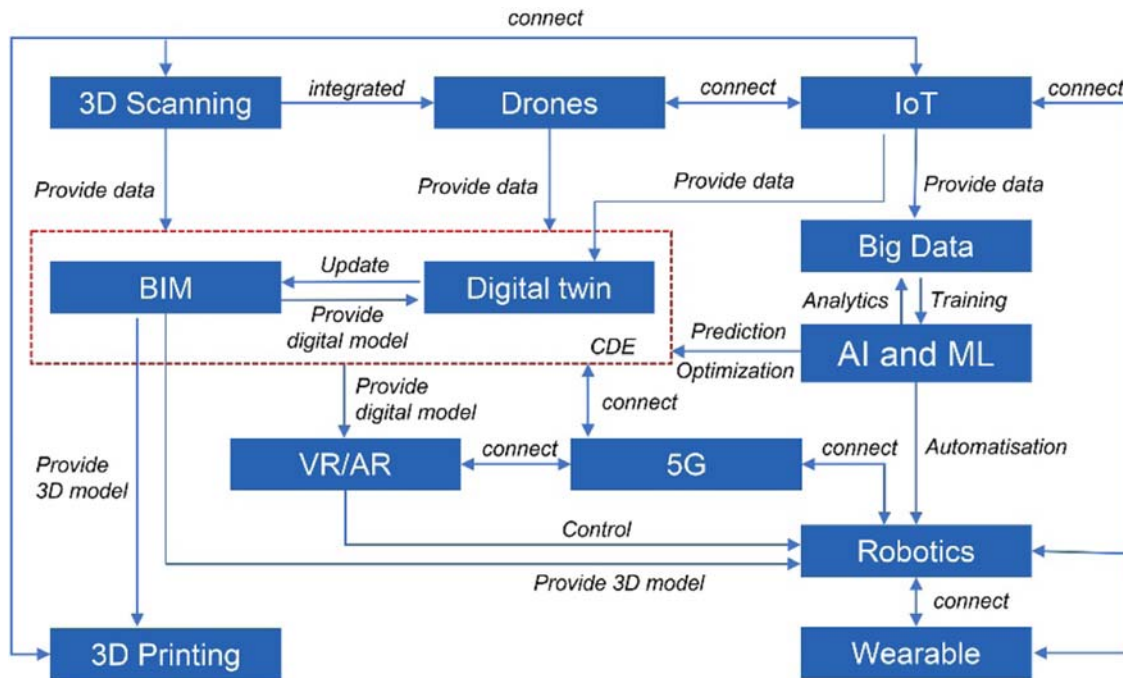


FIGURE 1.16 Overview of the interactions among digital technologies in the construction sector.

TABLE 1.13 The use of digital technologies in the construction sector.

	Design and engineering	Construction	Operation and management	Renovation and demolition
3D mapping and scanning	■	■		■
Additive manufacturing	■	■	■	
AI and ML	■	■	■	■
Autonomous vehicles		■	■	■
Big Data and analytics	■	■	■	■
BIM	■	■	■	■
Blockchain	■	■		
Building performance simulation	■		■	
Common data environment	■	■	■	■
Digital fabrication	■	■		
Digital twin	■	■	■	■
Extended reality (VR/AR/Mr)	■	■	■	■
IoT		■	■	■
Mobile Internet		■	■	■
Robots		■	■	■
UAVs	■	■	■	■
Wearable technology		■	■	

integration of sensing technologies in the physical world produces accurate data, both historical and real-time, which feed realistic and accurate virtual models that can be freely analyzed and configured, knowing that each informed decision made in the virtual world will be valid, and automatically implemented, in the real world in turn. This way, it is finally possible to eliminate most uncertainties, inefficiencies and errors that currently occur in the design, construction and operation processes of the built assets and that are the primary cause of insufficient productivity, excessive environmental impacts and unforeseen cost expenditures.

Some of the keys to this integration are the increasing collaboration, interoperability and the diffusion of shared standards among the different disciplines of the industry, which allow more systems to work with each other to exchange data, information, models, methods, and experiences, thereby unlocking a whole new level of interdisciplinary knowledge.

1.6.1 Construction 4.0 technologies

Construction 4.0 technologies can be organized in four main categories: data acquisition, digital information and analysis, automating construction processes, advanced materials, and products (Autodesk, 2016; ECSO, 2021; IEA, 2019b; WEF, 2016).

1.6.1.1 Data acquisition technologies

Data acquisition technologies, namely aerial mapping, 3D photo reconstruction, LiDAR scanning, wireless sensors networks and IoT, are the starting point for the digitalization of the construction sector, as they provide most of the data necessary to the virtual migration of physical structures and to build and develop the digital construction ecosystem.

Data acquisition technologies can provide unprecedented availability of massive amounts of data concerning all aspects of the construction, from geo-localization to operational status, to environmental parameters (temperature, humidity, air quality, etc.), to energy usage, up to image and video recordings. Such unprecedented availability of data will allow for a growing range of analytical services to improve productivity in all phases of the construction process (e.g., design and engineering, construction, operation and maintenance, etc.) and its subsectors (e.g., real estate, manufacturing, architecture, and engineering).

Advanced survey techniques allow the quick, inexpensive and accurate 3D reconstruction of any asset, be it an empty construction lot or a building to be demolished, reused or renovated, to allow design activities to start from a thoroughly informed dataset. Satellite and aerial imagery, ground and drone-mounted LiDAR and multispectral cameras allow to produce 2D orthophotos to use with GIS spatial analysis as well as 3D point clouds with billion points taken with millimeter accuracy, both indoor and outdoor, which can be directly fed to the BIM design process. During the construction phase, LiDAR scans and 3D reconstruction performed by autonomous robots can be used to compare the as built state of construction with the as-designed BIM model to assess progress and identify any deviation, or with the final outcome, to verify that the construction is compliant with the initial plan. In the maintenance phase, drones equipped with LiDAR and cameras can perform inspections and reconstruct accurate 3D models of any natural or man-made structure, including bridges, railways and water infrastructure.

Drones, in particular, are inexpensive and easy to maneuver aerial vehicles which can be equipped with high-resolution cameras, IR sensors or LiDAR scanners, as well as with other specific payloads (e.g., fire extinguishers, transport containers, paint cans, and airbrushes). The high interest in drones can be linked to their use in all stages of construction, from the preconstruction by providing field information for planners and real estate developers, to the final stages of a project, providing measures, photos, assessments and impact reports. Indeed, drones increase efficiency and productivity in all these stages by surveying the site for progress, verifying contractor's reports, identifying discrepancies, and assisting in confirming compliance with regulations, for example in the case of storage of materials or waste or of safety violations on the worksite, also providing access to areas particularly challenging or hazardous (roofs, trelis, bridges, etc.).

Among data acquisition technologies, a central point for the future of the construction sector is certainly represented by sensors, especially wireless sensor networks, and IoT devices, since they can be used pervasively on a variety of strategic tasks in the construction value chain. Indeed, preliminary studies have linked the use of IoT in construction projects with an estimated average cost saving around 22%–29% of the total project costs thanks to its benefits in prevention and safety, optimization, and efficient management (ECSO, 2021).

During the construction phase, sensors can be used to monitor the environment of construction sites (e.g., humidity level, presence of gasses, etc.) and detect local variations in material strength or work integrity, and can keep

monitoring the buildings once they have been completed (e.g., long-term health of concrete). Building machinery, power tools, and vehicles can be integrated with IoT sensors and connected to the cloud, allowing remote management of the fleet and reducing the risk and cost of repairs and breakdowns through predictive maintenance. Distributed sensors can deliver real-time updates on a project's status, on the location of vehicles, deliveries and assets, or on the condition of various features as they are built, thus providing a significant amount of precious and updated data to project managers and other stakeholders. Furthermore, IoT can be used to monitor workers' activities and safety by using a system of connected, wearable sensors to track movements and tasks and ensure that they are not exposed to hazardous substances or to situations of physical danger, or to alert rescue if any accident or sickness is detected.

Collected data can be fed to digital twins and to advanced analytics to gather relevant information and assess ways to optimize site operations: for example, fuel spending and energy usage, utilization rates of machines and equipment, location of storage and workstations to reduce clashes and nonproductive movements. In this context, sensors can contribute to create a more efficient supply chain, and hence improve the timelines of projects and foster better communication with clients.

In buildings operation and maintenance, sensors can be used to continuously monitor internal and external environment data to maintain optimal and safe living and working conditions, while also optimizing energy use. Based on data obtained, facility managers and owners can adjust HVAC, monitor air quality, turn lights on/off, detect excessive noise levels, and close the windows if rain or strong winds are sensed, or automate all these tasks with an advanced BAS. Optimizing building controls can improve comfort and save energy at the same time, either automatically or by providing feedback on building occupants' behavior. At the same time, motion and video sensors can be integrated in the building's security system, and eventually connected to the cloud, to improve the safety of the area. IoT devices can be integrated in any device that consumes energy, such as lamps, switches, televisions, or power outlets, and can be used for consumption monitoring or to implement advanced energy management functions such as demand response programs or energy diversion from on-site energy storage and renewable energy sources. Indeed, some studies have estimated that IoT can allow up to 35% of energy consumption reduction by using coordinated digital building systems (ECISO, 2021; IEA, 2019b). Sensors are also being increasingly integrated onto heritage sites or infrastructure, such as bridges, and used to monitor their conditions, in order to undertake timely interventions as soon as a potential issue is detected or foreseen.

1.6.1.2 Digital information and analysis

Digital information and analysis technologies include a vast variety of tools to create, visualize, understand and manipulate, in a CDE, a digital replica of a physical asset (already built or to be constructed) and to analyze and monitor its data, simulate and optimize its performances and to plan and execute its construction, operation and maintenance activities thanks a continuous and bidirectional connection between the digital and physical world.

Digital information and analysis technologies include BIM, parametric and generative design, BPS tools, XR, digital twin, construction and facility management software, AI and machine learning.

BIM is at the base of the operation of these technologies, as it allows to create an informed model of the building (and not only a 3D geometric model, as with CAD) capable of communicating along the entire value chain with all other technologies, including those of data acquisition and automation of the construction process, supporting designers, constructors and facility managers in identifying and optimizing the most effective outcome to the project requirements and to the building operation and management.

Design activities can be supported since the early stage by the use of BPS tools to optimize energy efficiency, internal comfort, safety, and environmental sustainability of the life cycle. Parametric design allows to create building models based on the input of parameters, such as materials, site constraints, and even environmental requirements, allowing to explore rapidly many options before deciding on the final design, as the software makes changes to the project in real-time and automatically updates the model. The identification of the optimal solution can be supported by Generative design, an iterative technique that uses advanced algorithms and AI to increase the designer's ability to define, explore, and choose alternatives: procedurally generated outputs are automatically ranked based on a predefined set of criteria provided by the designer. This allows to automate the elaboration of large amounts of complex data, thus saving time, reducing the likelihood of errors, and increasing accuracy.

Generative techniques are useful not only during the design phase, but, if provided with the right amount and type of data, also during the construction phase. Generative software can experiment with a multiplicity of options looking for the most efficient process to build (e.g., positions of the trucks for delivery of panels based on their weight, final placing, access points).

The construction process can also benefit from the application in the whole value chain of XR technologies, including VR, augmented reality (AR) and mixed reality (MR), able to create immersive digital experiences that allow to easily visualize, explore, and understand designs, models, and site conditions. In particular, the main applications of XR in AECO concern stakeholder engagement, design support and review, construction planning, progress monitoring, construction safety, and support to operations and management, as well as personnel training.

The BIM model of the building can be integrated with data sensed in the real world to create a real-time digital representation of the physical asset, the digital twin. Digital twins realize the full potential of BIM by connecting data and processes with dynamic, real-time, bidirectional information management, and can find effective application during both the construction and the operation phase of the building.

In the construction phase, data is continuously collected by sensors in the construction site, including LiDAR and drones, that monitor changes in the works and in the environment and report the updated state in the digital twin in the form of measurements, data and pictures. This way, project managers and contractors can leverage information from digital twins to compare the initially planned time schedule laid out in the BIM model (4D BIM) with the actual situation on the construction site to identify divergences and act timely, decreasing possibility of delays. Digital twins can also provide automatic resource allocation monitoring and waste tracking, allowing for a predictive and more efficient approach to resource management.

In the operational phase, digital twins collect and process functional data from mechanical, electrical, and plumbing systems, as well as parts and maintenance data or environmental data collected through IoT sensors. As the digital twin is constantly updated with the data supplied by its physical twin, it can be used to perform simulations and predictions based on real-time conditions. Digital twins use operational data to provide insights, simulate future scenarios and consider “what-if” questions. Paired with AI and machine learning capability, they gain the ability to learn and act on behalf of users, supporting facility managers in making informed decisions for daily operations, assess the extent of a component or system failure, steer decisions about maintenance and repairs, and prolong the technical life of the building.

Finally, thanks to AI and machine learning, all the enormous amount of data collected in the construction or management phase of the building can be easily analyzed to identify patterns within data, which can be used to create a data model to make predictions and support decision making along the whole value chain (predictive maintenance, risk analyses, management and resource optimization, costs prediction, etc.).

1.6.1.3 Automating construction process technologies

The automation of construction processes refers to the use of digital manufacturing techniques, including formative, subtractive, and additive methods, and of robots and autonomous or teleoperated vehicles to automate specific tasks or processes in both on-site and off-site fabrication activities. The benefits achievable consist of increased efficiency, greater precision, and improved workplace safety and security.

Digital fabrication processes such as CNC machines, robots and 3D printing can reduce construction time and costs, as well as achieve shapes with optimized performance/material ratio. Advancement in digital fabrication is also showing enormous potential in terms of new architectural possibilities, precise material processing, structurally effective shapes and graded assemblies, and lower environmental footprint of construction. This type of industrialized process allows to digitally link execution to BIM and CDE so that instructions can be seamlessly delivered for physical production.

In particular, additive manufacturing—also known as 3D printing—is the process of creating an object by adding layers of material (e.g., plastic, metal or concrete) upon one another under the control of a computer using a CAD or BIM file to guide the 3D printhead nozzle. 3D printing is particularly beneficial in the construction phase, in which it contributes to overall reduction of costs and construction waste. Thanks to their unique production and assembly method, 3D-printed elements benefit fully from the characteristics of the material they are built from and are proven to be more durable than conventionally fabricated elements. For this reason, it is often used for building lightweight and energy efficient building façade elements and structural elements such as bridges (e.g., 3D-printed pedestrian bridge in Madrid, Spain). 3D printing can also achieve unique designs and shapes that are less attainable using traditional methods.

Robots (single task construction robots, biomorphic robots, exoskeletons, autonomous vehicles, and teleoperated machines) are devices that execute specific operations (i.e., lay tiles, lift objects, etc.), either autonomously (i.e., under predetermined reiterative instructions) or under an operator’s direct control. The scope of robotics applications in construction encompasses the majority of the stages of the process, from initial construction to building operation and maintenance, to the eventual dismantling and recycling. In the construction phase, robots can deliver more precise and

uniform work than human workers, and replace them in activities that involve difficult physical labor, repetitive tasks and presence in hazardous environments. Robots deployment in the construction site reduces both safety risks for workers and the possibility of mistakes, which in turn translates to a higher quality of construction, lower final costs, and decreased likelihood of delays. For instance, the use of exoskeletons, that is, robotic body devices worn by the worker, can improve performance and significantly reduce safety risks when doing tasks such as lifting heavy loads, or using equipment in uncomfortable positions. These devices can be also equipped to conduct musculoskeletal stress monitoring, so as to regularly measure the worker's physical conditions. This is of particular relevance in the construction sector, where, according to the European Agency for Safety and Health at Work, 52% of construction workers report backaches, 54% show musculoskeletal disorders in the upper limbs, and 41% show them in the lower limbs. Robots can also be used to automate traditionally manual activities, such as brick laying, excavation, or wall painting, by being combined with other technologies, for example, sensors, drones, and BIM, to execute the task without the need for physical human presence on the construction site.

1.6.1.4 Advanced materials and products

Advanced materials refer to those materials, both new and deriving from the modification of existing materials, specifically designed to possess new or improved technical properties (structural or functional) or environmental features compared to materials traditionally used to perform the same functions. The introduction of advanced materials in the construction industry is contributing substantially to increase the productivity of the sector, to ensure more safe and comfortable buildings, and to improve energy and environmental efficiency of the built environment, leading to profound changes in the whole construction process, from design to maintenance. Advanced materials are considered in fact a key horizontal technology and have a main role in enabling advanced/high-value manufacturing and in addressing society's key socioeconomic grand challenges like climate change, urban air pollution and improved efficiency in using resources, supporting the development of new products through radically different and unique functionalities, including low carbon technologies.

Main advanced materials for building sector include nanomaterials and smart materials, biobased materials, advanced concrete, engineered mass timber structures, high performance insulators, dynamic windows, smart coatings, and mimetic photovoltaics.

Nanotechnology is certainly offering essential innovations for the development and formulation of innovative building products with increased mechanical, physical and chemical properties, with application potential in all technical elements, from structures to opaque and transparent closures, internal partitions, to systems and appliances. The new class of smart materials is finding application in architecture in a high number of products and systems, especially in building envelope components which can most take advantage of their properties of adaptation to different use conditions. The development of a new generation of multifunctional nano and smart coatings is currently a hot technological topic for enhancing the properties of all building surfaces from durability, to safety and health, up to climate mitigation and self-healing.

The goal to design more intelligent buildings, which feed on a continuous data stream from their components, is leading to the digitization of building components through the integration of micro and nano sensors within them, capable of collecting stimuli and information from the surrounding environment, including their thermo-physical state, and of communicating them in real time to the building management system both for the regulation of material and energy flows (adaptive envelope) and for their maintenance or replacement through building digital twin systems.

New advanced printable materials are entering the market, broadening additive manufacturing techniques and improving the productivity of the whole building sector. Currently, in fact, the materials applicable for 3D printing of construction components are still limited and require further development to overcome their shortcomings, especially with respect to structural strength and stiffness, as well as the constraints imposed by the extrudability of the material vs its rapid strength gain once printed. Along with 3D printable concrete, currently most advanced research activities are focused on shape memory materials for printing dynamic responsive building envelopes or self-assembly elements (4D printing), and on the combination of biology and technology in order to create sustainable components through living matter, such as bacteria or fungi, also with self-regenerative properties.

1.6.2 Benefits of Construction 4.0

Construction 4.0 framework is not limited to the mere application of new technologies, either physical or digital, but represents, exactly thanks to their support, a more efficient and effective way of working that aims to create more

sustainable buildings over their life cycle. Construction 4.0 indicates therefore a revolutionary approach to the architecture that intends to take on the new challenges of the society of the third millennium that require a different way of designing, constructing, operating and upgrading buildings to create a more sustainable, comfortable, safe and resilient built environment. In this sense, digitalization is a key enabler of working in a more sustainable way in construction. A greater collaboration across industries, supply chains and projects, having data at the heart of the business, will transform the perception of sustainability from a barrier to an enabler. A complete digital transition allows to better integrate the different phases of the construction model toward a “new operating model” for safer productive workplaces, more resilient sector, and upskilling the workforce.

Construction 4.0 is characterized by a holistic approach to design that follows the principle of “Life cycle thinking,” by taking into account the environmental, social and economic impacts of design choices along the entire life cycle of the building: from site identification, to construction, operation, until the final decommission and recovery or reuse of materials.

With the aim of promoting a more sustainable and inclusive building industry based on knowledge and innovation, more efficient in terms of resources, greener, and more competitive, Construction 4.0 is founded on a multidimensional design process, respectful of the context, and fully leverages the new possibilities offered by innovative digital design tools, advanced materials and technologies, innovative construction methods and techniques, and advanced building operation and management systems.

Construction 4.0 design process is oriented toward the optimization and the best harmonization of the four main elements that characterized a building—shape, envelope, systems, and people—that together concur in defining the quality of any manmade environment. The goal is to create a smart building, that is, a building designed, or renovated, with intelligence, that uses the best typological (smart shape) and technological solutions, both from the constructive (smart envelope) and equipment (smart systems) points of view, able to interact intelligently with the environment and with users (smart people) in order to provide an accessible, safe, comfortable and healthy built environment, capable of improving the life of all present and future stakeholders.

Applied this way, the Construction 4.0 framework can bring numerous benefits in the whole AECO value chain, and in particular (Qi et al., 2021; Sawhney et al., 2020):

- better performance at the company and project level, as cloud-based project management tools, blockchain, central repositories of information, and real-time data access, improve collaboration and communication and allow higher productivity, better management practices, and less incidence of delays, additional costs and errors in construction projects;
- improved sustainability of the industry, stemming from the design of more energy efficient buildings allowed by advanced tools (BPS, parametric/generative design), the integrated life cycle approach that ensures prudent use of resources finalized at their reuse or recycling, less environmental impacts in the construction phase as well as a more efficient use and maintenance of the built asset in operation thanks to digital twin and BAS;
- cost savings, allowed by the accurate modeling of project cashflows via BIM, by the application of industrialized construction, robotics and automation to reduce inefficiencies and waste, by real time data monitoring to predict and identify any deviation from budget, and by more cost-effective facility management in operation. In commercial and institutional buildings, digital technologies can reduce the costs of design, engineering, and construction by 10%–25% and of operation from 14% to 23% (Boston Consulting Group, 2016);
- reduced time and delays of the whole construction process, as BIM and CDE streamline design and planning activities, digital construction like prefabrication, additive manufacturing, and on-site assembly improves the speed of delivery, and real-time access to both physical and digital data, as well as enhanced project monitoring via LiDAR and 3D photo reconstruction, reduce errors and reworks;
- enhanced safety through the move of most construction activities in off-site, controlled factories, the use of robots and exoskeletons for most dangerous tasks, the deployment of XR-based training, as well as the introduction of wearable technologies, IoT devices and image and video AI processing on the construction site;
- improved capital management and funding, as project profitability can be accurately predicted as part of a data driven programming stage on the basis of Big Data and advanced analytics, while reduced risks in construction make investments more attractive;
- improved image of the construction industry at large by making jobs and workplaces more attractive for recruitment and retention of talent, further diffusing an innovation mindset in all levels of the industry and spurring the further creation of new integrated solutions to address the horizontal, vertical, and longitudinal fragmentation that still affects the sector.

All of these allow to optimize building performance, cost-effectiveness, employee satisfaction and productivity, bringing substantial value across the industry and greater alignment among stakeholders. This alignment results in greater profitability, enhanced project success, higher-quality built environments, and more empowered people.

Nonetheless, the Construction 4.0 framework can fully deliver its benefits only if all enterprises have access to a qualified workforce. Indeed, a more resilient and sustainable industry is driven by how these technologies are used, therefore requiring a substantial investment in attracting and training a smart, educated, and diverse workforce, as well as strategic leaders who work collaboratively with clients and partners for mutual success. “The construction industry of tomorrow will demand digitally literate, multiskilled, diverse and highly trained installation and assembly practitioners capable of operating in different environments, and technically proficient professionals capable of managing product integration and complex logistics aligned with the ability to collaborate, and to co-ordinate both site installation technicians and facility-based manufacturing teams” (Construction Leadership Council, 2019).

Regarding architecture and engineering firms, technology has substantially changed both the way designers work and the products delivered to clients during a project’s lifecycle, changing also career opportunities in the profession. Companies are looking for roles that didn’t exist few years ago in AECO disciplines. Main new roles include: Chief Technology Officers, BIM specialists, BIM managers, BIM coordinators, CDE managers, Immersive Reality Modelers, Virtual Simulation Designers, Haptic Interface Designers, LCA specialists, Data Scientists/Analysts. In addition to technical skills, the capacity to adopt new digital ways of working is also required, for instance moving from linear to iterative design processes in short test-and-refine loops (especially when reviewing and refining generative designs).

Concerning construction companies, the lack of skilled workers has always been a main issue, partly due to the unappealing traditional image of the construction sector. Compared to many other industries, in fact, the construction sector has traditionally been slow at technological development and has undergone no major disruptive changes in the last decades. Furthermore, jobs are often associated with long hours, harsh working conditions, and low salaries. As a result, companies struggle to recruit skilled workforce, as the sector is often not seen as a potential destination for (young) qualified individuals, in particular those studying ICT, who tend to prefer other sectors with a more innovative and dynamic image.

Transformation to Construction 4.0 can happen only if construction companies are able to attract, develop and retain skilled and qualified talents. More specifically, tomorrow’s construction workforce should master ICT, digital communication, data process, and digital content creation, should be able to communicate and work in digital environments, and should be familiar with the concept of data protection and with safely managing sensitive data. At the same time, the shift from exclusively manual labor, which is typically male-dominated, to new technology-enabled ways of working could mean increased interest from women. As construction needs to diversify its sources of talent to attract the best people, a higher female participation is a large opportunity, especially in emerging markets where male domination is even more pronounced.

1.7 Conclusions and future trends

The construction industry has a relevant significance in the global economy, as it employs millions of people and contributes massively to the GDP of individual nations and the world at large. However, due to various factors, both internal and external to the sector, productivity has remained stagnant over the last 80 years, growing at a much slower rate than the manufacturing sector and the industry in general. Today, the need to improve the efficiency and performance of the sector and the consistency and quality of its outputs intersects with four megatrends that are affecting the construction sector at the beginning of the third decade of the new millennium, that concern sustainability, demographic trends, increasingly digital connectivity, and global health issues.

The triple convergence of the urgent needs of the sector, of these new world trends and the recent emergence of some disruptive technologies such as AI, IoT, BIM, robotics, 3D printing, XR, are finally bringing the construction sector into a new digital era, with an impact analog to that of Industry 4.0 on the manufacturing sector in the last decade.

Construction 4.0 is a new revolutionary approach to the building process which exploits the potential offered by the digital revolution to radically improve the whole construction value chain, from the early design stage to the very end of an asset’s life cycle, in terms of better performance at the company and project level, improved sustainability of the industry, cost savings, reduced time and delays of the whole construction process, enhanced safety, improved capital management and funding, and improved image of the construction industry. This evolution in turn allows to optimize building performance, cost-effectiveness, employee satisfaction and productivity, bringing substantial value across the industry and greater alignment among stakeholders and resulting in greater profitability, enhanced project success, higher-quality built environments, and more empowered people.

However, some key obstacles are still hindering a faster and broader digital transformation of the construction sector. Main challenges include the investment linked to new equipment and software, the limited availability of skilled workforce, and a lack of awareness and understanding throughout the industry. Each of these factors impacts differently depending on the type of technology. For example, the upfront cost of equipment is strongly limiting for 3D printing and robotics uptake, but it is a secondary issue for the wider adoption of sensors. On the other hand, the lack of skilled workforce is particularly detrimental to the adoption of AI and, VR and AR tools.

Switching to digital tools often requires a substantial upfront investment from companies, as they need to buy the necessary equipment, purchase the software and upskill their employees. Although this initial investment is largely compensated by the gains in productivity and, more generally, by the added value brought by digitalization, the benefits provided by digital technologies are often not clear. Efficiency gains can be less apparent particularly in the case of SMEs, which tend to work mainly on smaller projects, either independently or as subcontractors. In addition to discouraging costs, such lack of awareness and understanding constitutes a main bottleneck for a wider uptake of most of the technologies, including Sensors, IoT, VR/AR, AI, and digital twins, as many companies doubt that the adoption of digital tools will provide sufficient benefits to justify the initial investment. Aware of this issue, national governments are increasingly providing support to incentivize construction SMEs to invest in digital technologies in the form of fiscal incentives, training, and technical assistance.

In addition, promoting more integral coordination among professionals across the different construction phases is crucial to incentivize all construction companies down the value chains to implement digital solutions. Currently, in fact, the design and construction phases are sometimes not adequately coordinated and integrated, which leads to inefficiencies, delays, and potential errors. The lack of involvement of contractors in the design phase hinders the upward integration of construction knowledge among stakeholders and professionals, diminishing the opportunity for them to influence design decisions and engage with other professionals involved on the methods, tools and technologies to be used. Moreover, failure by professionals to consider how other team members involved in all the construction phases will carry out the project may create scheduling problems, delays and disputes during the construction process.

In this scenario, the public sector plays a key role in supporting and incentivizing the adoption of digital technologies in the construction sector. This can be achieved through three main types of interventions:

- policymakers shall set the right rules and regulations and lead the digitalization process;
- buyers and administrators of public buildings and infrastructures shall influence the market by providing the right business opportunities;
- building-related public services administrators shall digitalize their own processes first, to facilitate the digitalization uptake down the value chains.

Several national governments are already fostering the adoption of digital technologies in construction projects by requiring their use in public procurement tenders, for instance making BIM mandatory in works over a certain value threshold. Nonetheless, in developing such requirements, public sector actors may also need to build their BIM related capacities, to balance their focus between low price and high quality and to make sure that all types of companies (small and large) can leverage on these opportunities to digitalize.

Governments promote the digital transition in the construction sector by providing e-services related to the built environment, for example, by issuing building permits and keeping the repository of building data and geospatial information digitally, including GIS and 3D models for digital cadaster of properties. In order to be effective, any policy intervention should be evidence-based and carefully monitored throughout its implementation, to adjust to possible changes and reflect the interests and constraints of construction actors and other public and private stakeholders.

Remarkably, although COVID-19 pandemic has strongly affected the activities of construction companies, it pushed both the private and public sector to digitalize their services and delivery mode in order to cope with restrictions. This may push the construction sector toward a new normal, where digital technologies play a more important role, spreading at the different stages of the value chain.

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Holistic building design approach

2.1 Life cycle design

The reference framework for the design and construction of building organisms has substantially evolved in the last 10 years with the goal to promote a more sustainable built environment in which humankind lives within the carrying capacity of the earth. In building construction, sustainability relates to how the activities, products, or services used in the fabrication work, as well as the actual use of the building, contribute to the safeguard of the whole ecosystem for generations to come.

Such building industry will be based on knowledge and innovation, will be more resource-efficient, greener, and more competitive, with a high employment rate, and will promote social and territorial cohesion. It will be understood as “a process in which all stakeholders (clients, financiers, engineers, builders, material manufacturers, authorities, etc.) apply functional, economic, environmental, and quality considerations to construct and renovate buildings and create a built environment that can be attractive, durable, functional, accessible, comfortable and healthy; efficient in terms of resources (especially in terms of energy, materials, and water) and of environment impact and able to encourage the use of environmentally compatible materials; respectful of the context and local culture and heritage; competitive in terms of costs, especially in a long term perspective” (COM 60/2004 and COM 718/2005).

The design activity must therefore have as its fundamental purpose the realization of a quality and technically valid intervention, in compliance with the best ratio between the benefits and the overall costs of construction, maintenance, and management, capable of satisfying the needs, expressed and implicit, of all the parties involved in various capacities by the intervention.

In essence, it is a question of creating buildings that maintain or improve the quality of life of the users, in harmony with the climate, culture, traditions, and environment of the place, using energy and resources rationally, recycling or reusing materials and reducing the release of harmful substances in the local and global ecosystem during their entire life cycles.

As already established in the manufacturing industry, in the construction sector as well it is necessary to pursue a holistic approach to design that follows the principle of “Life cycle thinking” and takes into account the effect of environmental, social, and economic impacts of design choices along the entire life cycle of the building: from site identification, to construction, operation, until the final decommission and recovery of materials (“from cradle to cradle”) (see Fig. 2.1).

Life cycle thinking considers the cradle-to-cradle implication of all actions involved. It acknowledges that societal actors cannot strictly limit their responsibilities only to those phases of the life cycle of a product, process, or activity in which they are directly involved, but expands the scope of their accountability to include environmental, social, and economic implications along the entire life cycle instead. This approach aims to reduce the overall environmental impacts in an integrated way, inviting to direct each improvement action to the phases of the life cycle in which it is more effective and at the same time avoiding that sustainable initiatives focused on single phases of the life cycle end up simply transferring the environmental load from one stage of the life cycle to another, from a location to another, from one environmental medium (e.g., air, water, or land) to another medium, or from the present to the future, without benefiting the overall environmental balance (problem shifting).

In the construction industry, the pursuit of sustainability means to interpret development over three closely linked aspects—the economic, environmental, and social ones (triple bottom line)—while always matching it with specific technical, functional, and quality requirements. In fact, the final quality of the building resides not only in meeting the needs of direct promoters and users, but also in providing a larger value for the community through the effects that any work of territory transformation determines in cultural, economic, environmental, and social terms. These aspects are interdependent to each other, and the dynamic balance between them may be fragile or robust. They have no particular

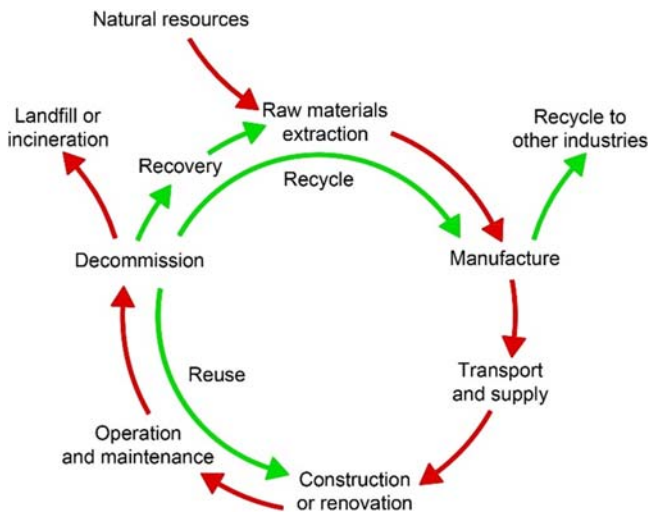


FIGURE 2.1 Building life cycle.

precedence, and each aspect needs to be addressed in a systemic way as a positive impact in one sphere may result in an adverse impact in the others. Nonetheless, the application of sustainability to building construction needs to reflect the context in terms of goals, priorities, preconditions, possibilities, and constraints (such as poverty, accessibility, and access to services). The overall aim is to minimize adverse impacts while providing the required value.

Economic aspects relate to the costs and benefits (investment, cash flow, market value, profitability, etc.) that measure the impacts on the economy of activities, products, or services pertaining the fabrication and use of the building. Besides direct and short-term economic considerations, economic aspects shall incorporate life cycle considerations that measure the long-term economic impacts, or economic legacy.

Environmental aspects consider impacts on the quality and the quantity of earth's resources as well as on local, regional, and global ecosystems. Life cycle assessment (LCA) shall be incorporated to evaluate the impact to the environment of both the construction work and the use of the construction works, including any legacy left behind.

Social aspects relate to intergenerational ethics (impact upon future generations) and recognize the inherent value of ecosystems, traditions, and cultures. Impacts to society and quality of life involve those on local culture and the provision for basic human rights and human needs and shall include any legacy left by the construction works. They include health and comfort, socio-economic aspects, as well as the cultural value of the building. They may relate to individuals (e.g., building occupants) and/or to groups (e.g., local society) and include accessibility, adaptability, health and comfort, loads on the neighborhood, maintenance, safety/security, sourcing of materials and services, and stakeholder involvement (EN 15643–3).

For the evaluation of economic aspects, the life cycle comprises the stages from construction to decommissioning. For consideration of environmental and social impacts, the life cycle instead comprises all stages from raw material acquisition or generation of natural resources to the final disposal.

The contribution of buildings and construction works to sustainable development can be considered on several levels, including the whole industrial sector, an enterprise, a community, a building stock, a group of buildings, or an individual building or asset.

The decision making usually relates to the planning, design, construction, management, and deconstruction processes. Typical phases of a project development are project inception, including the description of the project's characteristics; project development, calculation, and acquisition of the land or existing building; project conception including feasibility and profitability analysis; planning; construction; marketing; use; refurbishment; or redevelopment.

Applying the concept of sustainability to specific buildings or other construction works includes a holistic approach, bringing together the global concerns and goals of sustainable development and the demands and requirements in terms of product functionality, efficiency, and economy, and requires the direct and responsible involvement of all interested parties. This principle takes into account the contribution and requirements of all stakeholders relative to their respective areas of responsibility, and the timing of their involvement.

Indeed, the building and construction sector entails a wide range of agents which may demonstrate significant differences and multiple views in their appreciation and understanding of sustainable development in the context of building and construction, particularly in terms of scope, content, level of detail, priorities, etc. Main stakeholders include certification bodies, clients, contractors, designers, developers, facility managers, governmental and nongovernmental

organizations, insurers, investors, manufacturers, owners, planners, policy makers, promoters, real estate agents, researchers, standards developers, suppliers, users (tenants as well as public), etc.

The pursuit of sustainability of the building has the additional merit of contributing, in an essential way, to bond the design activity with those of construction and management. In fact, only by controlling all phases of the building process, to evaluate the environmental, economic and social impacts, it is possible to obtain a building production that expresses the compatibility between esthetic-functional purposes, regulatory requirements, quality and performance controls, organizational needs, socio-economic and environmental conditioning, and safety guarantees and achieve the planned useful life and a controlled aging of all components. This approach allows the designer to enhance their choices by satisfying formal needs and at the same time substantiating them from a technical-functional, environmental, and economic point of view. Therefore, sustainability represents one of the fundamental challenges for scientific and technological research as it calls for structural changes in the world of production. It can be said that sustainability for the built environment has the same importance that the industrialization process in the construction industry had in the past, and is imposing a profound evolution in all sectors of activity that pertain to architecture technology, from research to design, from standardization to management.

As contemporary society has challenged architecture to balance the world system of sustainable development, this requires a “global awareness” by all involved stakeholders and will certainly lead to structural changes in the production world and to an expansion of the regulatory framework which regulates the construction industry. A modification of the design process is thus expected, as it becomes more complex due to the introduction of the new sustainability parameter, necessitating the use of new skills along with new assessment and calculation tools. It is in fact necessary to simultaneously control the three environmental, typological, and constructive levels, harmonizing at best the compositional, structural, and technological choices. In this new scenario, the design process must necessarily go through a careful analysis of the context with which the intervention will have to interact during its entire life cycle. The reading of the programmatic framework in which the intervention is inserted, the knowledge of the approval procedures, the consideration of all actors involved in the construction process, become essential assumptions to take architectural and technological decisions according to precise objectives of environmental compatibility, architectural and functional quality, energy efficiency, and economy. The results of this analysis will produce all design inputs necessary to ensure the technical and economic feasibility of the work to be carried out and the meeting of the various needs of construction quality.

To achieve maximum sustainability of the intervention, the stage of conceptual design is of particular importance, as it represents the delicate moment of architectural inception of the project and at the same time of verification of its feasibility.

Conceptual design has, in fact, the task of defining the qualitative and functional characteristics of the intervention, the framework of the needs to be met, and the specific services to be provided, illustrating the reasons for the choice of the proposed solution based on the evaluation of any possible alternative, as well as its feasibility from a technical, environmental, and economic point of view. It is the moment in which the designer’s creativity expresses the idea of the work to be carried out and this idea is mediated, not in a negative sense but rather by subsequent enrichment, with the geomorphological nature of the site to be transformed, with the formal spatial, functional and social needs, with technological innovations, and with the budget available.

Furthermore, the early design phases are the ones which have the greatest influence on the project as-a-whole, as project planning is more flexible at this stage: the earlier the project stage, the more impactful—and more cost-effective—it is to introduce changes (see Fig. 2.2). As the project development proceeds, in fact, flexibility is reduced, the chance of making changes is smaller, or making changes involves higher costs. During the early phases, therefore, there is more potential for studying different alternatives, reducing costs, implementing changes, and improving performance, making them a key in achieving sustainability.

Sustainable design has to be meticulous and consider the entire construction life cycle, with increased effort in the early phases due to their influence over the project as a whole. It is important to view sustainable construction not as a complicated or expensive trend, but as a form of integrated design, where all components of a given project are seen holistically rather than individually. Various alternatives have to be compared in the early design phases with a view to selecting the most suitable one, based on the three pillars of sustainability (economic, environmental and social impacts). For this purpose, a huge amount of information has to be dealt with. This is one of the main reasons why, at present, sustainable methods are often implemented in the later project phases, when the final solution has already been developed, but, as reported above, the potential and capacity for influencing the project are greatly reduced.

In this context, the use of building information modeling (BIM) systems for the computable representation of construction projects has become imperative for achieving the objectives of building quality required by contemporary

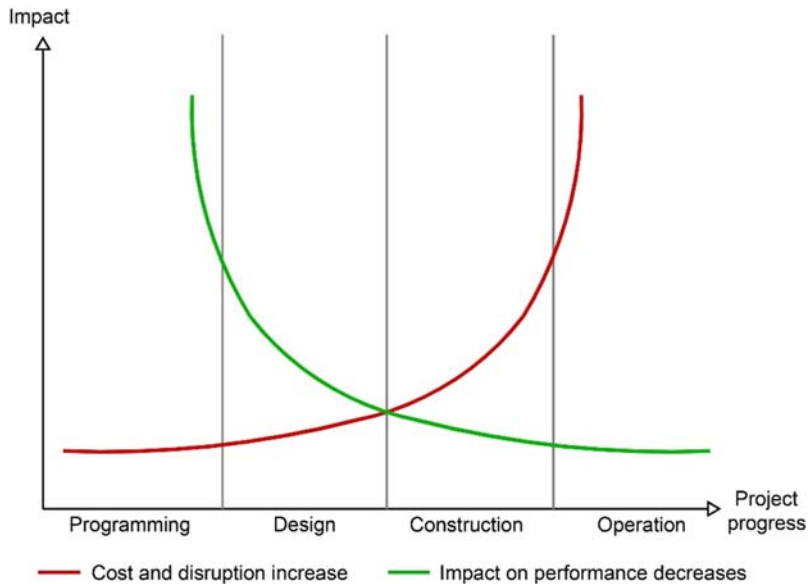


FIGURE 2.2 Influence of changes in project performance during project progress.

architecture and to reduce design, construction, and building management costs. BIM virtual modeling has opened up new and interesting perspectives to the design process in terms of creativity, verification and optimization of alternative solutions, process control and costs. Through BIM virtual modeling it is possible to integrate in real time the three-dimensional formal architectural solution (3D) with the effects in terms of energy and environmental performance (4D) and of construction, operation, and maintenance costs (5D, 6D, 7D), controlling the entire project up to the construction phase by the formal, technological, and economic points of view (see [Chapter 4](#)). With BIM, designers create digital 3D models that include data associated with physical and functional characteristics. The data can be used in powerful analyses and simulations and to include realistic visualizations. The power of BIM is how it allows architects, engineers, and contractors to collaborate on coordinated models; giving everyone better insight into how their work fits into the overall project—ultimately helping them to work more efficiently. This improves overall information flow and enhances transparency and collaborative work between the stakeholders. The resulting improvement in communication leads to redesign reduction and helps to avoid future, costly errors in the construction, operation or decommission phases.

Indeed, BIM greatly supports integrated design due to improved collaboration between the stakeholders and a better overview of the project as a whole. The particular features of BIM make it the go-to method for achieving sustainable construction, as it has a positive impact on all three pillars of sustainability. Firstly, concerning economic aspects, the better quality of information leads to cost reduction. Various alternatives can be analyzed in the early design phases of a project, which improves efficiency and decision-making. Secondly, regarding social aspects, BIM-based analysis and simulation make it possible to assess different parameters, such as daylight, sunlight, and ventilation, which leads to an improvement in working and living conditions. Such assessments are much more complex and time-consuming without the use of BIM-based tools. Thirdly, pertaining environmental aspects, BIM software can be applied in different ways for sunlight and energy analysis and greatly facilitates the conduction of LCA assessment in the design phase.

2.1.1 Life cycle analysis of buildings

The origins of the LCA can be traced back to the end of the sixties of the 20th century, when researchers who wanted to apply strictly scientific criteria to the issue of the consumption of resources, with particular regard to energy ones, realized that the only effective method to study production systems in a complete way was to assess performance by following the entire path taken by raw materials starting from their extraction from the earth, through all the transformation and transport processes that they undergo, up to their return to the earth in the form of waste. This approach is therefore defined “from cradle to grave,” or “from cradle to cradle” if it includes the re-entry of materials at the end of their life. The first examples of application of LCA date back to the early 1970s when some large United States companies, the American Environmental Protection Agency (EPA), as well as some British manufacturers of bottles, used this tool as a decision support. The term LCA itself was coined in 1990 during the congress of the Society for

Environmental Toxicology and Chemistry (SETAC), to better characterize the objective of the analyses carried out to that point under the name of “Resource and Environmental Profile Analysis” (REPA). Subsequently, the LCA method was standardized in 1997 with the standards of the ISO 14040 series and defined as the “compilation and evaluation, throughout the life cycle, of the incoming and outgoing flows, as well as the potential environmental impacts, of a product system.”

The core application of LCA concerns product-related decisions support. It can include hotspot identification, product development, product comparison, green procurement, and market claims. Next to other tools, LCA is also important for technology choices, contextualizing them into a product-related chain perspective. LCA is increasingly used at a strategic level for business development, policy development, and education.

Starting from the early 2000s, the LCA methodology began to be applied also in the construction sector as a tool to support the life cycle design approach, first at the product scale for drafting environmental product declarations (EPDs), then at the building scale as well to identify, possibly from the initial design stages, the solutions capable of ensuring maximum sustainability throughout the entire life cycle (whole building LCA, WBLCA).

Contextually, in fact, investors, tenants, and other stakeholders have been demanding transparency, especially when it comes to carbon footprint and other environmental and social impacts.

Conducting a WBLCA within the design process helps the project team understand the short- and long-term impacts associated with different design alternatives, allowing them to make better design decisions. WBLCA can be very helpful for identifying hotspots to direct the decision-maker’s attention to where changes should be made to get the biggest environmental benefit. The LCA methodology also allows to calculate the embodied energy and carbon footprint of the materials that make up the building, which reduction is becoming an increasingly weighty element in the concept of a zero-energy building as energy performance in the operational phase improves.

Following the demand from the construction industry for transparency, green building rating systems such as BREEAM, LEED, Green Star, DNGB or CASBEE, have been incorporating LCA into their credits system. Rating systems increase the credits given to simulation of buildings performance, basing the assessment on empirical calculation methods.

LCA software tools already present on the market since the 90 s for the evaluation of industrial products or processes, such as Gabi, SimaPro, Umberto and OpenLCA, have recently been joined by tools designed specifically to support WBLCA such as Athena Impact Estimator, EtoolLCD, Tally or One Click LCA, more accessible to professionals in the Architecture, Engineering and Construction (AEC) industry.

Compared to an industrial product, the environmental assessment of the entire building is a more complex procedure due to its own nature (Bahramian & Yetilmezsoy, 2020; Nwodo & Anumba, 2019; Roberts, Allen, & Coley, 2020).

Differently from products, buildings are unique, they have multiple functions, and they are assembled on-site. There is also a high degree of uncertainty concerning the use phase of the building, requiring assumptions which, in turn, increase the inaccuracy of the assessment.

Specifically, a building can be considered as an end-use product of itself. It physically consists of various construction materials and components which make up the building and its technical systems. Indeed, a building can be considered as an integrated assembly of component products, which are manufactured, used and disposed of, according to their service life. Because a building is an assembly of component products, their impact assessments become relevant for the analysis of environmental performance of the complete building. Therefore, the environmental performance of a building involves issues that relate to the characteristics of the building both as an end-use product and as an integrated assembly of component products. Each of these products has its own features and life span, which means that they have varying relevance with regard to environmental impacts. The life cycle of the products determines that of the building, which in turn influences that of its components through the methods of assembly, use, and disposal.

As an active process and in order to function, the building is provided with energy, water, and other resources. Consequently, the environmental performance of a building relates to input and output flows that a building generates as a process. Through its operation, the building provides a number of services to its users as well as the conditions appropriate for living, working, studying, provision of health-care, leisure activities, etc. This activity involves input and output flows to make the process function, including atmospheric emissions, wastewater, and other wastes. In addition, a building is linked to infrastructures both upstream and downstream, which also require energy, water and transportation energy and generate wastes. These processes also have input and output flows. Therefore, the environmental performance of the building relates to the quality of services to users as well as to relevant conditions that a building generates when perceived as an active process.

Applying LCA methods to buildings require significant time and effort for implementation, including obtaining complete environmental impact data for building components, tracking material flows, and clearly defining system boundaries.

To reduce the efforts connected with performing an LCA study, BIM can be used effectively (Llatas, Soust-Verdaguer, & Passer, 2020). Information required can be extracted directly from the BIM model, since this model is created during the early design phases and contains the main features characterizing the construction, avoiding manual data re-entry into the LCA software, which is one of the main drawbacks of the LCA performance. This also enables the real-time comparison of project alternatives. Furthermore, environmental properties of the BIM objects can be included along with the development of the project finding an automatic and efficient link between the design models and environmental information included in the life cycle assessment databases.

Considering that decisions made during a building's early design stages critically determine its environmental impact, the integration between BIM and LCA methods should be implemented since the early phases of the design process so as to be fully integrated in all decision-making (Rezaei, Bulle, & Lesage, 2019).

For instance, selecting an environmentally preferred building shape and orientation can allow to reduce a baseline design's environmental impact by 40%, whereas massing changes made during late design stages have considerable environmental and economic cost ramifications (Rezaei et al., 2019). Early-stage environmental impact performance feedback can have strong effects on design choices, resulting in less energy intensive buildings and increasing awareness of ways to reduce energy consumption.

With BIM, LCA can be performed from the digital model, potentially without even changing the software environment. This should allow teams to perform LCAs for different scenarios early in the process and whenever a design or execution choice needs to be made. Fully integrated with BIM and generative design, LCA can greatly benefit in the optimization of the form and orientation of the building.

2.1.2 Life cycle design strategies

For building design, the pursuit of a holistic approach oriented to life cycle basically means following two main interconnected objectives.

The first objective is to create buildings that in their useful life are able to offer users the best conditions of comfort, safety, and health through the least use of material, energy, and economic resources and the minimum impact on the environment. This means creating smart buildings, with very high energy performance, having the lowest environmental impact while enjoying a high level of social and economic development ensuring the best possible user experience under natural conditions throughout the year.

Without prejudice to the pursuit of the first objective, the second one is instead to reduce as much as possible the environmental, economic, and social impacts in terms of the use of resources and the introduction of pollutants, deriving both from the production and transport of materials and products, and from the construction, maintenance, updating and disposal of building components at the end of their life. This means taking into account the impacts deriving from the phases of the building process located both upstream and downstream of the operational phase.

The first objective, as illustrated in the following 2.2. and 2.3 sections, is pursued through a design that is attentive to the environmental context and capable of effectively combining both passive strategies, concerning the geometry and structure of the building, and active ones, concerning plants, renewable energy sources, and their management and maintenance methods.

Pursuing the second objective instead means creating high-performance buildings using the least possible quantity of materials (design for resource conservation), using more durable products and with a lower environmental footprint (design for low impact materials and cleaner production), and using methods of construction as efficient and clean as possible. These buildings must also be integrated into the surrounding landscape and be designed to ensure maximum maintainability (design for an extended service life), maximum adaptability to changing market and occupier needs (design for adaptability), as well as the recovery and recyclability of components at the end of life (design for deconstruction) (see Table 2.1).

The potential of the location and site already implies both opportunities and limitations arising from the urban environment and the influences of specific site conditions on the project, as well as the expected effects caused by the planned project itself.

Choosing a good location helps minimize disturbance, and the retrofit of existing structures or the recovery of brownfields can shrink the environmental footprint. The avoidance of interference with watersheds and wildlife corridors, as well as the use of native vegetation for landscaping, also contribute to maximize the site's value in relation to its carbon emissions. The selection of an urban location in walking distance from amenities and public transit can reduce transportation emissions. The existing natural environment must be thoroughly investigated for its potential integration into the project by analyzing all microclimatic indicators such as exposure and solar control, wind and

TABLE 2.1 Building life cycle stages.

Life cycle stage	Design strategies
Product stage	Adaptive reuse of structures and products Use of products with lower environmental footprint Design for an efficient building geometry and structure Sustainable resources supply methods
Transport to construction site	Use of local materials and sustainable transportation methods Additive manufacturing on-site
Construction stage	Sustainable construction methods Modular/ prefabricated construction Adaptive reuse and selective demolition Recycled materials from decommissioned buildings
Use stage—fabric	Use of products with lower environmental footprint Design for extended building and component service lives Design for adaptability and resilience
Use stage—energy and water	Passive and active design strategies in order to improve the building efficiency and reduce environmental impact in the use stage
End of life	Use of products with lower environmental footprint Design for deconstruction

precipitation characteristics and topographic and vegetation conditions. Tools such as Autodesk Insight help architects design with energy efficiency and environmental optimization at the forefront of the project. Autodesk Spacemaker, an AI-based tool used in the initial stages of planning and design, can even allow real-estate developers to think about the impact of their building location and orientation by using real-time, data-driven wind and daylight analysis and feedback.

Design for resource conservation entails to optimize the structure of a new building from the first stages of design, by pursuing more efficient building shapes or considering the feasibility of reusing the structure of an existing building. Any project that is located on a site with existing infrastructure should conduct a prebuilding audit that inventories available materials and assemblies for reuse or donation, including soon-to-be-demolished or decommissioned buildings. In this picture, digital solutions offer useful recycling and reclamation solutions that favor a more thoughtful approach. Using advanced survey systems (LiDAR, 3D photo reconstruction) and BIM data-management tools, an inventory of building materials can be digitized to create a faithful 3D model which can facilitate the development of a digital twin infused with construction and operational data. These, paired with material passports (MPs) (a database of all materials used for a project), can effectively transform old buildings into valuable material banks. This way, used steel beams or bricks can be rescued and given a second life in another building. The more is known about what is in the building before stripping and demolition, the easier and cheaper it will be to reuse those materials instead of disposing of them in landfills. Digital twins and MPs allow architects and designers to pursue adaptive reuse, for instance, rethinking and redesigning layouts that best use the space available using generative design tools, or reusing the core of existing structures or making recycled materials central to a new project's design. For instance, the Quay Quarter Tower in Sidney reuses 68% of a preexisting 1970s building, claiming an embodied-energy equivalent saving of 10,000 flights from Sydney to Melbourne. The White ReCapture process by White Arkitekter involves laser-scanning an existing structure to determine the value of every item and how it can be reused, including doors, glass partition walls, and ceiling tiles.

In the early stage of design, discussion and decision making involve several aspects that will directly or indirectly influence the choice of building structure and the main materials to use in the shell and core.

For instance, housing developments can be planned as blocks of flats, terraced houses, or detached houses. Flats blocks imply inherent material savings due to a common roof and common structural elements, with the trade-off of larger structural columns that take-up a larger share of the floor space. Terraced houses entail material savings compared to semidetached or detached houses due to shared walls. For office buildings, taller structures generally have same inherent impacts as taller residential units, with the aggravation that in high-rises (e.g., >30 stories), the extra material for lateral resistance becomes more dominant on the total structural mass.

Concerning structural materials, structural engineers often overspecify structures and material structure grades when a more detailed design may allow significant structural material savings without compromising functional requirements.

For concrete structures, the concrete usage index, expressed as m^3 concrete/ m^2 floor area, can be used as a metric for structural efficiency and benchmarked for similar building types (JRC, 2021a).

There are several possibilities for reducing the specific quantity of structural concrete, that include the use of:

- flat slabs with equal spans (i.e., square) as much as possible;
- standard beam and slab forms (and formwork) for lower wastage rates;
- post-tensioned slabs for longer spans (i.e., fewer columns) and thinner floors;
- voided floor slabs, which are lighter and require smaller foundations;
- exposed concrete to reduce the later need for fit-out materials.

Each choice may entail possible trade-offs as well, for example, thinner slabs present a lesser barrier to noise and may require materials for acoustic correction, or require higher contents of cement, which may offset the environmental impact of needing fewer m^3 of concrete in the slab.

For steel structures, the utilization efficiency of each beam within a given structure shall be analyzed in order to determine the potential to reduce steel mass without compromising design performance requirements and safety factors. Studies found that utilization rates of the beams can be less than 50% of their capacity, mainly due to the selection of beams based on availability, time and cost, rather than performance, or the use of “rule of thumb” instead of calculations, and suggested that, on average, 36% of the beams’ mass could be saved. Design and optimization software can be used effectively to improve utilization rates (JRC, 2021a).

With the goal of design for low impact materials and cleaner production, focus should be made on choosing materials and products with a lower environmental footprint, possibly with an ecolabel certification, favoring materials of natural origin (so called bio-based materials), renewable, recycled, recyclable, with a low embodied carbon, free of hazardous substances, whose processing cycles have low environmental impact and possibly supplied by companies holding an ISO 14001 or EMAS certificated environmental management system, or finally that participate on an extended producer responsibility program or are directly responsible for extended producer responsibility.

The search for more sustainable materials and the growing awareness of the importance of embodied energy in the global environmental impact of buildings has also brought designers’ attention back to the structural use of wood and bamboo and to engineered wood-derived products, so called “massive timber,” such as cross-laminated timber (CLT), laminated strand lumber, and laminated veneer lumber (see Section 7.5.2). Mass-timber construction can also help cut buildings carbon footprint by storing carbon in the building’s structure.

Life cycle design also pays special attention to resources supply methods, according to the principles of sustainable management (for instance, certified wood from forests managed according to the sustainability principles of programs such as *Forest Stewardship Council—FSC*, *Programme for the Endorsement of Forest Certification schemes—PEFC*, the *Sustainable Forest Initiative—SFI*, biobased products compliant to the Sustainable Agriculture Network’s *Sustainable Agriculture Standard*, tested using ASTM Test Method D6866 and legally harvested or stone products certified under the Natural Stone Council 373 Standard).

In choosing materials and technological solutions, it is also important to consider the potential trade-off between reducing CO_2 emissions in the use stage and the embodied energy CO_2 emissions associated with the manufacture of higher performance insulation, façade, and wall systems, windows, structural thermal mass and renewable energy technologies to achieve nearly zero energy building (NZEB) performance levels (optimized NZEB construction). Indeed, more efficient building alternatives normally include additional embodied energy from elements like high-performance insulation and glazing, and photovoltaics. Therefore, it shall be always verified that the energy embodied in the high-performing building components is paid back over time, and the overall impact of the zero energy building, embodied and operational, becomes less than that of the baseline building (see Fig. 2.3) (JRC, 2021b).

The objective of sustainability in construction also entails the incorporation of location-based solutions and the contribution to the expansion of regional economies rooted in sustainable practices, products, and services, focusing the use of local materials and products (so-called zero km material). The use of nonlocal components, as well as the use of materials and products with a greater ecological footprint, shall be justified only when it brings advantages in building performance and energy efficiency in particular, contributing to a significant reduction in operating costs. In such cases, transport methods with less environmental impact, such as rail transport, are to be preferred. A more efficient distribution also suggests the choice of lighter building materials and small size prefabricated elements to be assembled on site, or even to be directly realized on site via 3D printing processes.

Since the choice of materials will finally influence the environmental impact of the building at the end of its life-cycle, linked to the possibility to recover used materials and safely dispose of them reducing the production of solid waste, it is crucial to use products that can be easily disassembled into their components and reused or recycled at end

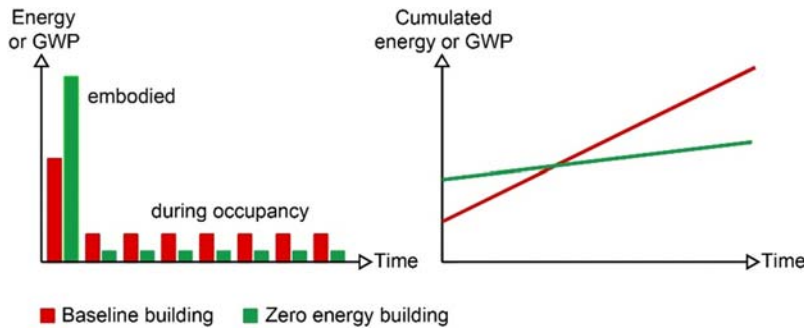


FIGURE 2.3 Trade-off between embodied and operational energy.



FIGURE 2.4 Construction and demolition waste management strategies.
Redrawn from (JRC, 2021d).

of life. In particular, design choices should favor materials capable of recovering the original performance characteristics and that do not imply particularly polluting or high energy consuming treatment processes, and technical components that contain materials which may be incompatible with one another in terms of recycling should be avoided. It should be noted, however, that the real possibility of recovering building materials is linked to not only the recyclability of the single products, but also to the construction techniques used and the method of demolition at the end of the building life. In order to close the waste cycle and to promote a circular economy, it is necessary that the building is designed with a focus on the recovery of its components (*design for disassembly, re-use, and recycling*) (JRC, 2021c).

Relevant data on the environmental impact of products and materials can be obtained by consulting their EPD or available inventories associated with a LCA database. Such inventories will support a more comprehensive assessment of the life cycle inventory flows and associated environmental impacts. Indeed, LCA software databases can reveal a broad range of construction materials and products to choose from. Once a representative dataset has been identified within the database, the materials are matched up to inventory flows of inputs and outputs associated with their production, generating what is called a “reference flow” for the target building element. Complex building elements with many component parts shall be analyzed at the level of their components and subcomponents, each with its own production processes and associated material resource footprint. The outputs for such analysis will be different life cycle impacts, for example, global warming potential and other such as acidification potential, ozone depletion potential, etc.

Finally, particular attention must be paid to the environmental and social impacts generated during the construction phase (noise, dust emissions, soil contamination, etc.) with particular reference to the production and management of waste from construction and demolition (see Fig. 2.4). Prefab, modular, and industrialized construction can speed up project timelines, codify construction, and cut waste from the lifecycle of the project (see Section 8.1). Embracing more efficient methods, such as lean construction, eliminates waste and cuts down on embodied carbon through better project management. Better BIM management and digital collaboration on the jobsite can save money, energy, hours required, and materials. Electric construction vehicles and trucks contribute to containing noise and emissions at the construction site.

Furthermore, before the start of the construction works, a waste management plan (WMP) must be prepared containing an estimate of the waste that will be produced divided by type, storage and transport methods, the measures to

mitigate environmental impacts and the final destination, favoring the reuse and recycling of materials as much as possible. If demolition activities are envisaged, an audit should be carried out with the aim of identifying the different elements, materials, and potential wastes and how they could potentially be dealt with by decontamination, stripping, selective deconstruction, and sorting techniques—within the time, space, and labor constraints of the project and the regionally available options for these elements, materials, and wastes. Indeed, disassembly and demolition techniques have a decisive influence on the quality of construction and demolition waste and consequently on the possibilities of their effective recovery.

Materials obtained from nonselective demolition procedures, which favor the speed of execution of the operations, have a highly heterogeneous composition that does not allow their recovery under economically advantageous conditions, or that even makes such recovery impossible because of the contamination, during the demolition process, of the recoverable waste with dangerous substances. On the contrary, a selective demolition, adequately planned, can allow the separation of the different recoverable fractions constituting the demolition waste, as well as the removal of polluting substances. Selective demolition is carried out as a real deconstruction process, the reverse activity of the construction of the building. Selective demolition of a building can take longer, but is less noisy, less polluting, and less destructive than ordinary demolition operations and is therefore a more appropriate practice in densely populated areas. The higher costs of selective demolition can be compensated for in the lower cost of landfill disposal and in the lower cost resulting from the use of recycled materials in the construction phase, thus allowing to combine the economic cycle and the environmental cycle.

Life cycle design also involves the impact of the intervention on workers and labor tasked with the actual construction works, which entail social and economic repercussions at both short and long term projection (e.g., accidents on the job, occupational diseases). These can be mitigated at both the design stage of the project, with the adoption of lighter, safer, and easier to install materials and products, and at the construction stage, by envisioning large portions of the building to be prefabricated off-site, in safer, more ergonomic and protected environments, and by delegating as many on-site operations as possible to autonomous and robotized construction methods (see [Section 8.2](#)).

2.1.3 Building life cycle costing

Life cycle costing (LCC) is a technique that “enables comparative cost assessments to be made over a specified period of time, taking into account all relevant economic factors, both in terms of initial capital costs and future operational and asset replacement cost” ([ISO/DIS, 2006](#)). In the context of buildings, this consists of initial capital cost, occupation costs, operating costs, and the costs incurred or benefited from its disposal.

By estimating life cycle costs of a building, important information can be provided to investors, asset managers and tenants. A life cycle cost perspective encourages clients and designers to consider the relationship between upfront capital costs (site, design, product manufacturing, construction) and use stage costs (energy and water consumption, waste management, maintenance and repair). It can also provide a more informed basis for understanding future performance, value and liabilities associated with a building. Savings associated with energy and water efficient buildings can be cash-flowed to capitalize the value of the savings and take it into account in property valuations and investment decisions. This may be calculated based on local market baselines, across a portfolio or on the performance of the same asset prior to energy retrofit. At the same time, LCC can assist in developing a medium/long-term maintenance and replacement plan can support more cost-effective management of assets. This can include decisions relating to the service life and durability of key elements and components, as well as predictions of potential future costs and liabilities that may be associated with the early failure of components.

As with LCA, LCC can be used in construction projects for design improvement, product selection, product/building certification, strategic planning, land use and zoning regulations, public policy making, procurement, and marketing purposes. The system boundary of LCC shall encompass all life cycle stages, including the cost of construction, operation, maintenance, refurbishment, and disposal. For renovated buildings, the system boundary shall encompass all life cycle stages that relate to the extended service life of the building.

The common unit of measurement for each life cycle stage is euros or dollars per square meter of useable floor area per year ($\text{€/m}^2\text{yr}$), based on the net present cost. Calculation should apply a discount rate to the costs estimated or reported for each year of the reference study period (commonly 50 years). The net present costs should generally be calculated using real costs, that is, excluding inflation. However, assumptions about inflation may also be included within the discount rate if nominal costs are required for the purpose of detailed financial planning.

Paired with LCA, LCC can lead to more holistic decision making, considering that most building projects are budget-constrained. In a given scenario, LCA can indicate the environmental impacts of different options. The

alternative with least impact would normally be identified as the best solution, but this option might have a large initial cost. In such cases, LCC can evaluate the economic impact of the option as well and help select the most suitable alternative based on a limited budget and calculated payback period, while simultaneously managing environmental impacts. Optimizing the design solutions ensures that available resources are invested in the best possible way to achieve the highest potential emission reduction.

To measure how improved performance affects the financial valuation or a financial risk rating of an asset, it is necessary to consider three main potential areas of influence (JRC, 2021e):

- increased revenues from more stable investments, by making properties more attractive within local markets, by keeping void rates low and by enabling properties to be adapted to future market conditions;
- reduced operational overheads, by minimizing operational expenditure (OpEx) relating to energy and water utilities, as well as projected maintenance, repair and replacement costs;
- reduced exposure to future risk by anticipating the effects of climate change, which could potentially lead to increased operational costs, unhealthy conditions, stranded assets as a result of emerging client and regulatory performance expectations, as well as increased insurance premiums.

In particular, the increased awareness and engagement of property investors on the challenges and potential of sustainable development has led in the last years in a growing adoption of green building certificates for the building stock: already in 2014, almost 40% of the assets in the 30 largest United States office markets had been either LEED or Energy Star certified. This has allowed a more accurate assessment of the value benefits obtainable through sustainable investing. In fact, literature studies have shown that the availability of certified environmental performance can lead to a mean increase of rental income and occupancy of more than 6% and an increase of sales price of almost 15% (Leskinen, Vimpari, & Junnila, 2020).

For the LCC evaluation of buildings, it is possible to use the same software used for the LCA following the reference standards EN 15459, ISO 15686–5 and EN 16627. For simpler calculations, useful to provide some guidance in early design stages, web applications such as Edge app or CRAVEzero LCC Web Tool can also prove effective, if not as accurate as dedicate software tools.

2.2 Climate and context adaptive design

The modernity of contemporary architecture lies in its connection with the context, which constitutes the network of constraints that each building must comply with: economic, environmental, cultural, symbolic, and technical. The challenge calls for an architecture that maintains or improves the quality of life of all stakeholders, in harmony with the climate, culture, traditions and environment of the place, using energy and resources in a rational way, recycling or reusing materials, and, generally, reducing the release of harmful substances in the local and global ecosystem during its entire life cycle, bringing value to all involved actors (Casini, 2009).

To achieve this objective, a holistic approach to design is necessary, one that, starting from the context and the elements that characterize the architecture and the culture of a given place, consolidated over time, is able to innovate within tradition and formulate a “2.0 vernacular architecture” enriched with the new possibilities offered by the materials and technologies of the 21st century (BIG, 2017).

The central element is the ability to exploit the environmental context in order to promote passive solutions capable of improving the internal microclimatic parameters with the least possible use of natural resources (Liedl, Hausladen, & Saldanha, 2012; Olgyay, 1969).

In this new scenario, the design process would necessarily pass through a thorough initial analysis of the needs to be met, the legislation to be respected, the services to be provided, as well as the environmental context being transformed. Results of this analysis will inform all design inputs necessary to ensure the technical and economic feasibility of the works as well as the satisfaction of the various needs of construction quality. The quality of architectural projects is strongly dependent on the quality of the information designers must work with. Hence, all decisions shall be based on site and project-specific information using a data-driven design approach, rather than on arbitrary esthetic or stylistic prejudice.

To design following a climate and context adaptive approach means to operate within a continuous feedback loop between design and analysis, between trial and error, based on technical simulations of daylight, sunshine, thermal exposure, airflow, turbulence, wind, space syntax, and traffic flow, with the goal to literally shape the project by the forces that surround it. In this scenario, concepts such as bioclimatic architecture and bionic green architecture (Hayes, Cheryl Desha, & Baumeister, 2020) (also known as biomimetic, biomimicry, or bio-inspired architecture) are arising

with the main goal of ensuring harmony between the building and the natural environment, maintaining the ecological balance while achieving sustainable development. Such approaches combine mechanisms found in biological systems (such as natural ventilation in termite mounds and insulation in polar bear fur) with modern building technologies.

From a methodological point of view, the initial analysis stage within a climate and context adaptive approach is divided into four main phases:

- delimitation of the programmatic framework (programming, planning, reference regulation);
- characterization of the requirements framework (demand, sector studies);
- definition of the project framework (performance level);
- identification of the environmental framework (morphological, geotechnical, archeological, vegetational, climatic aspects).

The analysis of the programmatic framework aims to identify the urban planning tools and sector programming in force in the municipality of settlement, the codes and regulations to comply with, as well as any legal constraints relating to the context in which the intervention is expected.

The analysis of the requirements framework has the objective of defining the general objectives that shall be pursued with the intervention, in line with the framework of needs that emerged in the feasibility study. The definition of general objectives provides functional information for the design, also identifying specific objectives and action strategies, which consider the overall scenario. It is necessary to investigate aspects such as the political, social, and technical motivation of the intervention and how it fits among the general program of the client; the strategies of the public body and the opportunity to use funds or grants; the possible synergies with other public/private subjects involved; the expectations of the client and the expected effects on the interested parties. Concerning the latter, it is a question of analyzing the results of the information campaigns conducted during the planning phase to identify the needs and requirements of all stakeholders involved. The different needs that the project must satisfy shall be analyzed separately, distinguishing between:

- user needs: health and safety, hygiene and well-being, management, usability, rational use of resources;
- client needs: rational use of resources, cost-effectiveness of management, durability, and maintainability of the intervention;
- community needs: protection of the environment, rational use of resources, safeguarding of cultural assets (i.e., social, environmental needs, methods of providing services, etc.), value and productive opportunities.

The analysis of the performance framework aims to define the performance levels that the work will provide. It includes the definition of the functions that the intervention must perform and of the technical requirements it must comply with. As regards the technical requirements, the analysis must highlight the specific requirements of the intervention area, of the building organism, of the environmental-spatial units, and of the technological units.

Finally, the analysis of the environmental context with which the intervention will interact during its entire life cycle is of particular importance, as it provides the potential as well as the constraints that will dictate how the project objectives will be achieved. Data and information collected in the analysis of the environmental context constitute a necessary prerequisite for making choices that are correctly motivated and ensure that the performance of the work meets the expressed and implicit needs of the various interested subjects. These choices shall allow on the one hand to optimize the performance of the building within the specific environmental context (functionality, well-being, and competitiveness), on the other hand to minimize the environmental impacts that organism will generate once realized (efficiency and environmental protection). In particular, the analysis of the environmental context can be articulated into the following main phases:

- analysis of the territory, including the geographical-territorial insertion; the geological, hydrological and hydrogeological structure; soil pollution and radioactivity; the landscape, historical and cultural framework; land use and vegetation, acoustic climate, electromagnetic fields, air quality;
- analysis of the climatic parameters, including the analysis of the climate and microclimate, the study of sunshine and daylighting, the investigation of the availability of renewable energy sources.

2.2.1 New building operational performance targets

The building life cycle overall consists of several phases which range from the extraction of raw materials to the disposal of the building at the end of its life. The goal of the holistic design approach is to improve the performance and environmental impacts in each of them, achieving an overall net improvement in building quality.

As for the operational phase, performance targets concern the aspects of functionality, well-being, efficiency, and quality that the building must be able to guarantee (see Table 2.2). As new needs of energy efficiency and sustainability have been posed by the architecture of the 21st century, the requirements of internal environmental comfort and efficiency in the use of resources have become increasingly important in design. Furthermore, these have been joined by the new objectives of adaptability, smart readiness, adaptation and resilience to climate change, and safe human interaction in response to global health issues.

Concerning the energy aspects, in addition to lower energy demand, the building's capability of self-generation, energy storage, and demand-side flexibility is becoming increasingly important. It must respond in real-time to the availability of renewable sources, to the needs of the occupants and to grid requirements in order to shift demand away from peak periods and improve match with daily solar and wind production cycles, securing the supply of energy to the building while at the same time lowering the load on the shared energy grid.

Regarding, in particular, the indoor environment quality (IEQ), today this is undoubtedly a priority objective of building design. According to the intended use of each space, it is necessary to ensure optimal comfort conditions from a thermal, visual and acoustic point of view, always ensuring an adequate quality of the air which must be free of odors, dust or contaminants.

In view of the considerable time spent inside buildings, the interior space should be a place of comfort able to improve the well-being of anyone who comes into contact with it to live or operate there. Thanks to an evolving evidence base, the relationship between the physical environment and human health is clearer than ever before and can be used to create spaces that enhance, rather than hinder, health and well-being.

Design strategies should focus on identifying and reducing the most common sources of physiological disruption and on enhancing acoustic, ergonomic, olfactory, and thermal comfort, to prevent stress and injury of occupants and facilitate their productivity and well-being. The envisioned built environment shall help to improve the nutrition, fitness, mood, sleep, comfort, and performance of its occupants, reduce occupant exposure to harmful chemicals and pollutants and encourage healthy lifestyles by promoting movement, fostering physical activity and active living and discouraging sedentary behavior. Equally important is today the possibility of ensuring interpersonal distancing to guarantee the safest possible interaction between users within the premises.

Indoor well-being is one of the pillars of most environmental sustainability assessment schemes for buildings such as LEED, BREEAM, Living Building Challenge or LEVEL's which, among the requirements for certification, include specific indicators on the quality of the built environment. In this picture, the WELL certification, specifically dedicated

TABLE 2.2 Building performance targets in the operational phase.

Building quality category	Operational performance targets
Functionality	Accessibility Adaptability Safety in use Fire safety Seismic resistance Security Community living Adaptation and resilience
Health and well-being	Thermal comfort Indoor air quality Lighting and visual comfort Acoustics and noise protection Safety and human interaction
Efficiency and sustainability	High energy performance Renewable energy generation (on-site or nearby) Water saving Loading on the neighborhood
Operational quality	Smart readiness Cybersecurity Durability and maintainability

to indoor well-being, was introduced in 2014 as a first international standard to define the parameters with which buildings can improve the lives of their occupants, focusing on people's comfort. Based on the analysis of the effects indoor spaces have on occupants' behavior and well-being, it aims to improve the interactions between human beings and the built environment, in order to obtain healthier and more comfortable buildings, also increasing productivity. The certification body (third party) is the Green Business Certification Inc, the same as the LEED certification. WELL is currently applied in 58 different countries around the world, with more than 220 certified buildings and nearly 4000 buildings under certification.

The protocol is divided into 10 categories, or concepts: air, water, nutrition, light, movement, thermal comfort, sound, materials, mind, community (see Table 2.3). All are based both on performance indicators, which provide specific and measurable thresholds, and on prescriptive indicators, which require specific technologies, design strategies or policies to be implemented. WELL promotes improvement actions on the building through a combination of active interventions by the occupants (e.g., the availability of healthy food and the encouragement of the use of stairs instead of elevators) and interventions which have a direct effect on them (e.g., the provision of sufficient air and water quality). On-site tests measure the quality of the air and water, the quantity of internal light, and the disturbances created by noise, while the building's performance is analyzed through annual surveys that reflect how well-being is perceived by its occupants. Finally, a significant part of the protocol consists of the policies of the companies that use the building. Evaluation criteria also consider the project location to take into account national population characteristics and health trends with the relevant WELL concepts associated, based on the Global Burden of Disease epidemiological study. Similarly to LEED certification, WELL ranks projects on four levels: Bronze (50–59 points); Silver (60–69 points); Gold (70–79 points); Platinum (> 80 points).

With reference to the new adaptation and resilience capabilities expected from buildings to cope with the increasingly frequent extreme weather events, in 2018 the USGBC launched a new rating system and leadership standard that takes a holistic approach to resilient design, which foundation includes the work of LEED, ASHRAE, Fortified,

TABLE 2.3 Well concepts (IWBI, 2020).

Concept	Description
Air	This concept promotes holistic design strategies to ensure high levels of indoor air quality across a building's lifetime through elimination or reduction of pollutants sources, active and passive building design, and operation strategies and human behavior interventions.
Water	This concept promotes strategies that favor the availability of drinking water to increase hydration in building users, reduce health risks due to contaminated water and excessive moisture, and provide adequate sanitation through better infrastructure design and operations.
Nourishment	This concept promotes the availability of healthy food and the limitation of highly processed products to building users, as well as nutritional transparency designing environments that nudge individuals toward healthier choices.
Light	This concept promotes the creation of lighting environments that reduce circadian phase disruption, improve sleep quality and positively impact mood and productivity, favoring visual, mental and biological health.
Movement	This concept promotes environmental design, policies and programs to ensure that movement opportunities and physical activity are integrated into the everyday life of buildings and communities.
Thermal comfort	This concept promotes the provision of the maximum level of thermal comfort among all building users through improved HVAC system design and control and by meeting individual thermal preferences.
Sound	This concept promotes occupants' health and well-being through the optimization and mitigation of acoustical comfort parameters of interior noise levels and audio devices.
Materials	This concept promotes the reduction of human exposure, whether direct or through environmental contamination, to chemicals that may impact health during the construction, remodeling, furnishing, and operation of buildings.
Mind	This concept promotes policy, program, and design strategies that address the diverse factors that influence cognitive and emotional well-being of occupants through a variety of prevention and treatment efforts.
Community	This concept promotes the implementation of design, policy, and operations strategies that focus on addressing health disparities and on favoring a culture of health that accommodates diverse population needs and establish an inclusive, engaged occupant community.
Innovation	This concept promotes novel strategies for creating healthier environments able to pave the way for future projects

Envision, and REDi. This system, named RELi, is aimed at companies, developers, city planners, architects, and bond insurers to assess and plan for the acute hazards that buildings and communities may face during unplanned events, prepare to mitigate against these hazards and design and construct buildings to maintain critical life-saving services in the event of extended loss of power, heating fuel or water. RELi promotes shock-resistant, healthy, adaptable, and regenerative buildings and communities through a combination of diversity, foresight, self-organization, and learning. The current RELi rating system includes 15 requirements and 43 credits across eight categories, including panoramic design, hazard preparedness and adaptation, community vitality, productivity, health and diversity, energy, water and food, materials and artifacts, as well as applied creativity ([United States Green Building Council, 2018](#)). As with other rating systems, the number of points that a project earns determines the certification level it receives: RELi Certified (300–349 points), RELi Silver (350–449 points), RELi Gold (450–599 points), RELi Platinum (600 + points).

2.2.1.1 Thermal comfort

Thermal comfort is a fundamental factor in all buildings, as it plays a large role in the way users experience places where they live and work, and directly affects their mood, performance and productivity. Therefore, each building shall be designed and built so that adequate summer and winter thermohygrometric comfort is ensured in all spaces intended for the presence of people, in relation to the intended use of the buildings and environments, without causing excessive energy consumption and favoring as much as possible passive solutions and the use of renewable energy sources. Specifically, thermal comfort can be described as the state of satisfaction that an individual feels with regard to the microclimate. Such condition can also be defined as “thermal neutrality,” which occurs when the thermal accumulation of the human body is null and the organism does not employ its mechanisms of behavioral thermoregulation (absence of chills or sweating) and vasomotor thermoregulation (absence of vasoconstriction or peripheral vasodilation).

However, a large proportion of the world building stock cannot provide adequate levels of thermal comfort because of a combination of a lack of insulation, poor quality windows, thermal bridges in the building envelope, high levels of air infiltration, and inadequate or poorly maintained heating systems (only in Europe between 50 and 125 million people are unable to afford a proper indoor thermal comfort). This can lead to insufficient heating which can put more vulnerable residents at risk from seasonal illnesses. Furthermore, even in cold locations, uncontrolled gains from solar radiation can lead to uncomfortable conditions that may in turn require additional cooling energy. In Europe, the control of overheating is specifically addressed by the Energy Performance of Buildings Directive 2010/31/EU (EPBD), as amended by Directive (EU) 2018/844, which states that there should be focus on measures which avoid overheating, such as shading and sufficient thermal capacity in the building construction, and further development and application of passive cooling techniques, primarily those that improve indoor climatic conditions and the microclimate around buildings.

In designing an indoor space, it is necessary to consider all the elements that can influence the conditions of thermohygrometric comfort and to define the so-called “design conditions,” that is, the microclimatic parameters that must be guaranteed within the environment in relation to the activity carried out, regardless the external climatic situation. However, thermal comfort preferences are highly personal and often differ from one individual to another. Balancing the energy requirements of buildings with the preferences of various occupants can thus be challenging.

The means to maintain well-being conditions as the external climatic parameters vary belong to two main categories: the constructive elements that separate the external and internal spaces, which constitute the building envelope, and the building technical systems. It is necessary to harmonize technological choices and plant engineering choices to identify solutions capable of offering the best comfort while containing costs; to do this, the designer must know the climatic conditions of the external environment and this will interact with the intervention.

The factors that affect thermohygrometric well-being are many and related both to the microclimatic conditions of the environment (environmental parameters) and to the characteristics of the user (subjective parameters).

Subjective parameters are represented by the energy metabolism of the individual (M), which dictates the heat produced, and by the thermal resistance of the clothing (I_{cl}), which opposes thermal exchanges with the external environment, as well as psychological parameters such as individual expectations that may also affect individual thermal comfort. As a unit of metabolic power (M), thermal power referred to the unit of body surface (W/m^2) is usually used, as well as the met, defined as the heat produced per unit of time and body surface by a man sitting and resting: $1 \text{ met} = 58.2 \text{ W/m}^2 = 50 \text{ kcal/hm}^2$ (for reference, the body surface area of an average man, 70 kg in weight and 1.70 m in height, is estimated to be 1.8 m^2) (see [Table 2.4](#)).

The thermal resistance of the clothing depends on the type of clothing worn by the user. In fact, clothes form a barrier to thermal exchanges between the human body and the surrounding environment that occur by radiation,

TABLE 2.4 Metabolism values for different physical activities (ISO 7730).

Activity	Metabolic energy	
	[W/m ²]	[met]
Laying down	46	0,8
Sitting, relaxed	58	1,0
Sedentary activities (office, home, laboratory)	70	1,2
Light, standing activities (shopping, laboratory, light industry)	93	1,6
Medium standing activities (clerk, housework)	116	2
Walking		
2 km/h	110	1,9
3 km/h	140	2,4
4 km/h	165	2,8
5 km/h	200	3,4

convection, and conduction. Generally, the resistance that clothes oppose to heat exchanges is measured with the unit clo (1 clo = 0.155 m²°C/W). The environmental parameters on which the thermohygrometric well-being depends are represented by the air temperature t_a , the relative humidity of the indoor air RH, the mean radiant temperature t_{mr} , and the air speed v_a . The ambient air temperature [°C] regulates heat exchanges by convection. In the cold season, an internal air temperature suitable for carrying out the planned activities must be ensured without presenting excessive unevenness within the heated space.

T_{mr} [°C] represents the average of the temperatures of the six internal walls (the four side walls, the ceiling, and the floor). Inside a confined environment, the body exchanges heat by radiation with the surrounding surfaces and with any concentrated heat sources. The temperatures of the internal surfaces must therefore be contained within appropriate values, in order to limit the inconvenience due to both irradiation and excessive convection of the air. The concept of T_{mr} simplifies a complex radiant environment by reducing it to a single temperature value.

Air speed [m/s], and consequently the ventilation of an environment, regulates heat exchanges by convection. It affects directly both thermal well-being of individuals (air currents cause situations of discomfort), and indoor air quality (IAQ) and therefore the health conditions of users.

Air relative humidity [%] is another important climatic parameter due to the effects it can have on biological organisms as it influences the exchange of water vapor between the organism itself and the environment.

Together, these environmental microclimatic parameters allow to predict the sensation of thermohygrometric well-being experienced by an individual within an environment (global comfort). The ISO 7730 standard indicates the values of various environmental parameters in winter and summer that ensure the conditions of thermal well-being. Nonetheless, even if global conditions of well-being are guaranteed, it may occur that in some points of the indoor space these conditions are not respected due to local nonuniformities, inducing discomfort in the subject (in particular in workplaces intended for sedentary activities). Therefore, once global well-being conditions have been ensured, it is necessary to ensure that they are still verified in the environmental subsystem consisting of the immediate surroundings of the individual workplace.

The main causes of local discomfort include temperature unevenness and air velocity fluctuations. In particular, high vertical temperature difference, high asymmetry of the mean radiant temperature, too hot or too cold floors, excessive air currents can all cause discomfort.

The high vertical difference in air temperature, detected between a person's head and ankles, can cause a feeling of discomfort in the occupants, especially when the temperature at the head level is higher than that at the ankles. According to ISO 7730 standard, the vertical temperature difference measured at 0.1 m and 1.1 m must not exceed 3 degrees of temperature (the ASHRAE 55–81 standard suggests the same gradient but measured at 1.7 m).

The asymmetry of the mean radiant temperature consists of the difference between the radiant plane temperature of two opposite surfaces within the space. In sedentary activities, the subject exposed to asymmetrical thermal radiation experiences a sensation of thermal discomfort, especially if the asymmetry is due to warm ceilings rather than cold

walls. This asymmetry shall be contained within 10°C for horizontal surfaces and 5°C for vertical surfaces for the winter (ISO 7730).

A floor that is too hot or too cold causes a feeling of discomfort due to a high or low temperature of the feet compared to the rest of the body. ISO 7730 standard establishes that the floor temperature in winter shall be between 19 °C and 29 °C.

Air currents represent one of the most recurrent causes of local discomfort, as they can cause unwanted cold sensation of some parts of the body (such as the neck and ankles). In evaluating the discomfort caused by air currents, the most immediate factor is certainly air speed, followed by its temperature. Generally, the discomfort increases with increasing air speed and decreasing temperature: current regulations set maximum values of 0.15 m/s in winter and 0.25 m/s in summer.

Summer and winter comfort conditions for sedentary activities (1.2 met) and a relative humidity of 50% are reported in Table 2.5. In particular, a 50% RH value is commonly considered to be optimal from a hygienic point of view and is usually required to remain constant throughout the year with sometimes very narrow tolerances ($RH = 50\% \pm 5\%$). Low relative humidity (less than 30%) in the long run leads to dryness of the respiratory system (throat and nose) and therefore a decrease in defenses against pathogenic germs present in the air. Too high humidity (greater than 70%) instead may cause onset of mold and condensation on the walls of the environment.

As the various parameters that influence thermohygrometric comfort may not produce the same sensations on individuals, specific indexes have been defined which, depending on the microclimatic variables, provide a statistical indication of the thermohygrometric sensations experienced by the subject (global comfort indexes). These comfort indices are divided into empirical (deduced based on surveys) and rational indices (obtained by integrating heat balance equations and statistical surveys). The empirical and rational indices are further divided into temperature and sensation indices. The former are essentially based on the definition of an equivalent temperature representative of the microclimate, the latter are based instead on the sensation of heat and cold of the subject within the considered environment and are expressed according to the rating that the subject himself gives to the microclimate according to preestablished scales.

The most used sensation indices are the predicted mean vote (PMV) and the predicted percentage of dissatisfied (PPD), both elaborated by Fanger in 1970 and introduced in the international standard for evaluation of moderate thermal environments since 1984 (ISO 7730). These parameters can be read across to the EN 15251 thermal comfort categories as shown in Table 2.6.

TABLE 2.5 Summer and winter microclimatic parameters for thermohygrometric well-being (ISO 7730).

Environmental parameter	Winter (1 clo, 1.2 met)	Summer (0,5 clo, 1.2 met)
Operating temperature	20°C–24°C (RH = 50%)	23°C–26°C (RH = 50%)
Vertical air temperature gradient	Max 3°C	Max 3°C
Radiant temperature asymmetry	Max 10°C horizontal Max 5°C vertical	-
Air speed	Max 0,15 m/s	Max 0,25 m/s
Floor temperature	19°C–29°C	-

TABLE 2.6 Comparison between Fanger and adaptive methods for predicting thermal comfort categories.

EN 15251 category	Fanger method		Adaptive method
	PPD (%)	PMV	Operative temperature variance (°C)
I (best)	≤ 6	$-0.2 \leq PMV \leq +0.2$	± 2
II	≤ 10	$-0.5 \leq PMV \leq +0.5$	± 3
III	≤ 15	$-0.7 \leq PMV \leq +0.7$	± 4
IV (worst)	> 15	$PMV < -0.7$ and $PMV > 0.7$	

However, the PMV and PPD model does not take into account humans' natural ability to cope to variable environmental conditions, and has proven ill-suited to support more modern passive design strategies such as naturally conditioned buildings or mixed-mode HVAC systems, in which occupants' discomfort is overestimated (Carlucci, Bai, de Dear, & Yang, 2018). For this reason, so-called adaptive comfort models have been developed that instead express acceptable indoor temperatures (called operating temperature) as linearly related to prevailing outdoor values. These models have been implemented in international standards including ISO 7730, ASHRAE 55–2010, pertaining buildings without mechanical cooling, and EN 15251, applicable to mixed-mode buildings.

2.2.1.2 Indoor air quality

Clean indoor air has a highly important influence on human health. In most developed countries, people spend more than 90% of their time inside buildings and most of the >10,000 liters of air they breathe each day will be indoor air. Time spent indoors may increase even further in the future due to the conveniences or necessities of e-commerce and working from home, which reduce the need for transit. IAQ is influenced both by outdoor air and by the presence of internal sources of pollution due to building materials, furniture, systems, electronic equipment, cleaning products, pets, people, and activities such as cooking or smoking.

Indeed, exposure to indoor air pollutants causes significant health damage globally, especially in developing countries, and the quality of air inside homes, offices, schools, day care centers, public buildings, healthcare facilities or other private and public buildings where people work or live is an essential determinant of healthy life and people's well-being. According to the World Health Organization, indoor air pollution (IAP) is responsible for the deaths of 3.8 million people annually (WHO, 2020). Therefore, over the past decade, research on air quality control has begun to shift from outdoor to indoor environments, as reflects lifestyle changes linked to increased levels of urbanization. Both short- and long-term IAP exposure can negatively affect human health by causing building-associated illness such as sick building syndrome (SBS) and building-related illness (BRI). (see table 2.7).

The prevention of the risk of internal pollution therefore constitutes a specific responsibility of the designer who has the obligation to ensure sufficient IAQ considering the exchanges of material and energy that occur between the building and the environment. Indeed, IAQ depends on a series of choices, such as orientation, location, construction techniques, materials, functional organization of spaces in relation to activities, and building systems, including monitoring and air purification equipment. In relation to their nature, the indoor pollutants emitted by the different sources can be divided into three main categories: chemical, physical, and biological (see Table 2.8).

Chemical indoor pollutants include gaseous substances such as carbon monoxide (CO), nitrogen oxides (NO_x), sulfur oxides (SO_x), volatile organic compounds (VOCs), including formaldehyde (CH₂O), benzene (CH₆), ozone (O₃), and corpuscular substances (PM), solid and or liquid, ranging in size from a few angstroms to a few hundred μm (asbestos, mineral synthetic fibers, PAH). Most of the chemical pollutants are also present in the outside air as they come from vehicular traffic, from civil heating systems, from industrial activities. Other pollutants, such as VOCs, are instead typical of confined environments where they can reach very high concentrations.

Physical pollutants include noise, electromagnetic fields and Radon (Rn), an extremely dangerous natural radioactive gas which prolonged exposure can cause lung cancer risk increases of 3% to 14% (USEPA, 2003; WHO, 2009).

Biological pollutants include bacteria, viruses, fungi, molds, mites, and allergens from animals. The major sources of bacteriological pollution derive from air conditioners, humidifiers and systems in which high humidity facilitates the emergence of microorganisms, which are then diffused into the rooms by the air distribution system. Nonetheless, the quality of the air, its percentage of humidity, and the characteristics of a material may allow the development of microorganisms themselves. The main pathologies caused by biological agents include infectious diseases, direct toxic effects, and allergic reactions.

TABLE 2.7 Common symptoms of SBS and BRI (WHO, 2010).

Sick building syndrome (SBS)	Building-related illness (BRI)
• Mucous membrane irritation: eye, nose, and throat irritation • Neurotoxic effects: headaches, mental fatigue, reduced memory, nausea, tiredness, dizziness, and irritability • Asthma and asthma-like symptoms: chest tightness and wheezing • Skin dryness and irritation, gastrointestinal complaints, and others	• Flu: fever, chills, chest tightness, muscle aches and cough • Legionnaires' disease, hypersensitivity pneumonitis, humidifier fever • Lung and respiratory problems

TABLE 2.8 Main indoor pollutants (Van Tran, Park, & Lee, 2020; WHO, 2010).

Indoor pollutants	Sources
Carbon monoxide (CO) Odorless, colorless, and tasteless gas, resulting from the incomplete oxidation of carbon in combustion processes.	Cooking stoves; tobacco smoke; fireplaces; gas and petrol powered heat generators and other equipment; outdoor air.
Nitrogen oxides (NO _x) Gases created by the reaction of nitrogen with oxygen both as a result of the combustion of fuels containing nitrogen compounds (NO _x from conversion), and as a result of the reaction between nitrogen and oxygen contained in the air during combustion which take place at temperatures above 1100 ° C (thermal NO _x).	Cooking stoves; tobacco smoke; fireplaces; gas and petrol powered heat generators and other equipment.
Sulfur oxide (SO _x) Gases originating from the combustion of fuels containing sulfur; about 90% of the sulfur contained in them, in fact, reacts during the combustion processes forming sulfur dioxide (SO ₂) and sulfuric anhydride (SO ₃).	Kerosene stoves and heaters; fireplaces; tobacco smoke; outdoor air.
Volatile organic compounds (VOC) Compounds having a vapor pressure of at least 0.01 kPa at a temperature of 20°C. They originate from synthetic products or during incomplete combustion due to lack of oxygen	Heating and cooking equipment; metabolic activities; paints, varnishes; solvents; pesticides; adhesives; wood preservatives; waxes; polishes, cleansers, lubricants, sealants, dyes, air fresheners, fuels, plastics, copy machines, printers, tobacco products, perfumes, dry-cleaned clothing, building materials and furnishings.
Ozone (O ₃) Blue gas with a pungent odor, consisting of molecules that contain three oxygen atoms, very chemically active. It is formed from oxygen molecules (O ₂) in the vicinity of electric discharges, sparks, lightning	Electric motors, laser printers and faxes, devices that produce UV rays, air purifiers that are not properly installed or maintained; outdoor sources.
Particulate matter (PM) Liquid or solid particles, ranging in size from a few angstroms to a few hundred μm, suspended in the air. Aerosols can find different names depending on their size (PM ₁₀ , PM _{2.5} , PM _{0.1}) and their formation process (dust, fumes, smoke, etc.)	Outdoor environment, cooking, combustion activities, cleaning activities, tobacco smoke, kerosene stoves and heaters, fireplaces.
Polycyclic aromatic hydrocarbon (PAH) Essential constituents of the particles of unburnt solid material commonly referred to as soot. They are formed in combustion processes.	Tobacco smoke, kerosene stoves and heaters, fireplaces.
Asbestos Group of silicates which come in a fibrous form and can be separated into filaments. Widely used in construction (1965–1983) for its excellent chemical and mechanical characteristics, such as resistance to chemical and biological agents, nonflammability and flexibility. It derives from the deterioration or damage of the materials that contain it.	Boards, panels, pipes, tanks, asbestos-cement flues, sprayed coat on metal structures and beams; prefabricated elements; plasters, panels for false ceiling, floor tiles, and underfloor filling.
Artificial mineral fibers Produced through the industrial synthesis of natural minerals and their compounds such as quartz and alkaline metal oxides.	Insulating materials in glass wool and rock wool, materials containing ceramic fibers, carbon fibers
Radon Odorless, colorless, tasteless natural radioactive gas. It originates as a result of the radioactive decay of elements such as uranium and radium present throughout the earth's crust.	Soil below the building, building materials, tap water.
Biological agents Bacteria, viruses, fungi, molds, allergens (pollen, mites)	HVAC and water systems, house dust, pets, pests, mold/dampness, outdoor air.

TABLE 2.9 Dangerous quantity and exposure to main indoor pollutants (Van Tran et al., 2020).

Pollutants	Concentration levels (mg/m ³)	Exposure time	Organization
CO	100	15 min	WHO
	60	30 min	
	30	1 h	
	10	8 h	
	29	1 h	USEPA
	10	8 h	
CO ₂	1800	1 h	WHO
NO ₂	0.40	1 h	WHO
	0.15	24 h	
	0.10	1 year	USEPA
PM	0.15	24 h	USEPA
	0.05	1 year	
O ₃	0.15–0.20	1 h	WHO
	0.10–0.12	8 h	
	0.235	1 h	USEPA
SO ₂	0.50	10 min	WHO
	0.35	1 h	
	0.365	24 h	USEPA
	0.08	1 year	
Pb	0.0005–0.001	1 year	WHO
	0.0015	3 months	USEPA
Xylene	8	24 h	WHO
Formaldehyde	0.1	30 min	WHO
Radon	100 Bq/m ³	1 year	WHO

Concerning IAQ monitoring, wireless sensor network, and Internet of Things (IoT)-based systems using smart sensors empowered by AI are today the most efficient and applied solutions (Patil, Laad, Kamble, & Laad, 2019; Van Tran et al., 2020). As for sensors, metal oxides (MO_x) are currently regarded as one of the most promising technologies, especially in consideration of their low cost, high sensitivity, simplicity, and compatibility with modern electronic devices of small size and low cost (see Table 2.9).

Available strategies for controlling IAQ mainly concern (JRC, 2021f):

- source control, based on the reduction or elimination of internal and external polluting sources;
- air quality control, using natural or mechanical ventilation to reduce concentrations of pollutants by diluting them with fresh clean air;
- air purifying with dedicated devices, which can be integrated with the other two methods;
- control of microclimatic parameters such as relative humidity and temperature with air conditioning systems.

Among IAP control strategies, advanced oxidation processes-based technologies have attracted great attention due to their minimum generation of secondary pollution. Photocatalysis is the process by which indoor air pollutants are disintegrated due to exposing semiconductor photocatalysts under sufficiently energetic irradiation and is considered particularly promising. Compared with conventional adsorption technologies, photocatalysis improves direct degradation of gaseous pollutants (particularly VOCs) into CO₂ and H₂O under ambient conditions and is suitable for the removal

of low-concentration pollutants (sub-ppm levels) as well. Semiconductors in the photocatalysis technology include titanium dioxide (TiO_2), most used due to its low cost, strong oxidative power, and chemical stability, as well as tungsten oxide, carbon nitride, bismuth, silver, cadmium sulfide (Park, Kim, Moon, & Choi, 2016; Weon, He, & Choi, 2019).

2.2.1.3 Lighting and visual comfort

The availability and quality of light are important factors in the design of healthy and comfortable homes and workspaces. Studies have shown the influence of better access to daylight and views on overall well-being, as well as the increased satisfaction that comes with personalized control of lighting and shading. Considering that more than 80% of the sensory information that is processed by the brain comes from vision, the correct lighting of indoor spaces contributes not only to the preservation of sight, but also to a better performance in the work activity, to the prevention of accidents, and to psychological and physiological well-being. The quality and composition of light can also influence circadian rhythms (the sleeping and waking cycles of the human body) (IWBI, 2020, JRC, 2021g).

In particular, exposure to adequate levels of daylight is critical for health and well-being, with effects ranging from visual comfort to potential psychological and neurological gains. Indeed, in addition to performing an antibacterial action, solar radiation has a stimulating physiological effect on many metabolic functions such as the formation of vitamin D from provitamin and skin pigmentation, a therapeutic effect on surgical tuberculosis, tuberculous states, rickets, lymphatism, and exerts a positive action on blood composition by promoting the renewal and production of red blood cells.

Therefore, proximity to windows, outdoor views, and daylight in indoor spaces are some of the most sought-after elements of design, with the added objective of reducing energy consumption deriving from artificial lighting. Ideal lighting involves proper exposure to diffuse daylight, as well as appropriate sizing of windows and glazing to avoid excessive glare and heat gain. Windows and shading systems are therefore key variables for both ensuring that occupants receive enough light for positive physiological and subjective effects, but also not too much causing discomfort or distraction. The proper balance of energy performance, thermal comfort, and access to daylight becomes an essential aspect of building design.

Current lighting codes and guidelines provide illuminance standards and recommendations for different room types, aimed at ensuring good visual acuity in a variety of tasks to avoid eyestrain and to minimize productivity losses and headaches. Adequate light levels are needed for a broad variety of activities and contribute to the perception of spaciousness, as well as to the overall visual appeal of illuminated spaces. Ambient light levels of 300 lux are sufficient for most tasks. Adjustable task lighting can provide the necessary amount of light at workspaces without overilluminating ancillary spaces and can be paired with indirect or diffuse ambient lighting to provide more suitable background light.

As regards daylighting, the illuminance levels are quantified by the daylight factor (DF), defined as the ratio [%] between the illuminance measured in a point of the interior space and the external illuminance received, under the same conditions of time and place, from the entire celestial sphere on an open horizontal surface without direct sunlight. Current building codes normally set for new buildings, depending on the type of building (home, school, hospital, etc.) and the latitude of the place, minimum values of the median DF equal to 2%–6%, enough to ensure in the worst conditions of the sky an average internal illuminance of at least 100–150 lux. Nonetheless, although DF is a useful metric, it is unsuited to characterize the building over annual climate conditions. A metric called spatial daylight autonomy (sDA), which measures the percentage of floor area that receives adequate sunlight over the year, is more useful to understand the sufficiency of daylight for a space (see Fig. 2.5). Daylight penetration into a building can be simulated with typical meteorological year (TMY) that is representative of the building location.

Though bright light during the day is conducive to good health, uneven levels of brightness in the visual field can cause visual fatigue and discomfort. Glare, or excessive brightness, is caused by light scattering within the eye (intraocular scattering), thereby creating a “veil” of luminance that reduces the luminance contrast as received by the retina. The resulting discomfort (discomfort glare) can be a hindrance to an otherwise comfortable and effective work environment and can cause fatigue, visual impairment, and even injury (disability glare). Finally, direct solar radiation, especially in its UV component, can cause deterioration of furniture and interior materials. Glare is often caused by unshielded or poorly shielded light, or sunlight directly hitting the eye or reflective surfaces. It is therefore necessary to minimize direct and overhead glare by setting limits on luminaire intensity and by blocking or reflecting direct sunlight away from occupants. To enjoy the benefits of daylight exposure in all seasons while avoiding excessive sunlight, it is necessary to balance sDA and annual sun exposure (ASE), which measures the percentage of floor area receives too much direct sunlight. Daylight glare probability (DGP) is another metric that attempts to describe the likelihood that glare will be present in a given view from an occupant position in a building. DGP can be controlled by incorporating



FIGURE 2.5 sDA design targets in a school buildings.

Courtesy of SOM.

shades in building design, as detailed in standards such as EN17037. Lighting and daylighting design of buildings can be greatly supported by the use of specific building performance simulation (BPS) capable of predicting light penetration and diffusion indoor based on realistic physics engines and of providing quick response on the relevant lighting parameters (see [Section 5.1.1.2.](#)).

To both ensure best visual comfort and enhance spatial esthetics, it is advised to use lamps with quality color rendering abilities and automatic dimming features to change light distribution, intensity and color temperature according to the time of the day, human needs and visual tasks. Color quality in fact directly impacts visual appeal and can either contribute to or detract from occupant comfort, with poor color quality reducing visual acuity and rendering accuracy of illuminated objects. Color rendering index (CRI) is a common method to characterize color quality, measured as a light source's ability to accurately reproduce the colors of a set of eight standard swatches (R1-R8) compared to sunlight, which is considered the CRI 100 benchmark. LED luminaries in particular are highly amenable to dimming control and allow many different possible distributions of light output due to the flexibility in arranging the assembly of the diodes onto LED modules. Furthermore, the spectral output (in terms of correlated color temperature) of light from diodes can be varied across a wide range (from 2000K to >5000 K) to suit user needs, whereas traditional light sources are much more limited in these aspects.

Finally, it is important to also consider the view out as part of the daylight quality. People appreciate a view to the outdoors, including the landscape, sky, and other exterior surroundings. The EN 17037 standard can be used to define horizontal sight angles, outside distance of the view, as well as the number of layers seen in the view.

2.2.1.4 Acoustics and noise protection

Protection from environmental noise is an essential requirement for the health, safety, and well-being of the occupants of a building. Exposure to high levels of noise, in addition to causing sleep, communication, and activity disruption, causes a reduction in concentration, mental arithmetic performance and greater distraction and can cause auditory and extra-auditory physiological damage, mainly of the cardiovascular type, and widespread ailment resulting from continuous disturbance. Each building must therefore be designed and built in such a way that the noise affecting occupants and people located in the vicinity is maintained at levels which do not harm their health and which allow satisfactory conditions of sleep, rest, and work.

Building sound insulation issues are divided into airborne and impact sound insulation. Airborne sounds are generated in the air and are radiated toward the building structure and include speech, television, or traffic noise. Impact sounds are generated by physical interaction with the building structure causing it to vibrate, and include footsteps, moving of furniture, dropping objects, vibration from systems and equipment.

Design choices, materials used for construction, and their installation must therefore guarantee adequate acoustic protection of building spaces with regard to noise coming from outside (vehicular, railway and air traffic, pedestrian activity, commercial, or industrial activity), noise from systems or appliances installed in the building, airborne noise from adjacent rooms and spaces, and the sound of impacts from adjacent spaces, floors or walls. Equally important is the control of reverberation time, background noise level, and speech intelligibility or privacy within spaces. Since the early stage of design, first indications to create a quality acoustic environment and to control noise shall be used to assess potential risks based on the building use, its location, and the potential interior layout. Moving into the detailed design stage, focus should shift on façade design, separation walls, floors, internal subdivisions and partitions, surface finishing materials and other architectural elements that can influence acoustic performance. Upon completion, it will

become possible to carry out field surveys and measurements to determine the as-built performance of the building and its internal spaces.

To ensure adequate protection from noise, the reference building codes establish minimum passive acoustic requirements for the facades, for the vertical elements separating distinct habitation units (apartments, hotel or hospital rooms, classrooms, etc.) and for floor slabs according to the use of building (home, school, hospital, etc.) (see [table 2.10](#)).

Most used evaluation indexes include the weighted apparent sound reduction index R'_w between two spaces (i.e., also considering the flanking effects) to be calculated according to the ISO 717-1 standard, which minimum values required commonly vary between 50 and 55 dB; the weighted standardized façade level difference $D_{2m,nT,W}$ (i.e., referring to a reference reverberation time) to be calculated according to ISO 717-1, with minimum values between 40 and 48 dB; the weighted normalized impact sound pressure level ($L_{n,w}$) defined by the ISO 717-2 standard (referred to a value of the reverberation time of the receiving room), with maximum values between 55 and 63 dB. The $L'_{n,w}$ index characterizes the noise perceived in an environment when a normalized impact sound generator acts on the floor of the disturbing environment. The lower the value of $L'_{n,w}$, the higher the ability of the floor to dampen the impact noise. The level to be respected is normally that of the disturbing environment.

As regards the protection from noise produced by technological systems (HVAC, lifts, drains, etc.), codes establish the maximum acceptable noise levels within the environments to be measured in the most disturbed space when the system is in operation. The evaluation indices are the maximum weighted sound pressure level in curve A with slow time constant ($L_{A, Smax}$) for systems with discontinuous operation, and the continuous equivalent sound pressure level weighted in curve A (L_{Aeq}) for continuous operation systems. In principle, noise in residential spaces should never exceed 40–45 dB (A), a value which is often exceeded due to traffic noise (> 70 dB (A)), even with closed windows. Noise produced by the building systems must not exceed 35 dB (A) $L_{A, Smax}$ with slow time constant for discontinuous operation services and 25 dB (A) L_{Aeq} for continuous operation services.

Moreover, to ensure adequate acoustic comfort particular attention shall be given to optimizing the reverberation times of indoor spaces (classrooms, canteens, gyms, offices) to ensure their livability, as it can affect the concentration of noise within a shared office space, as well as speech intelligibility and the indoor background noise level.

Optimal reverberation times vary depending on the volume of the room, on its intended use and on the frequency of the transmitted sound. In rooms with high reverberation times, the sounds of voices and footsteps take longer to dissipate, contributing to higher levels of ambient noise. The noise produced by reverberation can decrease speech intelligibility and, in some situations, cause additional stress. Reverberation time T60 is measured as the time necessary for the sound pressure level inside a room to decrease by 60 dB after the emission of the source ceases. It can be derived analytically from the relationship $T60 = 0.161 V/A$ where V is the volume of the environment and A the equivalent sound absorption. Additionally, descriptors like speech intelligibility (STI), equivalent sound absorption area (A_{eq}), strength (G), definition (D50) and clarity (C80), that can be estimated using numerical simulation or ray-tracing models for acoustic prediction, can also be defined for certain relevant room types.

Control of the reverberation time can be obtained through sound-absorbing materials characterized by high values of the sound absorption coefficient (porous or fibrous sound-absorbing materials for medium-high frequencies, flexible or vibrating panels for low frequencies, resonant panels for medium frequencies). Average absorptive properties of a material are expressed with the noise reduction coefficient (NRC): the larger the NRC value, the better the material is at absorbing sound under standardized conditions. Sound reduction elements that incorporate absorptive surfaces, such as wall panels, ceiling baffles, and surface features, can help with reverberation management and improve acoustic comfort. (see [table 2.11](#))

2.2.1.5 Safety and human interaction

Recent global sanitary emergencies have clearly shown that not only the quality and characteristics of spaces, but also the way in which people experience these spaces and interact with each other can have a direct influence on people's health. The problem of movement and interaction of people within both closed and open spaces has now become a critical issue for safety linked to the transmission of diseases, equal in importance to established concepts such as systems safety and fire protection and evacuation. Therefore, understanding how to arrange spaces and how to organize the movement of people has now become a central theme of planning at the building and district scale, aimed at minimizing health risks by maximizing well-being and productivity. Spaces where people can congregate—offices, construction sites, schools, retail spaces, warehouses—must be designed to reduce the risk of disease transmission. They must be built with enough flexibility to adapt to rapid changes. Moreover, this needs to happen in a way that meets a range of critical health, economic, psychological, and organizational needs, as well as fundamental life safety concerns on par

TABLE 2.10 Main parameters and indicators for acoustic quality and protection against noise (JRC, 2021h).

Acoustic design aspects	Quantities to be assessed		
	Related to	Index	Description
Façade sound insulation: protection from noise coming from the outside	Façade insulation	$D_{2m,nT,w}$	Weighted standardized level difference for traffic noise (sound insulation)
		R'_w	Weighted apparent sound reduction index
		R'_{45°	Apparent sound reduction index
	Indoor noise level	L_{Aeq}	A-weighted equivalent continuous sound pressure level
		L_{Amax}	A-weighted maximum sound pressure level
		$L_{den,indoor}$	Indoor day-evening-night sound pressure level
	Environmental noise	L_{day}	Day period average noise level
		L_{night}	Night period average noise level
		L_{den}	Day–evening–night period average noise level
Airborne sound insulation: protection from airborne noise from adjacent rooms and spaces or buildings	Airborne sound insulation	R'_w	Weighted apparent sound reduction index
		$D_{nT,w}$	Weighted standardized level difference.
		$R'_w + C$	Weighted apparent sound reduction index + spectrum adaption term
		$D_{nT,w} + C$	Weighted standardized level difference + spectrum adaption term
		$R'_w + C_{tr}$	Apparent sound reduction index + spectrum adaption term for traffic noise
		$D_{nT} + C_{tr}$	Weighted standardized level difference + spectrum adaption term for traffic noise
	Indoor noise level	L_{Aeq}	A-weighted equivalent continuous sound pressure level
		L_{Amax}	A-weighted maximum sound pressure level
		$L_{den,indoor}$	Indoor day–evening–night sound pressure level
Impact sound insulation: protection from the sound of impacts within adjacent spaces or an adjacent floor or wall	Impact sound insulation	$L'_{n,w}$	Weighted normalized impact sound pressure level
		$L'_{nT,w}$	Weighted standardized impact sound pressure level
Service noise equipment: protection from noise generated by service equipment	Noise generated by service equipment	$L_{Aeq,nT}$	A-weighted standardized continuous sound pressure level
		$L_{AFmax,nT}$	Maximum time-averaged and frequency-weighted standardized sound pressure level
Sound absorption in enclosed spaces/ room acoustics: acoustic indoor comfort	Control of the reverberation time	T	Reverberation time
		A_{eq}	Equivalent sound absorption area
	Background noise level and speech intelligibility	STI	Speech intelligibility

TABLE 2.11 Reverberation time requirements of building spaces (USGBC, 2019).

Room type	Application	T60 (sec), at 500 Hz, 1000 Hz, and 2000 Hz
Apartment and condominium	-	< 0.6
Hotel/motel	Individual room or suite	< 0.6
	Meeting or banquet room	< 0.8
Office building	Executive or private office	< 0.6
	Conference room	< 0.6
	Teleconference room	< 0.6
	Open-plan office without sound masking	< 0.8
	Open-plan office with sound masking	< 0.8
Courtroom	Unamplified speech	< 0.7
	Amplified speech	< 1.0
Performing arts space	Drama theaters, concert and recital halls	Varies by application
Laboratories	Testing or research with minimal speech communication	< 1.0
	Extensive phone use and speech communication	< 0.6
Church, mosque, synagogue	General assembly with critical music program	Varies by application
Library	-	< 1.0
Indoor stadium, gymnasium	Gymnasium and natatorium	< 2.0
	Large-capacity space with speech amplification	< 1.5
Classroom	-	< 0.6

with the potential for fires and natural disasters. It takes a significant amount of care to ensure that any group of people can move and interact safely. Such planning requires an understanding of mathematics, biomechanics, data science, design, demography, psychology, local regulations, sociology and geography, among other disciplines, which today can find support in simulation software and artificial intelligence (see [Section 5.1.2.5](#)). Until recently, the goal of spatial planning was to bring people together to promote socialization and productivity. Today, the problem is instead to find a balance between the interaction of people and interpersonal distancing, with the main objective of reducing the risk of exposure and transmission of infections by minimizing the proximity, frequency and duration of social interactions. Designing for social distancing requires the ability to consider thousands of factors and analyze many different types of data about what people do and the roles they play in physical spaces, be it institutional settings like schools, offices, and hospitals or social settings like stadiums and tourist attractions.

Design objectives depend on the type of building or public space being considered. The first step shall be to define the relevant parameters that describe the environment and how it is used, also taking into consideration the way in which spaces influence individual and collective behaviors. The number of people allowed within a given space will vary based on how they occupy that space: standing, sitting, walking, or waiting in line. The recommended social distance will depend on the type of infectious agent and local norms. Important factors to be taken into consideration regarding the movement of people are the modalities, whether individually or in group, the direction, whether mono or bi-directional, and the speed, which will vary according to the activity and the environment.

The additional space required for safe distance severely limits doors ingress/egress capacity and requires to rethink how to measure one-way flows. Planners need to minimize the cases of people crossing each other by considering one-way motion in most situations and incorporating partitions to facilitate safer routes within buildings. Partitions in offices and other environments have become a key part of planning. Transparent or semi-opaque partitions are best, as they provide protection against transmission by allowing people to see others and avoid collisions. Equally important has become the ability to maintain a high quality of indoor air through natural ventilation and/or the use of systems capable

of ensuring filtration and continuous exchange with outside air (Megahed & Ghoneim, 2021). Additional features such as no-touch surfaces, doors, and devices, mobile log-in and access systems, thermal cameras, HVAC units equipped with UV purifiers, and UV-C lamps should also be considered.

Concerning residences, new interior layouts need to accommodate a space for home working, even in small apartments, to be distinct and separate. Innovative design solutions have emerged, for example, using sliding walls to hide workspaces. Remote schooling could also impact student housing, at least in the short to medium terms: investments in student accommodation rose over the past few years leading to an oversupply by the end of 2019. In the United Kingdom, student housing investment rose from £31 billion in 2015 to £51 billion in 2019. However, as both domestic and international students attended virtual classes from home during the emergency, vacancy rates increased and such assets became less attractive (WEF, 2021).

2.2.1.6 Energy efficiency

In view of the high energy consumption that buildings have in their operational phase, and the environmental consequences in terms of polluting emissions into the atmosphere directly or indirectly associated with such consumption, a high energy performance of buildings is undoubtedly one of the main targets of building design in the new millennium. The demand currently expressed by the society at large is in fact that of a building system able to finally switch from its role of an energy consumer to that of an energy producer. This new concept, which constitutes a cultural revolution compared to the past, cannot do without profound and important rethinking on the design canons that guided the architectural form of the last century. The goal is to create “zero energy buildings” capable of ensuring adequate thermohygrometric comfort over the year with the minimum energy requirement in relation to the climate, covered entirely, or to a very significant extent, by energy from renewable sources, preferably produced on site or in the vicinity of the intervention area. Indeed, buildings have a strong potential of reducing their energy consumption and greenhouse gas emissions, and the main challenge is to achieve this objective without compromising indoor comfort. The energy needs for space heating, space cooling, domestic hot water, ventilation, lighting, and other technical building systems shall be calculated in order to optimize health, IAQ, visual, and acoustic comfort also considering human and psychological factors.

It is apparent that strategies to reach the net-zero energy objective are numerous and diverse and should be carefully tailored for the specific building type, use and operation, and climate conditions (Kumar & Cao, 2021; Rodriguez-Ubinas et al., 2014).

Energy use and generation shall necessarily be placed at the forefront of the design process, along with more conventional considerations such as architectural shape, function, and costs, but with comfort at least equally important.

In particular, the goal of achieving a zero energy building shall be pursued at four different levels:

- at the typological level, concerning the geometry of the buildings, the positioning and sizing of the windows and interiors layout;
- at the technical and construction level, regarding the thermo-hygrometric characteristics of the building envelope;
- at the technological level, inherent to the choices of equipment and the use of renewable energy sources;
- at the management level, through the use of advanced building automation systems.

For new buildings, it is possible to intervene in all four of these levels, whereas for existing buildings design, solutions are normally concerned only with the technical construction (building envelope), technology (equipment), and management levels.

Together, typological and technical construction levels allow to reduce the energy requirements of the building (energy sufficiency measures) down to less than 15 kWh/m² making the use of air conditioning only marginal (passive buildings). The technological level instead allows, for the same energy requirement, to reduce both total primary energy consumption, through greater equipment efficiency (energy efficiency measures), and nonrenewable primary energy consumption, thanks to the use of renewable sources (clean energy measures). Finally, the management level allows to reduce energy waste, bringing real end consumption closer to the theoretical standards (consumer behavior measures) (see Table 2.12).

The design of an optimized, high energy performance building starts with the analysis of the building use, its interior comfort necessities, as well as the study of the natural and environmental resources available on the building site. Then, passive strategies for IEQ must be established, including hygrothermal comfort, daylighting, and air quality conditions, taking advantage of the natural resources available. In terms of hygrothermal comfort, strategies for winter season look to optimize direct and indirect solar gains, thermal energy storage and the reduction of heat losses, whereas strategies

TABLE 2.12 Building energy efficiency design strategies.

Indicator	Definition	Design strategies
Energy needs (net energy demand)	Energy to be delivered to the building in order to satisfy its standard comfort requirements.	Energy sufficiency measures on building geometry and building envelope (passive strategies).
Energy demand	Total energy delivered to the building, renewable and nonrenewable, in the form of electricity, heat and fuel in order to satisfy energy needs within the building (heating, cooling, ventilation, domestic hot water, lighting, appliances, etc.).	Energy efficiency measures on equipment and appliances Smart living measures on building management system.
System efficiency	Factor used to translate net energy demand to end energy consumption; it is the ratio of the net energy demand to the total energy required at the building location to meet the net energy demand in magnitude, temperature level and at the time it is needed. It comprises the combined efficiencies of the production, storage (if any), distribution, emission (only in case of space heating), and control systems.	Energy efficiency measures on equipment and appliances
Nonrenewable primary energy consumption	Quantity of nonrenewable primary energy consumed in order to satisfy energy needs within the building	Clean energy measures on renewable energy sources
Global primary energy consumption	Quantity of global primary energy, renewable and nonrenewable, consumed to satisfy energy needs within the building. It is the sum of the renewable energy generated and the nonrenewable energy taken from the grid minus the amount of renewable energy exported.	Energy sufficiency measures Energy efficiency measures Smart living measures Clean energy measures

for summer months include keeping the heat from building up and removing the built-up heat, reducing heat-generating sources and taking advantage of natural heat sinks. Depending on climatic conditions, adding or reducing the humidity can also increase the interior comfort in cooling periods (Rodriguez-Ubinas et al., 2014).

Therefore, in order to obtain zero-energy buildings, the energy performance must be adequately simulated in the design phase using input data representative of the site conditions, of the building geometric and fabric, and of occupants' energy needs, and in particular:

- site specific weather data, using weather files that are as representative as possible of site of intervention;
- certified performance specifications of proposed construction products and energy systems;
- in the case of major renovations, actual construction details of the existing building (this could include existing Energy Performance Certificates (EPCs) or other studies that have been used to demonstrate compliance with minimum energy performance requirements);
- actual conditions of use and occupancy patterns expected for the building (in the case of building renovations, surveys of the existing occupants of a building or a building portfolio can provide further insight into occupancy patterns and user behavior).

The calculation methodology should follow the overarching international standards, namely, ISO 52000–1, 52003–1, 52010–1, 52016–1, and 52018–1, containing a comprehensive method of assessing energy performance as the total primary energy used for heating, cooling, lighting, ventilation, and domestic hot water of buildings. Calculation time step can follow a quasi-steady state or hourly dynamic method as described in ISO 13790.

The energy performance of the building is determined based on the amount of annual primary energy that is expected to be required to meet the different energy needs with a standard use of the building, such as winter and summer conditioning, domestic hot water production, ventilation and, for the tertiary sector, lighting, elevators, and escalators systems (energy and transport services). For new buildings, energy performance is normally calculated both before (design energy performance) and after construction (as-built energy performance) and always refers to standard use (interiors temperature, light comfort, etc.), climate data and occupancy patterns associated with the building. Therefore, both design and as-built energy performances may differ greatly from the real ones in relation to the actual climatic conditions and use of the building by its occupants (see Table 2.13).

TABLE 2.13 Types of energy performance calculation.

Sub-type	Input data			Type of application
	Use	Climate	Building	
Design	Standard	Standard	Design	Building permit, certificate under conditions
As built	Standard	Standard	Actual	Energy performance certificate, regulation
Tailored	Depending on purpose			Optimization, validation, retrofit planning, energy audit

Parallel to standard energy modeling and calculations, used to verify code compliance and assess performance in comparison with established benchmarks, tailored simulations can be carried out to align as much as possible theoretical values to those of effective utilization of the building. In particular, the performance gap registered between simulated and operational results depends mostly on the inadequate characterization of operational schedules and occupants' behavior (OB) and on the quality and reliability of data contained in weather files used for energy modeling (see [Section 5.3](#)). More refined OB patterns can be input based on the actual indications by the client or by the building program (e.g., teaching hours for a school building, office schedule for a commercial building, etc.) or can be inferred from literature studies and investigations on the existing building stock. OB influences the built environment through both the sheer presence of users (e.g., heat release and carbon dioxide emissions) and their interactions with buildings elements (e.g., lighting, windows, blinds, HVAC setpoints and plug appliances). Conversely, reference and standard weather data do not take into account the local, microclimatic conditions that pertain the specific intervention site and may refer to data from far weather stations that are accurate and reliable, but not fully indicative.

Moreover, the net-zero energy objective places greater emphasis on ensuring that the building performs as expected after occupancy. Therefore, designers should be involved in the commissioning and first operation period of the building to provide some fine tuning of specific features and instruct occupants on the building's proper functions, as energy performance, comfort, and building operation—both passive and active—are more intertwined than ever. In case of building energy renovations, it is fundamental to involve the building users across the whole energy retrofit process and instruct them about correct energy behaviors.

The overall aim of the design is to identify the energy performance level through an iterative simulation and optimization process, which leads to the lowest cost during the estimated economic lifecycle (cost-optimal level) determined taking into account energy-related investment costs, maintenance, and operating costs (including energy costs and savings, earnings from energy produced) and disposal costs.

2.2.1.7 Water efficiency

Among the global emergencies of this century, the problem of the scarcity of drinking water is made even more urgent by the ongoing climate changes that are leading to an increase in water evaporation around the world and are creating increasingly irregular rainfall. Although water covers 72% of our planet's surface, only 3% of that water is fresh water, and two thirds of this is trapped in glaciers and polar ice caps ([United Nations, 2020](#)). According to the United Nations, 1.1 billion people around the world have no constant access to water and 2.7 billion suffer from water shortages for at least one month a year ([UN-Water, 2021](#)). These communities often endure long periods with limited water and undertake long journeys in search of new sources. While many regions have not yet reached crisis level, six in ten people around the world are projected to have no regular access to water by 2050 ([Boretti & Rosa, 2019](#)).

The trend of growing urban population is also placing more pressure on water supply in urban areas. Around 21% of all water abstracted in the EU is used for public supply, the majority of which is used in buildings. On average, each EU citizen directly uses 160 l/day of water. Water consumption is also an operational cost to building owners and users. Reducing water consumption will decrease the environmental impacts of delivering said water to the point of demand (i.e., from water abstraction, treatment and pumping through the distribution network). For hot water, increased efficiency also delivers significant energy savings and a decrease in air pollution and greenhouse effect. A more efficient use of water in buildings will reduce pressure on freshwater resources, especially in river basins that experience continual or seasonal water scarcity and in areas where desalination is necessary for water supply and much more energy is needed to treat that water ([JRC, 2021i](#)).

In this context, the water cycle of a building must be designed in such a way as to provide a high degree of comfort to users and at the same time ensure the lowest possible consumption of drinking water (high quality water) and the use of alternative lower quality water sources (gray water and rainwater) for all uses allowed both inside and outside the premises. Drinking water should in fact be used exclusively for food and personal hygiene uses. For different uses, such as irrigation, washing common and private areas, toilet flushing, and washing cars, rainwater and gray water should be used. Gray water should be purified preferably with suitable phytodepuration systems that use the filtering and purifying power of the vegetation.

Building plumbing system must be developed aiming for the maximum efficiency in water saving and human health in compliance with the local codes and requirements, with more and more regulations internationally that subject the building permit to the presence of structural building features aimed at water saving and reuse.

Therefore, it is important to be able to estimate potential water savings since the early stages of building design and to be aware of the relative importance of water scarcity in the region where the building is located. While improving the water efficiency of buildings via design choices is important in all cases for the environmental benefits it can deliver, it is even more important in areas that suffer from continuous or seasonal water scarcity. In particular, design strategies to reduce water consumption in buildings include:

- the use of appliances with high water use efficiency, of smart taps that self adapt to the users' activities, of heat recovery systems from discharged water, of leakage control systems with alert and flow stop, and of consumption measurement and display systems to encourage users' good practice;
- the use of native vegetation with low water demand, the staging of vegetation, and other factors that can create microenvironments that reduce evaporation rates and the use of smart watering systems based on soil conditions and weather forecasts;
- the recovery, treatment and reuse of rainwater, condensation from air conditioning systems and gray water.
- the installation of multiple meters onsite to better monitor where water consumption is happening in the building, to better quantify the impact of irrigation and any contributions of harvested rainwater and reused graywater on total water consumption.

The three main sources of water consumption in buildings all relate to sanitary fittings: toilets, showers/baths, and bathroom/kitchen taps. Bathroom fixtures account for around 61% of total household water consumption. Compared to the products currently in use in homes, the latest tap dispensers on the market today allow an improvement of a factor between 2 and 3 in the specific consumption of water for activities related to personal washing and toilets ([The Water Label, 2021](#)).

Rainwater recovery is already mandatory in many countries for all new constructions. Rainwater is normally collected from roofs but may also be collected from other impermeable or pervious ground surfaces depending on the risk of contamination and the intended end use. The recovery of HVAC condensation is recommended whenever there is a large production that justifies its implementation. The allowed uses in both cases are irrigation, cleaning, WC flushing, clothes washing, and water features. Rainwater harvesting systems are fairly low-tech and can be completely separated from the building (e.g., collecting water from the roof for garden irrigation) or can be integrated into the building plumbing grid to supply water for flushing toilets. Rainwater is generally free of impurities but it may pick up sediments, dust, bird droppings, and leaf litter as it flows across collection surfaces. There are no standard quality requirements for harvested rainwater. If used for irrigation or toilet flushing, simple filtration or first-flush diversion may be all that is needed. If other sanitary purposes are envisaged, harvested rainwater might need to be disinfected, for instance, via in-pipe UV sterilizers. Treatment of rainwater can be applied upstream (e.g., screening >1 mm), within (e.g., sedimentation) or downstream (e.g., filter and/or disinfection) of the rainwater storage tank, which in turn will be sized according to how much rainwater can be harvested and how much potable water demand the designer wishes to substitute. In climates with prolonged dry seasons, the storage capacity should be sufficient to cover the targeted needs during the dry months, provided that a larger storage capacity increases the cost. An overflow device must be in place to divert the excess rainwater away from the tank (e.g., to a natural watercourse, storm drains or sewer network), as well as a back-up supply of potable water or nonpotable water from other sources should be available in case of insufficient rainwater to supply relevant devices and appliances.

Gray water is the domestic discharge water coming from wash basins, showers and bathtubs, washing machines, dishwashers and kitchen sinks, thus excluding WCs (black water). The reuse of gray water is relevant for all building types, regardless of climate and building morphology. Gray water can be reused safely, effectively reducing water supply and disposal costs, and reducing water consumption by up to about 40%–50%. Its recovery is recommended in many countries and contributes to all international building environmental certification rating systems. The treated gray

water can be utilized for WC flushing, irrigation, cleaning, clothes washing and water features. For graywater reuse to be feasible, it is necessary to have:

- a separate collection networks for graywater and for other domestic wastewater;
- a graywater treatment system;
- a dedicated distribution network to take the treated graywater to the point of reuse.

Several graywater treatment options are available, with increasing complexity:

- direct reuse with no treatment (only recommended for subsurface and nonspray irrigation);
- short retention systems with basic skimming and limited sedimentation of large particles;
- basic filtration and disinfection systems that remove solid particles and carry out disinfection through the addition of chemicals or UV sterilizers;
- biological systems where bacteria or vegetation metabolize dissolved organic material;
- bio-mechanical systems which also include mechanical aeration and the separation of solids (e.g., via sedimentation, filtration, or floatation).

The extent of treatment is dictated by the source and by the intended use of the graywater. Greywater and rainwater storage tanks, pipes, and valves shall be adequately labeled to prevent any misuse. The capacity of rainwater storage is commonly much greater than that of graywater due to the more regular production of graywater, the concerns about graywater turning anaerobic and the need to optimize rainwater supply for prolonged dry periods.

2.2.1.8 *Smart readiness*

The integration of smart technologies in buildings can be a cost-effective solution to enable healthier and more comfortable spaces with a lower energy use and carbon impact, and can also facilitate the integration of renewable energy sources in future energy systems.

In the last decade, important market changes have occurred in the building sector, on the one hand with the emergence of smart meters, wireless sensors, small-scale renewable energy systems, connected smart appliances, home networks, smart energy infrastructures and local energy storage systems, on the other hand with the introduction of products, software, and engineering services for automatic control, monitoring and optimization, and management to achieve energy-efficient, economical, and safe operation of services equipment, setting the path toward increasingly smart buildings.

Such systems and technologies are today becoming more and more necessary in a scenario where energy systems will be characterized by larger share of renewables, distributed supply, and energy flexibility that is also managed on the demand side (EV infrastructure, onsite electricity generation, energy storage). Smart technologies, such as building automation systems (BAS) or smart meters, allow to flexibly adapt the energy consumption of buildings, thereby contributing to the development of smart grids and to a better integration of renewable energy, for example, through self-consumption (see [Section 12.3](#)).

The diffusion of smart technologies is expected to lead to significant energy savings in a cost-effective way and at the same time to improve comfort in buildings, allow adjustments to the needs of users and reduce the current performance gap between building EPCs and the actual operational behavior. An enabling factor in this progress is their capability to raise awareness among owners and occupants of the optimal use of the building systems and to engage them in actively managing their energy demand and supply through better understanding, information, and market transformation. In particular, building abilities enabled by smart technologies include:

- optimization of its energy performance and operation through the adaptation of energy use and supply, for example, by using energy from renewable sources;
- adaptation of its operation mode in response to occupants' needs in an user-friendly way, maintaining healthy indoor climate conditions and reporting on energy use;
- flexibility of its overall electricity demand, including participation in active and passive as well as implicit and explicit demand response in relation to the grid, for example, through peak-shaving and load shifting capacities.

Smart technologies include both ICT features (e.g., communication protocols or optimization algorithms) and physical products (e.g., sensor networks, cabling for bus systems), as well as combinations thereof (e.g., smart thermostats). Smart active components can potentially:

- improve the level of control of the building systems by the occupants and building manager via BAS;
- facilitate building energy management and maintenance, for instance with automated fault detection;

- automate reporting of the energy performance of buildings and allow real time inspections;
- optimize building operations with advanced control methods such as data analytics, self-learning control systems, and model predictive control;
- enable buildings systems, appliances, storage systems, and energy generators to participate actively in demand response setting.

All individual building subsystems (energy generation, storage, and distribution, HVAC, water systems, lighting, data network, access and elevator control, fire and security systems, electric mobility) can become part of a single central BAS and gain the ability to learn users' needs and behavior, to anticipate solutions or provide use recommendations (see [Section 10.3](#)). These systems make use of forecasting, optimization, and evaluation algorithms that acquire real-time data from strategically placed smart sensors and meters, capable of detecting internal microclimate parameters, use of spaces and ICT infrastructure, attendance, weather data, and energy quality.

By analyzing input data, the system can suggest actions to optimize energy consumption; users can become an active part of the system by monitoring consumption in real-time on their personal devices and improve their behavior accordingly. Depending on the type of system used, smart building systems are able to perform partially autonomous (following fixed and predetermined responses to environmental parameters) or fully autonomous programmed functions, based on responses to environmental parameters directed by dynamic programs that can be generated or improved by self-learning.

In a smart building, the energy management system (EMS) can exploit energy price data from the smart grid, weather forecast and occupancy patterns and schedules to determine the optimal strategy in terms of energy, cost, or carbon saving and pursue it by controlling the charge/discharge of energy storage devices and EVs, the temperature set-points, the use of connected appliances and equipment and by deciding whether it is more convenient to sell the power generated by building-integrated renewables or to use it internally. Vehicle-to-building (V2B) or Vehicle-to-Grid (V2G) technology is particularly interesting, as it allows to take advantage of energy contained in vehicles batteries at times when electricity is most expensive and recharge them when energy costs less, or to use parked vehicles as an emergency power supply in case of power shortages (see [Section 12.3.3](#)).

Smart meters are increasingly widespread and permit real-time two-way communication between the building and the grid, enabling advanced load management strategies in commercial and residential buildings. They allow to obtain real-time pricing signals for the BAS, thus providing clear information about incentives and most favorable fares. Electric and thermal energy storage technologies are another major technology driver for load management, as they allow to easily plan the use of energy resources over time.

In order to communicate more effectively the added value of building smartness to building users, owners, tenants and investors, the 2018/844/EU Directive introduced a rating scheme for smart buildings, the Smart Readiness Indicator (SRI). SRI allows to gage the adaptation of building energy consumption in response to both availability of renewable sources and needs of the occupants, as well as the flexibility of the power demand of a building, expressed as participation in demand response strategies in relation to the grid requirements. SRI is calculated according to a multicriteria assessment method that considers the impacts in terms of energy performance and operation, response to the needs of the occupants, and energy flexibility of nine technical building services: heating, cooling, domestic hot water, controlled ventilation, lighting, dynamic building envelope, electricity, electric vehicle charging, and monitoring and control ([JRC, 2020](#); [Vigna, Roberta Perneti, Pernigotto, & Gasparella, 2020](#)).

Impacts are in turn divided into seven categories: energy savings on site, flexibility for the grid and storage, comfort, convenience, well-being and health, maintenance and fault prediction, information to occupants (see [Table 2.14](#)). Smartness of various domain services is assessed based on their functionality levels, each representing a different degree of performance. For instance, a functionality level 0 refers to a not-smart service implementation, while the highest level 3 indicates an advanced functionality, where the control is based on demand. Functionality levels consider, in particular, the controllability of performance, storage and connectivity, as well as reporting capabilities. A higher functionality level reflects a “smarter” implementation of the service, which generally provides more beneficial impacts to building users or to the grid compared to services implemented at a lower functionality level.

Since smart buildings are connected infrastructures and require real-time data transfer, data security is an important aspect of their performance. Therefore, cyber security strategies are necessary to protect the building's assets, which may include system security plan (SSP), incident communications procedures (ICP), security auditing plan (SAP), information technology and concept of operations plan (ITCP), and plan of action and milestones (POAM). Standards from National Institute for Standards and Technology (NIST) and ISO (specifically SP 800–37 and NIST SP 800–53) can be used by government and industries as qualified references to protect both the building software and hardware from cyber-attacks.

TABLE 2.14 Example of matrix showing SRI scores by domain and impact criterion, aggregate scores per impact criterion and the overall SRI score (JRC, 2020).

Domains	Criteria and subcriteria						
	Energy saving and operation		Respond to user needs				Respond to needs of the grid
	Energy saving on site	Maintenance and fault prediction	Comfort	Convenience	Health and well-being	Information to occupants	Energy flexibility and storage
Heating	32%	18%	62%	55%	24%	74%	0%
Domestic hot water	17%	0%	45%	70%	67%	83%	0%
Cooling	65%	51%	78%	72%	61%	55%	0%
Controlled ventilation	41%	0%	55%	60%	34%	44%	0%
Lighting	85%	14%	90%	100%	83%	15%	0%
Electricity	10%	0%	31%	56%	22%	46%	0%
Dynamic envelope	10%	0%	-	-	-	68%	0%
EV Charging	-	38%	-	82%	-	84%	0%
Monitoring and control	52%	43%	62%	72%	45%	64%	0%
Total	39%	18%	60%	71%	48%	59%	0%
SRI							42%

2.2.1.9 Durability and maintainability

The fundamental objectives of building design and construction include those of durability of materials and components, ease of maintainability, replacement and upgrade of elements, technical and environmental compatibility of materials and easy controllability of the building's performance over time. These requirements are indeed essential for maintaining the performance levels of the building, including safety of occupants, and for containing its life cycle costs to allow its intended use in an economically sustainable form. As commonly established for public works, they shall be subject to verification of the compliance of the design solution with the expected quality requirements and shall constitute an important criterion for identifying the most convenient proposal and therefore awarding the contract for a work.

All technical elements of the building system undergo a natural drop in performance over time according to the operating life of the materials used, to external agents, to the methods of installation, and to the interaction between the various materials that make up the different functional layers. Therefore, the durability of a building component expresses its ability to perform the required functions during a specified period of time under the influence of the agents expected in operation. Durability must ensure that the geometry and characteristics of the materials that make up the building structure are maintained over time, so that it retains its functionality, esthetic appearance, and strength.

The agents affecting the building's performance are due to the external and internal climatic conditions and the conditions of use. Their actions may exert effects on building components that include: deformations in the structures; cracks (external, internal, or across) in structures and coatings; detachments of elements and local breakdowns; breakage of anchoring systems; breakage, deformation or dislocation of the sealing elements; stains, decoloration, degradation and detachment of cladding; surface condensation, mold or efflorescence; growth of microorganisms, oxidation of metal elements; infiltration of air and water into indoor spaces; loss of operating performance.

The durability of the building components ultimately depends on the choice of materials with adequate resistance and stability requirements, on the correct sizing and sequential arrangement of the different functional layers, on the construction details at the most critical points of the structure (nodes), on the possible application of protective substances or layers, and on the correct methods of installation. In order for the building components to continue to perform their intended functions over time, they must allow an easy routine maintenance. The maintainability of a building

component expresses its ability to return to the expected performance in a limited time and cost following a maintenance intervention. In this sense, maintainability has several subrequisites such as: nonsoiling ability, self-cleaning capacity, self-maintenance capacity, cleanability, maintainability by a user, inspectionability, repairability, disassembly, replaceability.

Maintainability factors, reliability of the system and its parts, and the presumed life of the components should be factored in all design decisions pertaining the choice of the most effective technical solutions, also in terms of life cycle costs of the building. Detailed design of structures must include the maintenance plan of the structural part of the work. For public works, a specific maintenance plan is usually required as part of the detailed design deliverables, referring to the significant parts of the asset and the technological systems, consisting of a user manual, a maintenance manual, and a maintenance program. The user manual contains all the information necessary to allow the user to best use the asset, as well as all the elements necessary to limit as much as possible the damage deriving from improper use, to carry out conservation actions that do not require specialist knowledge, and to promptly recognize anomalous deterioration phenomena in order to request specialist interventions. The maintenance manual provides, in relation to the different technological units, the characteristics of the materials or components involved and the information necessary for correct maintenance as well as for contacting assistance or service centers. Finally, the maintenance program identifies, according to preestablished time intervals, the inspections and maintenance interventions to be carried out in order to correctly manage the asset and its parts over the years.

2.2.1.10 Adaptability

Adaptability of buildings can be defined as the ability to accommodate the needs of different users, the change of user requirements, technical changes, and change of their intended use. Indeed, over the course of a building's lifetime, change is inevitable, in the social, economic, and physical surroundings as well as in the needs and expectations of the occupants. A building's useful life may therefore end long before its potential design life if it fails to adapt. This may be due in part to market or regulatory factors that make it obsolete, or to changing needs of users. All other things being equal, a more adaptable building will be used more efficiently and will stay in service longer because it can respond to changes at a lower cost than one that has no adaptable features. A longer and more efficient useful life for the building can, in turn, translate into better environmental performance over its entire life cycle.

The major obstacle to designing for the adaptability of buildings is certainly the difficulty of accurately predicting what the future requirements may be over a time horizon of at least 50 years. While it is possible to identify features of existing buildings that have improved their adaptability over time, it is by no means certain that these will work equally well in the future. The kind of changes that might occur in the 21st century may indeed be completely different from what has happened in the past. A fourth industrial revolution is underway, the nature of work is evolving, and even the climate is changing, as is the average age of the population. The pace of change could also be significantly greater in the coming decades. Given the inherent uncertainty associated with decisions and investments aimed at adaptability measures, it is important to combine planning with an analysis of the real estate market at least in the medium term. The use of dedicated software tools can also support the probabilistic analysis of life cycle scenarios for the future occupation of the building. For example, the EU-funded CILECCTA project provides an online software tool that allows users to analyze future scenarios for different building configurations and the influence that such scenarios would have on the environmental and costs impact. Users can specify the local market conditions, their probability of occurring during a defined study period, and the building specifications that can allow for adaptation to potential future changes in market conditions. Examples include potential increase in the height of a building or changes in the primary uses. Present and future costs for adaptations can be defined by runs of the model over a defined period of time using a Monte Carlo simulation. This way, the net present cost of different adaptability measures can be evaluated based on reasoned assumptions about the future market conditions.

From the design point of view, the concept of adaptability can be divided into three main strategies: flexibility, that is, the ability to allow small changes in the layout and use of space by users; convertibility, that is, the ability to allow changes in the intended use within the building (e.g., from residence to office and vice versa); and expandability, that is, the possibility of adding new volumes in height (JRC, 2021j).

Design aspects to consider vary depending on whether the building is an office or a residential one and concern architectural (height of the floors, width of the spans, plan depth and daylight penetration, accesses), construction and systems engineering choices. In particular, the ways to make buildings more adaptable over time concern:

- to allow easy adaptation to the accessibility and visitability of the building by people with reduced motor skills, in consideration of the aging of the population and of possible changes in the intended use;

- to extend the life span of components, and of structures in particular, as much as possible, ensuring that this duration reflects the expected building life;
- to ensure the seamless improvement of the operational performance of the building over time by allowing easy updating of lighting, air conditioning and energy production systems as technological innovation advances. In fact, the average efficiency of many energy technologies in buildings has improved between 20% and 100% in the last decade alone (design for technological upgrade);
- to favor the functional adaptability of spaces and the disassembly of components for the reuse and recycling of materials;
- to favor the updating of facades for energy or esthetic needs;
- to allow increases in static loads due to changes in intended use or expansions in height.

It is also important to combine the strategies for adaptability with the environmental effects that these can have on the life cycle of the building. For instance, the use of post-tensioned concrete instead of in situ concrete to achieve wider spans could lead to greater impacts in terms of greenhouse gas emissions, while a high flexibility of the layout of the interior spaces could encourage more frequent refitting of the offices. Design for adaptability therefore requires the need to envisage, develop, and test possible future scenarios for the use of the building and can be supported in particular by parametric and generative design approaches (see [Section 6.4](#)). These assisted design techniques in fact make it possible to automate the geometric design of spaces based on mathematical functions, thus allowing the designer to envision the future needs of any alternative uses and solutions and effectively integrate them into the project specifications.

2.2.1.11 *Adaptation and resilience*

Buildings and communities have always been subjected to destructive forces from natural and human-caused hazards such as extreme weather events, natural disasters, critical infrastructure failures, and even intentional attacks ([JRC, 2021k, 2021l; Murtagh, Scott, & Fan, 2020](#)).

Weather patterns, in particular, have played a substantial role in the evolution of building forms, structures and materials and have greatly influenced the location of cities, infrastructures and settlements.

Disruptions affecting the built environment may include outdoor air pollution, wildfires, earthquakes, hurricanes, flooding, heat waves, power outages, water shortages as well as pandemics, as demonstrated by recent global emergencies ([Attia et al., 2021](#)). Today, these forces affecting the built environment are evolving with climate change, environmental degradation, population growth, globalization, and migration. Rising sea and land temperatures are changing precipitation patterns and causing an increase in extreme weather events such as heat waves, heavy precipitation and droughts in many parts of the world. Real estate value has soared in areas surrounding urban and suburban centers, leading to uncontrolled urban sprawl on many sites that were previously undeveloped, especially on riverside and sea-side areas with high exposure hazards.

Climate extremes are especially relevant in coastal areas, where risks increase due to a combination of gradually increasing mean sea levels, storm surges, wind damage, and erosion. Arguably, the most significant change will be with extreme sea level events, where 1 in 100 year occurrences (according to current records) are expected to happen every year by 2100 in most coastal locations. Extreme heatwaves also create drought conditions and an increased risk of wildfires. In addition to more obvious drought-related problems, if a drought is followed by heavy rains can reduce soil stability and lead to landslides. In a scenario where global warming is 3°C or more above preindustrial temperature levels, the PESETA IV report by the JRC estimates that droughts would happen twice as often in most of southern and western Europe.

In such scenarios, it is evident that standard building designs that have worked satisfactorily for decades are not sufficient anymore and, in the short-term, a paradigm shift among designers of the built environment is necessary in order to reduce harm and property damage, adapt to evolving conditions, and recover from adverse events more readily, effectively, and efficiently. The design of climate change-proof buildings requires adaptation and resilience measures that can be incorporated into buildings now or, if necessary, could be easily incorporated at a future point in time.

Adaptation is about the transformation to alternative domains of operations, meaning that the built environment will be designed, constructed, and operated differently than we do now as humanity flexibly responds to the uncertainty associated with climate change. Architecture should therefore incorporate the capacity to accommodate changing environmental and social conditions within the building's useful life. This can be accomplished by first performing risk and vulnerability assessments based on data and research on hazard and climate projections. For instance, projections for

future climates in the coming decades under different “degree scenarios” should be used as the basis for modeling performance, instead of only present and past weather data. By simulating and evaluating future scenarios for the thermal comfort and resilience of a building according to climate change projections, designers can identify measures that have the potential to minimize future risks and liabilities. Furthermore, it is particularly important to consult with authorities in charge of risk assessment planning (e.g., flood risk management, drought management, national planning for adaptation to climate change) and check for regional or national bodies that can provide support for adaptation efforts.

Resilience is the ability of a system and its component parts, be it a building or a community, to anticipate, absorb, accommodate, and recover from the effects of a hazardous event by ensuring the preservation, restoration, or improvement of its essential basic structures and functions in a timely and efficient manner. As a building requirement, resilience builds on the concepts of resistant building (a building that is able to withstand foreseen extreme events without irredeemable loss of performance), and robust building (a building able to cope even to unforeseeable disruptions, although by first failing its intended use then recovering its operation to a minimum or critical level of performance in a reasonable time), by implementing a series of strategies and measures that manage to remove temporary failure altogether and ensure continuity of operation, even if at a compromised level, until full recovery of the original performance (Attia et al., 2021).

Fundamentally, resilience is about the elasticity to revert to the full operations of the status quo and has multiple connections to architecture. Indeed, resilience requires adaptable structures that can “learn” from their environments and sustain life, even in the face of disaster, and asks architects to learn from their buildings and refine their designs. Moreover, resilience means involving people directly in the design and creation of strong and inclusive buildings and cities. Resilience measures should therefore be discussed and incorporated during predevelopment, programming, and planning phases by thinking across scales of the passive ability of a building to operate in the face of extreme events. Mitigation planning includes the identification of hazards, the assessment of vulnerabilities, the analysis of impacts, the integration of programming with the desired outcomes, the creation of performance targets, as well as their design and implementation.

It is necessary to consider carefully how resilient interventions can create value in terms of continuity of building operations and in terms of mitigating harm to users and communities, and to balance upfront costs and long-term value over the intended service life. Cost considerations should include the potential increased complexity of the construction works, increased capital costs, and increased maintenance costs. Conversely, benefits may pertain lower insurance premiums and a reduced risk/cost of damage in the event of extreme weather events.

It is also important that clients and building users are informed about hazards, climate, and extreme weather events that fall outside of historical precedents. Social resiliency shall be built between owners, operators, and users, for instance, by implement some redundancy in daily systems and supplies, preparing emergency kits, promote self-sufficient individuals, communities, and buildings.

Design strategies that reduce the risk of damage caused by extreme weather events are primarily focused on the building envelope and structure but may be extended to features beyond the building boundary itself, for example, flood or erosion barriers erected at the site boundary that are part of a larger flood protection infrastructure designed to solely protect the building in question or to protect the neighboring areas and buildings as well (see Table 2.15). A recent example of climate change resilient building is the headquarters for the Global Center on Adaptation in Rotterdam, the world’s largest floating office, which is designed to rise with the tides and to get all of its electricity needs from an on-site solar array. Following a circular economy approach, the building can be moved to another location, depending on requirements, and can be easily recycled once it reaches the end of its useful life.

Raising global temperatures are particularly concerning in view of the rapid increase of air conditioning in buildings worldwide, and mostly in hot, densely populated and developing parts of the world. Therefore, there is a growing need for low energy and low carbon cooling solutions able to strengthen the ability of individuals and communities to withstand, and also prevent, thermal and other impacts of changes in global and local climates. This approach, called resilient cooling in buildings, is also the subject of several ongoing studies such as IEA-EBC Annex 80—Resilient Cooling for Residential and Small Non-Residential Buildings (IEA EBC Annex 80).

Given the potentially long lifetimes of buildings, the potential future changes in regional water scarcity and the different possible attitudes of potential future owners/occupiers, making provision for future rainwater harvesting and graywater reuse infrastructure is also recommended, for example, by leaving sufficient space in service conduits for additional piping to be installed in the future. This way, any future renovation could be carried out with relatively little additional complication and disruption. Rainwater collection also reduces the risk of flooding in downstream areas.

TABLE 2.15 Main resilience design strategies.

Disruptive event	Mitigation actions
Severe storms, hurricanes	• Optimization of the building's shape to reduce structural wind loads • Bracing of gable-end roofs • Installation of roof tie-down clips and roof-to-wall clips • Window shutters
Power outages	• Provision of back-up power for vital services for up to 36 hours • Natural ventilation of habitable zones sized to accommodate the total building population in case of emergency • Ability of the building to passively maintain thermally safe conditions during peak summertime and wintertime conditions
Heat waves	• Design using suitable future air temperature projections at national, regional or local level, or employing reference weather files derived from extreme hot weather events in the last 30 years
Floods	• Locate/relocate boilers and other utilities in the building above expected flood levels • Wet-flood proofing of spaces to minimize the damage inside a property once floodwater has entered and to prevent the collapse of the building as a result of hydrostatic pressure • Dry-flood proofing of spaces to prevent water from entering the building altogether, for instance by waterproofing walls and floors up to a safe height • Reinforced walls to withstand the buoyancy force of floodwater • Wall openings to allow the ingress of floodwater into basements and garages to prevent buoyancy forces from building up • Backflow valves on drainage infrastructure to prevent backflow of sewerage and stormwater • Shielding for doors, gates, and windows to prevent water ingress

2.2.2 Context analysis

Context analysis is a fundamental activity of holistic design and is represented by the study of the territory that will interact with the future intervention, investigated under the different aspects of land use, morphology, landscape quality, historical cultural values, vegetation, geological, hydrological and hydrogeological situation as well as the state of soil pollution. Context analysis has been traditionally based on gathering geographical data from different sources (maps, cadastral parcels, local government acts) as well as on site measurements and investigation. In the last years, the wider availability of digital technologies and databases has greatly expanded the scope, convenience, and accuracy of this activity, providing urban planners and architects with powerful tools to assess site conditions and characteristics, identify main constraints, and potentials from the get go and pinpoint aspect to later investigate at a deeper level (see [Section 6.1](#)). In particular, digital cartography is now widely used in the form of satellite and aerial imagery, freely available or produced on demand at low price, which combines excellent ground detail and reliable size scaling. Geographic information systems (GIS) allow to superimpose base maps with all sorts of data layers containing geophysical, economic, social or infrastructure information, in order to perform advanced spatial analysis and evidence relevant patterns and indicators. Concerning on-site surveys, current tools allow a much quicker and more accurate representation of the site and its surroundings by employing automated distance measurement and GNSS receivers to trace point and outlines up to the creation of digital 3D point clouds of the site with millimeter precision via LiDAR and imaging reconstruction from drones or ground pictures.

Once this wealth of data is at the designer's disposal, AI-powered generative design tools can support architects and developers in identifying potentials, constraints, and strategies emerging from each unique context of intervention. Software including Delve, by Google's sister company Sidewalk Labs, and Spacemaker, recently acquired by Autodesk, exploit cloud-based AI, machine learning, Big Data, and generative design algorithms to optimize feasibility design proposals for single developments, neighborhoods, or districts. These allow to automate weighing up factors such as accommodation density, access to daylight and views, access to local amenities, proximity to open space or transport links, traffic and parking, noise, as well as local microclimate, heat island and wind characteristics, and consequently analyze, suggest, generate, simulate, and visualize alternative designs at much quicker pace compared to conventional early-stage and masterplanning tools.

Other AI-based generative tools such as Parafin are more geared toward real estate development (prop-tech) and promise to accelerate the site evaluation and acquisition process by rapidly generating design concepts, budgets, and

investment proforma for real-estate developers, each searchable by variables such as height, guestroom count, square-footage, budget, floor area ratio (FAR) and profit margin. From there the developer can extrapolate whether their investment decision makes financial sense in the current climate. The availability of accurate and precise data allows to precisely tailor the intervention to its market and its location. For instance, the developer can pull the data off the cloud for a specific project, plug in the data from the site being proposed, then—using business analytics technologies like Microsoft’s Power BI service—analyze what it will cost to build and operate that building type in that place.

2.2.2.1 Land use

The in-depth analysis of land use for a territorial area congruent with that of intervention allows to acquire a wealth of fundamental information for all future phases of design.

First, as a preliminary operation, it is necessary to identify the effective dimension of the area to be investigated, by interpreting the boundaries of physical (sea, rivers, lakes, landforms), productive (farms, industrial districts), urbanistic (districts, building sectors, homogeneous areas), or cultural and historical landscape nature.

Once the size of the study area has been defined as a first approximation, the actual use of the land shall be analyzed according to two main categories: functional characteristics of the urban fabric, and typological characteristics of the building fabric.

The first category concerns the intended uses in the territory within the identified area (public and private services, production activities, green areas, agricultural areas, uncultivated areas, brownfields), the network infrastructures (sewage collectors, power lines, aqueducts, railway and underground lines, roads), as well as eventual historical-archeological structures. In particular, the activities that may directly and indirectly interfere with the new intervention will be investigated, both from the aspect of environmental impact (landfills, quarries, power lines, thermoelectric plants, highways, etc.) and from the aspect of protection and enhancement of the historical and environmental assets present, even if unlisted (archeological areas or artifacts, woods, parks, gardens).

The second category concerns the structure of the territory and the morphology of the built environment. In particular, typologies that characterize the building fabric within the identified area (such as building heights, materials, heritage value) will be investigated in terms of both environmental impact—such as shading, view outside (see Fig. 2.6)—and the compatibility of the future intervention with sensitive buildings.

All information acquired in this phase of the analysis, correctly interpreted, must be summarized and translated into specific indicators of a prescriptive (such as distance of the building from polluting sources, detachments from buildings or roads, maximum heights) or of a demanding nature (such as respect for visuals, accessibility).

2.2.2.2 Landscape, historical, and cultural context

The objective of the landscape, historical, and cultural framing is to achieve an in-depth knowledge of the context in which the intervention will take place in order to evaluate all possibilities and potential for transformation of the

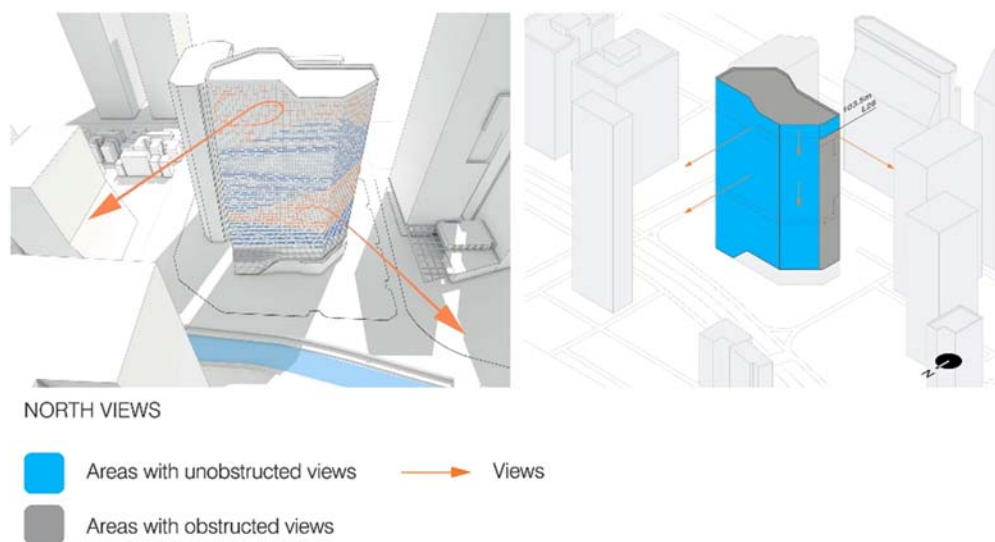


FIGURE 2.6 Outside views study in context analysis.
Courtesy of UNStudio.

territory and guarantee the harmonization of the work with the evidenced characteristics. This analysis will result in important indications on the overall massing configuration (system of buildings and open spaces), on the dimension, shape, distributive characteristics of the intervention, on the visual and perceptive aspects, and on the chromatic-material choices, which shall be consistent with the landscape and the surrounding environment. A correct historical, cultural, and social analysis, including the tradition and use of local materials, provides a necessary prior knowledge to be able to design in coherence with the elements that contribute to the landscape as a whole. This guarantees the harmonization of the intervention with the characteristics of the natural environment and the historical and typological characteristics of the built environment in which it will be placed. Indeed, along with the natural environment in which it is inserted, the architecture of a place represents an integral and essential part of the landscape that characterizes it. The morphological, technological, and chromatic-material characteristics of the intervention as a whole must therefore be aimed at optimizing the inclusion in the context (urban, rural or mountain) through the adoption of:

- typologies consistent with the characteristics of the place;
- solutions that facilitate orientation, with respect to geographic and orographic coordinates, and the readability of the geomorphological characteristics of the place;
- architectural features compatible and consistent with the relevant aspects of the context;
- spatial massing characteristics consistent with the typology of the surrounding buildings, with the shapes of the natural landscape and with the architectural value of the built environment;
- protection of local characters, materials, and construction technologies in new interventions, and maintenance of both historical materials and their application techniques in recovery and restructuring interventions;
- appropriate colors linked to the historical tradition.

In particular, in extra-urban sites, it is necessary to identify strategies for the elimination of the possible negative effects of the construction of new buildings, especially in naturalistic contexts, through the minimization of the visual-perceptive impact by, for example, using local materials linked to the historical tradition and typological elements characteristic of that place. In urban contexts, it will be necessary to harmonize forms, materials, and building typologies with those that have constituted the characteristics of that place in its historical evolutionary process and to take into account the color prescriptions, if any, or in any case to use colors linked to historical tradition. From an operational point of view, the survey of the typical characteristics of the territory will have to concern both the typological-morphological aspects and the perceptive characteristics of the natural and anthropic landscape, also through their historical evolutionary process. Of course, the depth of the analysis should be commensurate with the size and importance of the intervention and the characteristics of the site in which it is inserted. Such investigation shall be particularly detailed for those interventions that fall into areas subject to landscape or heritage-environmental constraints.

2.2.2.3 *Morphology*

Morphological analysis constitutes an extremely important step for the characterization of the site and for a correct placement of the building. The analysis shall include a description of the morphology and topography of the area, as well as any water bodies present (lakes, rivers, streams, etc.). In addition to the altitude of the site and the landforms, the orientation and grade of the slopes must be investigated, as they considerably affect the air temperature: south-facing slopes receive a greater amount of solar radiation and therefore determine a higher local temperature. In the same territory, two relatively close places located on slopes with different exposures are characterized by notable microclimatic differences.

Furthermore, under the same conditions of orientation of the slopes and height of the sun, objects placed on the slope cast shadows on the ground which width depends on the grade of the slope itself. It is therefore evident that, with the same solar path, the distance to be maintained between two buildings to prevent one from casting shadow on the other depends exclusively on the slope grade.

2.2.2.4 *Vegetation*

The study of existing vegetation represents a strategic element in the design choices for a given site both at the urban and building scales.

In addition to having a vital importance at a global level for life on earth as a primary source of oxygen in the atmosphere, and being responsible for the regulation of numerous biogeochemical cycles, such as the water, carbon, and nitrogen cycles, vegetation has a decisive role in the control of some aspects responsible for environmental quality and well-being at the local level. These include urban microclimate, solar radiation on open spaces and buildings, speed and

direction of air currents, atmospheric and acoustic pollution, water quality, soil protection, as well as conservation of animal life. In addition, vegetation can play a decisive role in characterizing the landscape and in the quality of living (for issues of identification, visual comfort, privacy, etc.).

Landscaping is therefore a design component of great importance and complexity, which embraces different disciplines, and which requires a careful study of the characteristics of the place and of plant species present therein with the aim of protecting the existing biome and integrating the intervention in its context, exploiting the full potential of newly planted vegetation.

From a methodological and operational point of view, the analysis usually entails the following phases:

- filing and mapping of plant species characteristic of the territory, including photographic documentation, highlighting any species of particular value;
- study of the influences of existing vegetation on the site and on the building to design;
- identification, based on the project objectives, of the plants to be maintained and indication of any new plant species to introduce;
- description of the landscaping of the project highlighting the role played by vegetation in achieving building quality objectives.

The analysis of the existing vegetation must, for each species surveyed, highlight the useful elements for the purpose of a correct design. In particular, essential data must be collected for:

- identification of the species: family, scientific name, synonyms, common names, distribution;
- the esthetic-shape characterization: form, dimensions (crown, total height, crown/height ratio), shape of the crown (fusiform, ovoid, spheroidal, conical, hemispherical, etc.) and of the leaves (broad-leaved, coniferous), seasonal behavior (evergreen foliage, deciduous foliage), type of roots (taproot, fibrous) and preferential direction of propagation, bark, flowers, fruits;
- the characterization of ecological needs: altitude limits, soil substrate requirements, climatic compatibility, resistance to pollution, frugality or rusticity;
- functional characterization in relation to the project objectives: maintenance, factors limiting use, allergy risks, recurring adversities, specific properties.

Esthetic-formal characterization is essential for the geometric schematization of each individual species during the year and to determine the shading phenomena on the ground and on the buildings, the windbreak effect, and the noise barrier potential.

As for shading, tall and medium-sized trees cast shadows on the ground or buildings to a greater or lesser extent depending on the shape of the crown. In general, the shading effect on the ground is modest for the fusiform and ovoid crowns, while it is sensitive for the spheroidal, conical, and hemispherical ones. However, it must be considered that on the vertical walls of buildings, shading can be significant in relation to the density of the trees. Depending on the seasons, shading caused by trees can be a favorable or unfavorable element. In summer, the trees produce a favorable effect as they protect ground crops from excessive transpiration, create shaded resting places, prevent overheating of opaque walls and excessive sunshine on passive solar systems. On the other hand, trees can produce unfavorable effects during winter by hindering the evaporation of water from the ground or preventing the melting of any ice crusts; they can also limit the heat gain of buildings from solar radiation, causing condensation phenomena in the walls that are kept cold. To determine of the quantitative extent of the shadow cast in the various seasons and its duration during the day, the crown of a single tree or a set of trees can be assimilated, with good approximation, to a geometric solid.

2.2.2.5 Soil pollution and radioactivity

The analysis of the site soil is extremely important in order to safeguard the well-being of the buildings and their occupants. It aims to verify that the soil itself does not have chemical, physical, and biological characteristics that may cause undesirable effects, and to identify any future mitigation measure. The design process shall consider the conditions of the site from the very beginning, as the choice of land use (e.g., where to create green areas) should be made on the basis of any constraint.

The identification of potential forms of pollution that may affect a certain area passes through a careful historical analysis of land use (agricultural, building, or industrial). Each past use must therefore be documented as accurately as possible, from the specific activities carried out, their time duration and their spatial distribution points of view.

For each specific anthropic activity, past or current, the analysis shall assess the possibility that contaminants may be present in the various elements (soil, subsoil, surface water, groundwater) in concentrations dangerous to human health or to the natural or built environment.

Particular attention must be paid to the levels of natural radioactivity of the terrain, due to the possible emission of radon (Rn) from the most superficial layers, in order to have suitable preventive measures for the containment of concentrations in confined environments. Radon is an extremely dangerous natural radioactive gas, which has been included by the International Commission for Cancer Research (IARC) in Group 1 of recognized carcinogens.

It is a noble gas, like helium or argon, odorless, colorless, tasteless, and hardly reactive with other chemical compounds. Eight times heavier than air, it originates from the radioactive decay of elements such as uranium and radium present in the earth's crust. Its concentration is usually measured in becquerel per cubic meter of air (Bq/m³), where a becquerel represents the activity of a radionuclide that has one decay per second. The greatest emissions of radon occur from rocks of volcanic origin such as lavas, pozzolan, tuffs, granite, and porphyry. Nonetheless, high concentrations of radon can also be found in sedimentary rocks such as marbles, marls, and flysh.

Once produced, radon can migrate through the soil and diffuse from building materials. As the building interiors are generally depressed compared to the outside, convective motions triggered in the soil cause radon to be sucked into the building and penetrate through cracks in the floors, floor-wall junctions, ducts and pipes, electrical and gas utilities. Indoor concentration is usually three times the outdoor one and corresponds on average to 78 Bq/m³ in countries with volcanic geology such as Italy, although some environments may have a radon concentration higher than 1000 Bq/m³, more than double the intervention threshold, mostly in ground level or underground spaces.

In absence of reference standards, the assessment of radon presence in the site shall be based on the following main elements:

- information from regional surveys conducted by the control authorities which indicate areas at greatest risk;
- soil composition and permeability, looking for high levels of radium and uranium;
- radon concentration in local water wells;
- measurements of radon levels in buildings within the same geological area.

If a high concentration of radon in the soil is detected, appropriate techniques must be provided to reduce the concentration in confined spaces below the safety thresholds. The first choice shall be to not locate habitable rooms on the ground floor or basement, as this considerably reduces the risk. Preventive intervention techniques include the limitation of the entry routes of radon toward the interior of the building through passive (natural ventilation of the crawl space, gasproof membranes) or active systems (forced ventilation), as well as the reduction of the depressurization of the building toward the surrounding environment and especially the ground below.

2.2.2.6 *Acoustic climate*

The acoustic climate of a given territory is an important aspect which can deeply affect the environmental well-being of indoor and outdoor living spaces and consequently the design choices at the district and building scale. In fact, due to its spread and constant growth, noise has become a substantial source of environmental pollution is now considered as an actual threat to public health (see [Table 2.16](#)). In particular, the harmful effects caused by noise exposure on humans belong to three categories:

- physical damage to the auditory system (hearing fatigue, numbness, discomfort accompanied by buzzing and dizziness) and to the body (physiological stress, cardiovascular reactions);
- disturbances in activity and sleep (difficulty in falling asleep, quantitative and qualitative changes in the sleep cycle);
- state of discomfort referred to noise that the individual knows or believes can act on him in a negative way (annoyance).

To protect the health of citizens and the quality of the environment, most current regulations establish precise limits for the emission of noise in external environments in relation to the intended use of the area, as well as passive acoustic requirements for buildings concerning facades, internal partitions, and systems.

In the early stages of the design phase, therefore, an analysis of the acoustic climate of the intervention area shall be carried out through the identification of the noise levels in the area, of those permitted by current codes, the location of the main noise sources, and the location of any sensitive areas or targets.

The objective of the analysis is to provide precise inputs to optimize the design choices in terms of location and orientation of the building, location, and sizing of the openings, soundproofing of the facade, and location of open spaces

TABLE 2.16 Acoustic intensity of various sound sources and related effects.

Source of sound	Level (dB)	Noise effects
Hearing threshold	0	Noise that does not bother or harm (0–35)
Rustle of leaves	20	
Whisper	30	
Theater, home spaces	50	Annoying noise, which can disrupt sleep and rest (35–65)
Normal conversation, noisy office	60	Disturbing and fatiguing noise, capable of causing psychic damage and autonomic neuropathy, and in some cases hearing damage (66–85)
Phone ringer, printer, high volume TV and radio sets	70	
Alarm, medium street traffic	80	Noise that produces psychic damage and autonomic neuropathy, determines specific effects at the ear level and can induce psychosomatic illness (86–115)
Busy street traffic, noisy factory	90	
Truck, freight train, construction site	100	
Rock concert	110	Dangerous noise: specific effects prevail over psychic damage and autonomic neuropathy (116–130)
Siren, jackhammer, plane at take-off	120	
Threshold of pain	130	Very dangerous noise: impossible to bear without adequate protection, immediate or very rapid onset of damage (131–150 and beyond).

and vegetation in order to improve the acoustic climate of the building spaces through passive protection systems. Moreover, results of the investigation allow to determine the alterations that will be introduced by the intervention and verify their compliance with permitted levels and with preexisting anthropic activities. It is necessary to locate and describe the main noise sources in a radius of at least 500 m which can cause noise pollution: roads, railways, airports, maritime infrastructures, industrial, commercial and agricultural facilities; parking lots; freights warehouses; areas used for sports and recreational activities, air treatment plants.

Most noise is not characterized by a single frequency or tone, but rather by a wide range of frequencies, or spectrum. The identification of these frequencies and their relative intensity (mix of tones) is as important as the corresponding prevailing sound level. Most common noise problems come from road traffic, which occurs mainly at low frequencies with heavy vehicles resulting in a higher dB (A) weighted overall sound level.

Railway noise has a spectrum generally quite similar to that from road traffic, with the difference that it presents a higher contribution of the medium frequencies and a sharp decrease of the high ones. Although the noise level near a railway can be very high, the human ear's tolerance toward it is higher, as the sound peaks are predictable and short-lived for the listener. In fact, in some regulations railway noise can exceed road noise by 10 dB, as this creates the same level of annoyance. Air traffic noise varies significantly whether the plane is taking off or landing, with the take-off phase dominated by low frequencies and the landing dominated by the high frequencies caused by the engines in reverse thrust. As for conversation noises, most relevant frequencies of human voice are between 500 and 2000 Hz (medium frequencies). In this case, suppression of higher frequencies is most important factor in ensuring privacy in conversations and reducing disturbance, as these contain the sounds essential for intelligibility.

If necessary, instrumental measurements of the sound pressure levels shall be taken in significant points within and in the vicinity of the area of intervention, and at significant times of the day. These must be mapped in a planimetric distribution of the sound levels forecast. Then, it is necessary to localize any sensitive areas in relation to the acoustic impact that may be caused by the intervention.

Public and private entities interested in the construction or modification of certain categories, such as airports, railways, roads, discos, or sports and recreational facilities, are normally required to produce noise impact documentation.

At the same time, sensitive buildings such as schools and nurseries, hospitals, nursing and retirement homes, urban and extra-urban public parks, new residential settlements are required a forecast assessment of the acoustic climate of the areas interested before permitting.

Once the acoustic climate of the intervention site is known, the main methods for reducing the levels of noise exposure consist of reducing noise at the source by limiting speeds, traffic volume, and the use of tools and machinery, of hindering sound transmission by placing barriers between the source and the receiver along the propagation paths, and

of reducing noise at the reception points by adopting passive protection systems pertaining the location, shape and orientation of the building, the interiors layout, and soundproofing the building facades.

2.2.2.7 Air quality

Main analyses to carry out during the preliminary design stage include that of the quality of air around the site subject to the intervention. This analysis pertains, in particular, the identification and location of the main polluting sources present in the site and neighboring areas; the assessment of the average concentration and yearly trends of atmospheric pollutants by collecting data from the air quality monitoring units, where present, or through dedicated targeted campaigns; the study of atmospheric phenomena (winds, thermal inversion) and topographical features (reliefs, vegetation) capable of influencing the quality of the air in the site; the identification of any neighboring areas that are particularly sensitive to air quality.

The objective of the analysis is to identify, from the preliminary stage, appropriate design or mitigation solutions aimed to protect the health of the intended users of the building, as well as to reduce the impacts resulting from the intervention itself. Main sources of atmospheric pollution of anthropogenic origin are constituted by vehicular traffic, combustion of energy sources for the production of electricity (power plants) or thermal energy (heating systems, cooking appliances), substance releases caused by industrial processes (refineries, mining activities, etc.), and from the avio-dispersion of agricultural chemicals (fertilizers or pesticides).

Atmospheric pollutants are made up of both gaseous substances (actual gases or vapors) and corpuscular substances (particulate matter—PM), solid and liquid, which determine the formation of aerosols. Airborne particulate matter represents a complex mixture of organic and inorganic substances, many of which are hazardous. This complex mixture contains for instance dust, pollen, soot, smoke, and liquid droplets. These suspended particles vary in size, composition, and origin. Particles are either directly emitted into the air by sources such as combustion processes and windblown dust or formed in the atmosphere by transformation of emitted gases such as sulfur dioxide (SO_2). Particles are sampled and described based on their aerodynamic diameter, usually called simply the “particle size,” that is the size of a unit-density sphere with the same aerodynamic characteristics, and that govern both the transport and removal of particles from the air and their deposition within the respiratory system. Based on size, particulate matter is divided into two main groups:

- the coarse fraction contains the larger particles with a size ranging from 2.5 to 10 μm (PM_{10} — $\text{PM}_{2.5}$);
- the fine fraction contains the smaller ones with a size up to 2.5 μm ($\text{PM}_{2.5}$). The particles in the fine fraction which are smaller than 0.1 μm are called ultrafine particles.

Among the gaseous pollutants, the main ones are CO , NO_x , SO_x , VOCs, and tropospheric ozone (O_3), all with important effects on the respiratory system such as acute bronchitis and cough and phlegm, particularly in children, and on the environment with the formation of acid rains (in presence of water, NO_x and SO_x form H_2NO_3 and H_2SO_4 , i.e., nitric and sulfuric acid).

After the emission of pollutants into the air, they interact with other substances present therein and create chemical compounds (such as tropospheric ozone), only partially predictable, whose genesis and dynamics also involve chemical, physical, and environmental reactions as well as conditions of atmospheric stability or instability. The state of pollution can therefore be influenced by the formation of secondary pollutants and by particular climatic and geographical conditions, which intensify its effects or modify its initial characteristics.

The phenomena that may affect pollutants released into the atmosphere can be grouped into transport, dilution, modification, and removal categories. Transportation is the most obvious effect exerted by the atmosphere on emissions. Although the evaluation of the influence of winds at great distances is complex and entails ascending, descending and horizontal currents as well, it is commonly accepted that the prevailing winds affect the distance between the emission source and the point of deposition on the ground of the pollutants.

Dilution is due to turbulent movements of the air that allow a high mixing and dispersion of the pollutants in the air itself. In conditions of high turbulence, complete dispersion of pollutants is possible even at a short distance from the source.

Modifications are attributable to physical, chemical, and photochemical phenomena that determine a change in the qualitative and quantitative composition of atmospheric pollution.

Finally, removal processes are consequent to the action of precipitation (rain, snow, etc.) on the substances dispersed which are removed from the air and precipitated to the ground through physical transport or solubilization mechanisms.

Some meteorological factors, also in relation to the orographic, urbanization, and vegetation characteristics of the territory, can determine particular conditions in which the polluting substances produce more or less harmful effects. In

addition to identifying the characteristics and localization of the pollution sources, it is therefore required to develop a thorough analysis of the site aimed at identifying the parameters related to the orography, the presence of vegetation and the examination of air flows due to winds or breezes, to predict probable convective movements of the air, wind shadowed areas, and slowed air flows.

To avoid, prevent, or reduce the harmful effects on human health and on the environment as a whole deriving from atmospheric pollution, regulations on ambient air define for the main atmospheric pollutants precise limits not to be exceeded, concerning both emissions from the different sources and concentration levels admissible in the atmospheric air. As regards the air quality limits, the following are normally defined:

- *Limit value*: level set on the basis of scientific knowledge in order to avoid, prevent or reduce harmful effects on human health or the environment as a whole;
- *Target value*: level set in order to avoid, in the long term, further harmful effects on human health or the environment as a whole;
- *Alarm threshold*: level beyond which there is a risk to human health in the event of short-term exposure and upon which action must be taken immediately.

2.2.3 Climate analysis

Climate aspects are those that most influence the design choices at the building scale. Indeed, the climatic characteristics of the site dictate shape and orientation of the building, type of materials, characteristics of the envelope, interiors layout, and equipment and systems solutions (see Table 2.17). The building exposure to climatic loads not thoroughly considered during the design phase can also lead to a premature decay of the building envelope, roof and facades in particular, which are directly attacked by wind and rain, by high temperature variations and by water vapor diffusion (Liedl et al., 2012).

The climate can be defined as the set of normal and abnormal atmospheric conditions that characterize a region. It is defined by the statistical behavior over long historical series (25–30 years) of some variables such as temperature, humidity, precipitation, winds, and pressure relative to a specific geographical area. Therefore, the climate is not to be confused with meteorological weather, which is in fact the state of the atmosphere in a given place and at a given time. The climate of a region is determined by zonal factors such as latitude, general atmospheric circulation, the greenhouse effect and albedo, and geographic factors including altitude, the presence of mountain ranges, proximity to the sea and to large water basins, sea currents, vegetation, urban fabric, human activity, etc. In relation to the extension of the geographical area taken into consideration, the terms macroclimate, mesoclimate, and microclimate are also used. A macroclimate exists over very large geographical areas and long periods of time. It is identified and assessed using solar radiation distribution, terrain height, the distribution of land and sea, and global circulation. Areas with similar climates are grouped together as climate zones. One of the most used classifications is the Koppen one, introduced in 1884 and subsequently updated over time, which divides climates into five main groups based on seasonal precipitation and temperature patterns: A (tropical), B (dry), C (temperate), D (continental), and E (polar). These groups are in turn divided into subgroups for a total of 30 climate types (see Fig. 2.7)

From a methodological point of view, the climate analysis is divided into the following main phases:

- collection of available climatic data and their adaptation to geographic location;
- analysis of the significant environmental elements present in the intervention area;
- adaptation of the climatic data collected to the environmental elements analyzed;
- definition of the climatic data of the intervention area.

Once the data relating to the geographical location of the intervention area (latitude, longitude and average height above sea level) are known from the territorial classification phase, the available climatic data will be collected, in particular relating to air temperature, relative humidity, winds, precipitation, state of the sky, solar radiation, solar elevation angle, and duration of the day (see Table 2.18).

Information sources for the description of the climatic profiles of a specific area are based on the processing of data usually recorded by the World Meteorological Organization (WMO) and International Civil Aviation Organization (ICAO) meteorological stations (detection networks). Climatic data available from meteorological services can refer to a particular time period of data collection, to a “typical year” defined on a deterministic basis through mathematical averages of data collected during an adequately long observation period, or to a “probable typical year” defined starting from data collected during an adequately long observation period and re-elaborated with probabilistic criteria. Airport

TABLE 2.17 Climate context influence on design choices.

Climate parameters	Design choices	Design objectives
Air temperature	Building surface-to-volume ratio and orientation Interiors layout Building envelope thermal resistance Shading systems Mechanical equipment sizing Outdoor spaces characterization	Thermo-hygrometric comfort Reduction of energy consumption
Wind	Building surface-to-volume ratio and orientation Interiors layout Sizing and position of openings Building envelope thermal resistance Renewable energy sources Noise and pollution barriers	Thermo-hygrometric, physiologic, respiratory/ smell comfort Exploitation of renewable energy sources and reduction of energy consumption Structure cost reduction
Humidity	Thermo-hygrometric characteristics of the building envelope (humidity condensation) Ventilation needs Mechanical equipment sizing Outdoor spaces	Thermo-hygrometric, physiologic, respiratory/ smell comfort Structure maintenance
Rain	Roof type and grade, rainwater harvesting and disposal, choice of vegetation	Rainwater recovery and reduction of water consumption Correct disposal of wastewater Vegetation management
Sun radiation	Layout and orientation of the building Sizing, orientation and position of glazed surfaces and shading systems Inclination of sun-collecting surfaces Interiors layout Thermal inertia of building envelope	Improvement of hygienic and thermo-hygrometric well-being Reduction of building energy consumption Exploitation of available solar energy via passive and active systems
Sky conditions	Sizing, orientation and position of glazed surfaces and shading systems Average reflecting factor of indoor surfaces	Improvement of visual comfort conditions Reduction of building energy consumption

ICAO stations and WMO stations generally have the best quality data. Smaller airports and nonairport WMO stations are more variable: some are accurate, but others have a suboptimal recording frequency, for example, may only record the temperature every 6 hours or may not record at night. It is recommended to use a TMY derived from a medium term (20 or 30 year) time series for a standard local weather station. The length of this time series will ensure that the TMY is representative of climatic variations in the short to medium term.

At this stage, climate data retrieval and analysis can be supported by several software tools, some stand-alone and suitable for general use, others integrated within main BPS tools or even in BIM authoring software such as Revit or Archicad and geared toward building design. There are number of web-based applications that allow to visualize, create graphics, and perform computations on multiple data sets, mostly at large scale. Common tasks include difference maps, correlations, composites, climate monitoring, and deriving climate indices. These include NASA Giovanni and Panoply webtools, Climate Explorer by the Royal Netherlands Meteorological institute, ClimateReanalyzer by UMaine.

Specific software such as ClimateTool and Climate Consultant feature a database for most worldwide locations, and feature a graphic interface to translate raw climate data into meaningful graphics and charts. Outputs include courses over the year as well as averages and extremes for several climate parameters, psychrometric charts, climate, and frequency diagrams. Some even allow to compare different climate change scenarios up to the year 2100.

Climate analysis tools within BIM and BPS software can provide relevant data from built-in weather stations databases, and some also allow to import TMY or EPW weather files (specific for EnergyPlus program). Climate data are mainly employed to conduct simulations and calculations on the buildings to predict their energy needs; however, they can display basic information such as monthly temperatures, wind rose diagrams, solar irradiation. BPS tools with climate analysis functions include Autodesk Revit with Insight, DesignBuilder, IES VE Gaia, and others (see [Chapter 5](#)).

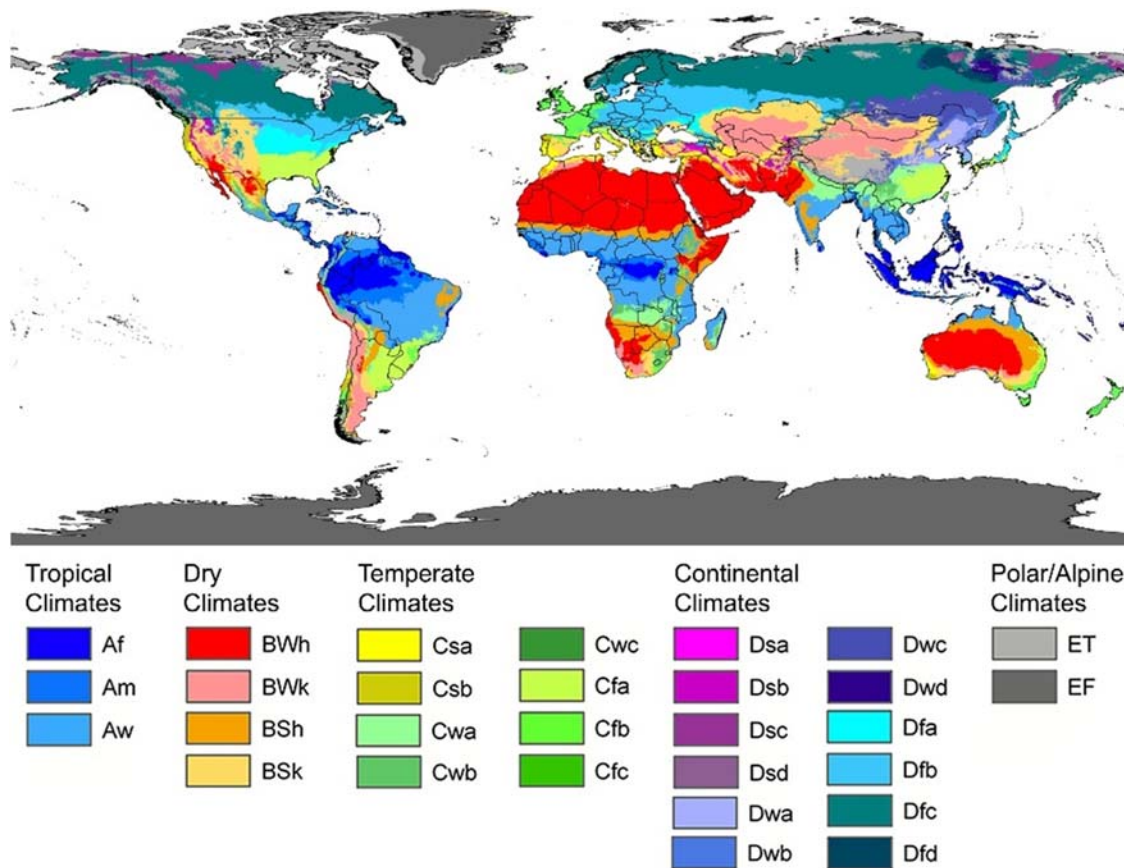


FIGURE 2.7 Koppen classification of climate zones.

Once climatic data have been collected, they will have to be adapted to the area subject to the intervention, taking into account the different geographical location with respect to the climatic station source of the data and the presence of local elements that may potentially influence the formation of a specific microclimate. Microclimates characterize the climate of the building context and concern areas with a horizontal extension of a few hundred meters and a vertical one corresponding to the average height of trees, in extra-urban areas, and of taller buildings in urban areas. At this scale, the local climatic conditions are also strongly influenced by the topographical characteristics of the place, and therefore, the knowledge of these elements is crucial to identify any corrective intervention tools. In particular, the elements capable of influencing the local climate of a site include:

- topography of the area: morphology, slope, orientation, geological and terrain composition; relative height with reference to the immediate surrounding; obstructions to solar radiation and wind;
- water bodies (seas, rivers, lakes);
- vegetation;
- urban morphology aspects: urban form, building density, height of buildings, type of urban fabric (orientation of buildings in the lot and with respect to road conditions, reciprocal relationship between buildings, etc.), development forecasts, etc.

In particular, the topography of the intervention area can have a great influence on the climate. For instance, cold, denser, and usually humid air accumulates in the valley floor areas. On the contrary, in flatlands or elevated areas, exposure to wind and solar radiation is greater. Areas located at a lower altitude are generally colder and humid in periods without wind, due to the accumulation of cold and polluted air which increases the phenomena of fog and mist; the presence of fog does not allow access to solar radiation and prevents the air in contact with the ground from heating up and therefore from triggering the convective motions that form breezes. Slope and orientation affect sunshine on the ground and the relation with the prevailing winds.

TABLE 2.18 Climate analysis.

Climate parameters	Data
Air temperature (°C)	Monthly daily average, monthly minimum daily average, monthly maximum daily average, monthly record high, monthly record low
Air humidity (%)	Monthly daily average, monthly minimum daily average, monthly maximum daily average
Atmospheric precipitation	Monthly average of rain, snow and hail [mm/month] Number of rainy days (daily precipitation >1 mm) [days/month] Cumulative height [mm]
Wind	Main wind sector of origin for each month Average speed associated with prevailing wind (m/s) Presence in the main sector (%) Wind calm (%) Average monthly wind speed (m/s) Wind diagram
Sky conditions	Cloud cover tenths of overcast sky, number of clear days (sky coverage ≤ 4 tenths) [days/month]
Solar radiation	Monthly daily average global, direct and diffuse radiance on horizontal plane and on a plane with optimal orientation and inclination angle (W/m^2d) Monthly total of the solar radiation energy that hits a horizontal plane and a plane with optimal orientation and inclination angle (kWh/m^2month) Monthly value of the ratio of the diffuse and the global horizontal irradiation Max solar elevation angle [°] on 21 Dec, 21 Mar, 21 Jun, 21 Sept
Daylight	Monthly average daily daylight, monthly average daily sunshine Solar diagram

As for water bodies, large masses of water (lakes and the sea) can act as thermal regulators: the strong thermal inertia of water allows the air temperature to stabilize. This effect is very marked near the sea and persists, although decreasing, even at a certain distance from the coast. Thermal inertia is one of the factors that influence the formation of local breezes linked to the temperature variations that occur in the daily cycle (day and night). Breezes are potentially very effective for passive cooling during the hot season. The presence of water is also a factor that produces an increase in humidity close to the coast. It should also not be forgotten that, albeit with a much lower intensity, even smaller quantities of water can have an influence on the microclimate.

The presence of vegetation and the thermophysical properties of the soil (significantly different between a bare ground, a ground covered with vegetation, a rocky ground, or an artificial surface such as asphalt) produce considerable microclimatic variations in the environment, causing effects on the thermal exchanges between the ground and the atmosphere, that is, on air and radiant temperature, on evaporation-transpiration, on air humidity, on the quantity of direct solar radiation on the ground or on other surfaces, on the dynamics of the winds and on air quality. The transpiration of plants plays a fundamental role in the thermoregulation of the environment. As an evaporation phenomenon, it involves the absorption of substantial amount thermal energy as latent heat. Therefore, the presence of large green areas in an urban environment can greatly contribute to mitigating summer overheating situations by locally reducing the temperature. A tree-lined square of 10,000 m² can transpire up to 50,000 liters per day and absorb about 30,000 kcal, thermal energy that would otherwise be absorbed by the built structures and pavements and re-emitted in the form of heat. The microclimatic effects of evapotranspiration are more prominent in poorly ventilated areas exposed to strong solar radiation. Experimental measurements have shown temperature differences of over 5 °C between areas inside large parks and surrounding urban areas. Furthermore, the presence of vegetation can shield from solar radiation and limit radiative exchanges toward the celestial vault. The presence of lawn areas can also limit the amount of reflected radiation and act as a temperature regulation. Finally, the shielding effect of the vegetation, combined with evapotranspiration, favors passive cooling in the hot season and also has the effect of acting as a barrier to the wind and changing its direction. In the case of large tree masses, there is also the formation of night and morning breezes similar to those of coastal areas. The presence of deciduous trees allows to mitigate solar radiation in the hot season maintaining solar gains in the cold season.

Finally, as regards the urban morphology aspects, the site microclimate can be influenced by the type and shape of urban fabric: its density and the relative height. It largely depends on how those modify the amount of sunshine, but the

effects on wind, humidity, and the ability to accumulate heat are also relevant. Large urban areas normally produce more extreme local climatic conditions than those found in rural areas. In particular, a greater urban density produces a drier climate, with higher and more fluctuating temperatures, less wind and a higher pollution rate that contributes to creating the greenhouse effect. This characteristic microclimatic phenomenon of cities is called urban heat island (UHI) and is generated by a combination of factors that include vehicle exhausts, heat rejection from building air conditioning systems, street canyon geometry, reduced evapotranspiration by vegetation as well as increased absorption and re-radiation of heat by roads, paving, and structures. Recognizing the significance of this effect, a great number of cities have put in place initiatives to support designers to take UHI more into account when modeling the external air and radiative temperatures around a building in an urban area. Relevant examples include London ([London's urban heat island](#)), Stuttgart ([Climate ADAPT case study of Stuttgart](#)), and Zaragoza ([Cuadrat Prats, Vicente-Serrano, & Saz Sánchez, 2005](#)).

2.2.3.1 Air temperature and humidity

The analysis of the temperature and humidity of the air in the intervention site provides strategic information to achieve the objectives of hygiene, thermohygrometric comfort, reduction of energy consumption and maintenance of the integrity of structures over time. The results of the analysis will in fact become important inputs for the design choices regarding aspects such as the surface-to-volume ratio (S/V) and the orientation of the building, the interiors layout, the thermohygrometric characteristics of the envelope (insulation and thermal inertia, vapor permeability), the potential for natural ventilation, the type and size of HVAC systems. For investigating air temperature and humidity, the monthly average and the maximum and minimum daily values must be analyzed with reference to at least the previous 5 years in order to identify the needs for heating, cooling, ventilation, humidification, or dehumidification in the various months of the year.

Concerning air humidity, the most relevant value is that of the relative humidity (RH or ϕ), corresponding to the % ratio between the mass of water vapor contained in a volume unit of air (absolute humidity) and the mass of vapor that could be contained in the same volume, under the same temperature and pressure conditions, if the air were saturated (maximum humidity). An RH of 100% indicates that the air contains the maximum amount of vapor possible under the set conditions of temperature and pressure. The importance of RH derives from the effects that this can have on biological organisms since it influences the exchange of water vapor between the organism itself and the environment. The human organism, in fact, is not affected so much by the water vapor content in the air (absolute humidity), but more so by the fact that this represents a certain percentage of the maximum content that could be present at that temperature (RH). For example, the human organism can withstand high temperature values better with particularly dry air, but if the high temperature is coupled with high RH values, the possibilities of heat exchange of the organism by skin evaporation, normally entrusted with about 30% of body heat transfer, are severely limited. Indeed, if the dry temperature is 30°C and RH is 50%, then it will feel like 31°C; but if RH reaches 100%, then it would feel like 44°C.

Among the climatic data relating to air temperature, particularly important for the purposes of building design is the index that provides the number of degree days of heating (HDD) and cooling (CDD) of a location (see [table 2.19](#)). Degree days indicate how cold or warm a given location is by comparing the mean of the high and low outdoor temperatures recorded each day to a standard temperature. This standard temperature may differ across countries, depending on conventions, cultural norms, and individual expectations of thermal comfort. More extreme outside temperatures

TABLE 2.19 EU Climate zones and corresponding HDD and CDD ranges.

Climate zone	Parameters		Representative EU cities
	Heating degree days	Cooling degree days	
Zone 1	<1500	>1200	Athens—Larnaca—Luga—Catania—Seville—Palermo
Zone 2	<1500	800–1200	Lisbon—Madrid—Marseille—Rome
Zone 3	1500–3000	400–800	Bratislava—Budapest—Ljubjana—Milan—Vienna
Zone 4	1500–3000	<400	Amsterdam—Berlin—Brussels—Copenhagen—Dublin—London—Macon—Nancy—Paris—Prague—Warszawa
Zone 5	>3000	<400	Helsinki—Riga—Stockholm—Gdansk—Tovarene

translate to higher number of degree days, then consequently to higher levels of energy use for space heating or cooling. In particular:

- HDDs are a measure of how much (in degrees), and for how long (in days), the outside air temperature is lower than a specific “base temperature” or “balance point” (15°C or 20°C) and are used for calculations relating to the energy consumption required to heat buildings;
- CDDs are a measure of how much (in degrees), and for how long (in days), the outside air temperature is higher than a specific base temperature (18°C or 24°C) and are used for calculations relating to the energy consumption required to cool buildings.

Both HDD and CDD tend to be correlated with latitude, with some exceptions. Some regions with cold or even very cold winter climates, such as Northeast and Midwest United States, as well as parts of Canada and the Russian Federation, can also have a very hot summer lasting several weeks, resulting in relatively high CDD levels and large cooling demands.

To account for the influence of humidity, a heat index can be used to correct CDDs by combining air temperature and RH to determine the temperature as perceived by humans. For instance, the average CDDs number in Indonesia is around 3400, and increases by about 10% on average when the heat index is used. Moreover, rising global average temperatures will lead to a significant increase in CDDs around the world, though at differing rates across regions.

2.2.3.2 Winds

The study of the winds that characterize a given location constitutes an extremely important step in the context of building design in order to improve both the conditions of thermohygrometric comfort and energy performance. The goal is to take advantage of air movements for summer cooling and at the same time protect the building from cold winter winds. The characterization of the wind zone in which the site is located is also essential to determine the characteristics of air permeability, water tightness, and wind resistance of windows, doors and curtain walls, as well as assess the potential for integrating wind power renewable energy systems.

The wind can be defined as a horizontal movement of the air originating from the differences in atmospheric pressure existing between two different areas of the earth’s surface, triggered in turn by differences in temperature and humidity. The displacement of the air masses occurs from the higher-pressure area toward the lower pressure one, until the baric equilibrium has been reached, with a speed that is directly proportional to the pressure difference and inversely proportional to the distance of the points of maximum and minimum pressure. Winds that blow in the free atmosphere over 1000 m in height, called geostrophic winds, are determined solely by pressure differences. Surface winds (up to 100 m from the ground) are instead strongly influenced by characteristics of the territory such as the morphology and the presence of vegetation, water bodies, and obstacles.

To define a wind, it is necessary to know its direction, intensity, and frequency (daily or in percentage terms of time). The direction is that of origin and is expressed through the cardinal points or through the angle measured clockwise from the geographic North. There is also specific terminology for the eight cardinal and intercardinal directions reported in the common rose of the winds. The intensity of the wind is usually measured in meters per second, kilometers per hour or in knots, that is, nautical miles per hour. The greater the distance from the ground, the greater the wind speed due to the decrease in the frictional force exerted by the ground. For reference, outdoor comfort favors calm or light breeze wind conditions, with wind speed below 5 m/s. Conversely, wind turbines require average wind velocity of at least 5–7 m/s to be efficient in electricity production (see [Section 12.3.1.2](#)).

A daily measurement campaign of the direction, speed, and frequency of the wind blowing in a given place (using a cup anemometer, vane, temperature sensor, ultrasonic anemometers, etc.) usually takes place over a period of one year. The collected data can be shown in special diagrams and graphs that describe the frequencies and average speeds detected for each month of the year and for each direction ([Fig. 2.8](#)).

Winds can be defined as local winds, if typical of a specific region following the orography of the place, constant, if they always blow in the same direction even if with different speed (e.g., the trade winds), or periodic, when they blow on the same orientation, periodically reversing the direction, albeit with different speed. The period can be seasonal, as in the case of the monsoons or the Etesi, or even simply diurnal as in the case of the breezes. There are two types of breezes: coastal breezes and mountain breezes.

In addition to field measurements, useful insights on local wind patterns dictated by the neighboring buildings and orography can be obtained by performing computational fluid dynamics (CFD) analyzes, which allow to predict to a great degree of accuracy the current air flows in the intervention context as well as how these will be affected by the proposed design (see [Fig. 2.9](#)), in particular concerning pedestrian wind comfort (PWC).

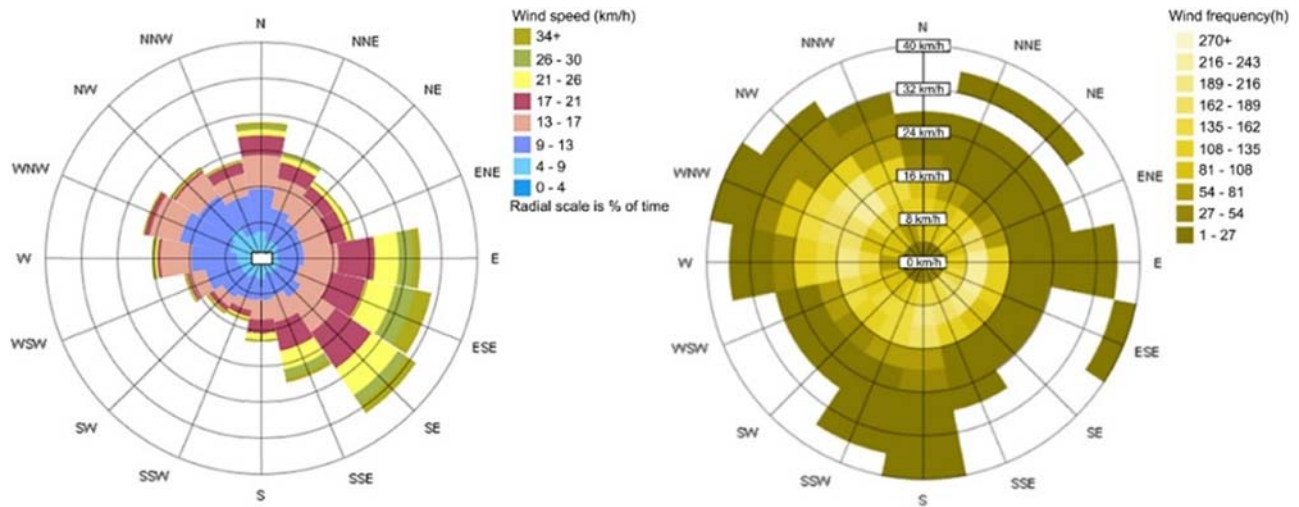


FIGURE 2.8 Yearly wind characteristics diagram.



FIGURE 2.9 Local PWC analysis with CFD software.

Courtesy of SimScale.

In coastal breezes, the wind blows from the surface of the water toward the land during the day and in the opposite direction during the night. These breezes originate from the daily cyclical variation of atmospheric pressure determined by the differences in temperature and, therefore, in the density of the air, which are created as a result of the greater thermal capacity and albedo of water bodies.

Mountain breezes originate from the radiative heat exchange between mountain slopes and the air that laps them, which generates temperature differences between the air masses in contact with the slope and the more distant masses

with equal altitude. This phenomenon causes hot air to rise along the slopes during the day and cold air to descend at night.

Finally, another important classification of winds, relating to the local conditions of a place (individual cities or regions, or even larger macroareas) is that between prevailing and dominant winds. Prevailing winds blow predominantly (and not necessarily with the greatest intensity) from a specific direction in the year, in that given area, city, or geographical area. Dominant winds instead blow from a specific direction with the greatest intensity, in absolute value, in the year, but not necessarily for the greatest number of days.

2.2.3.3 Solar radiation

The knowledge of the apparent path of the sun and the intensity of solar radiation incident during the year on the differently oriented surfaces within the intervention site is an element of extreme importance since the initial stages of the design of a building. Such information is necessary for the correct determination of the floorplan and the orientation of the building, of the size and arrangement of glazing and shading surfaces and of the slope of the surfaces capturing solar energy. These choices are indeed decisive in order to improve the conditions of hygiene, well-being, and thermohygrometric comfort, to reduce the energy consumption of the building and to exploit the solar energy available through passive (greenhouses, Trombe walls, etc.) and active systems (solar collectors, photovoltaic panels).

The identification of the solar path in the intervention site is essential to determine the number of hours of sunshine available during the year, also in relation to any shading phenomena due to neighboring obstacles, as well as the angle of incidence with which the solar radiation will affect the different facades or penetrate inside.

The position of the sun in the celestial vault with respect to the horizon plane is determined by two angles (see Fig. 2.10):

- the solar elevation angle (h), or altitude angle, measured between the line joining the apparent position of the sun with the point where the observer is and its projection with the horizon plane. Conversely, the solar zenith angle θ_z is the angular distance of the sun from the vertical ($h = 90^\circ - \theta_z$), with zenith defined as the point of the celestial vault perpendicular to the place where the observer is located;
- the solar azimuth (α) angle, formed on the plane of the horizon by the projection of the aforementioned conjunction and by the line that goes from the observer to the South in the northern hemisphere, or the North in the southern hemisphere. The solar azimuth is measured clockwise in the northern hemisphere and counterclockwise in the southern one, using projections on the local horizontal plane. It is negative in the morning (to the east), equal to 0° or 180° at noon, and positive in the afternoon (to the west), around the globe. Solar azimuth is different from the geographical azimuth, measured clockwise from the north, across the globe.

The value of these two angles depends on the latitude, the time of day and the day of the year. In the northern hemisphere, the angle of elevation is maximum on 21 June at noon. At the same hour, the angle of elevation reaches its minimum value on 21 December. As latitude increases, the elevation angle decreases progressively, in fact the sun reaches the zenith during the year only at the latitudes between the tropic of Cancer ($23^\circ 27' \text{ N}$) and the tropic of Capricorn ($23^\circ 27' \text{ S}$). In same hemisphere, the azimuth angles of sunrise and sundown increase with latitude and are maximum in the summer months (21 June). The apparent motion of the sun in the celestial sphere can be described by a solar map projected on either the horizontal plane (polar diagram) or on the vertical plane (cylindrical diagram). The coordinate system used is centered in the observer and has the horizon plane as its reference. There is a diagram for each

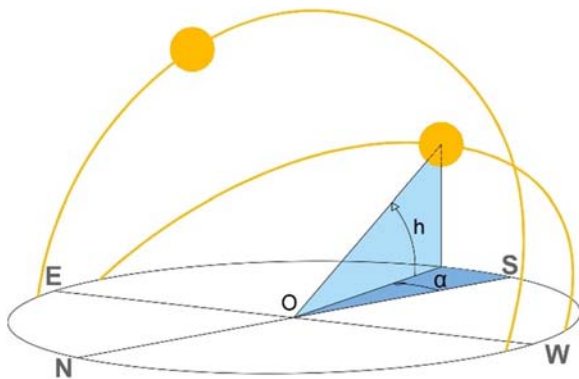
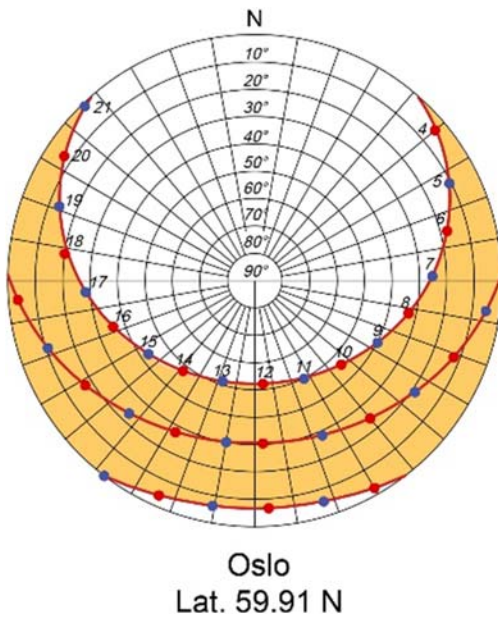
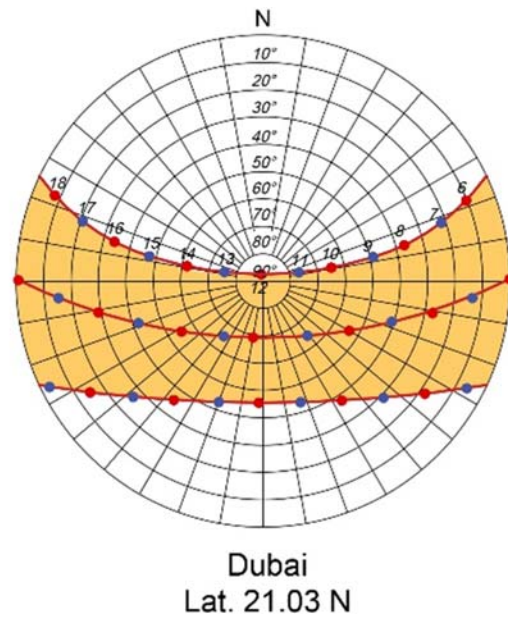


FIGURE 2.10 Graphical definition of solar elevation and azimuth angles.



Oslo
Lat. 59.91 N



Dubai
Lat. 21.03 N

FIGURE 2.11 Solar diagrams for Oslo and Dubai cities.

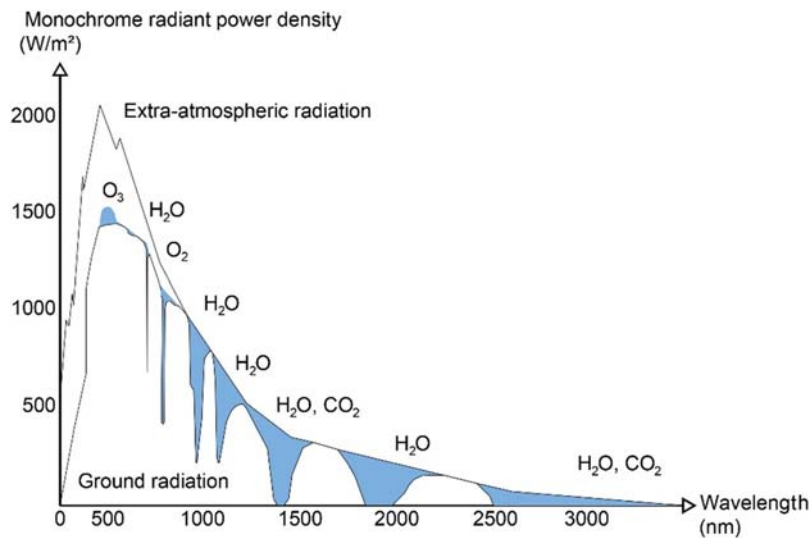


FIGURE 2.12 Influence of earth's atmosphere on the spectrum of light radiation.

latitude and those for the northern hemisphere can be used for the corresponding southern latitudes by mirroring the image and replacing the north with the south (see Fig. 2.11).

Solar diagrams have several useful applications. They allow to determine if and when a certain portion of a building will see the sun, as well as from what direction and at what angle of incidence the sun's rays will arrive at different times of the year, useful for knowing both the intensity of the incident solar radiation and whether the rays will be transmitted or reflected by a glass surface. Solar diagrams also allow to predict the shadows cast on a given surface by other surrounding buildings, trees, or mountain ranges (constrained sunshine) and therefore can be used for the sizing and positioning of different shading building components (screens, canopies, curtains, etc.).

Passing through the atmosphere, radiant energy from the sun undergoes three orders of changes, due to the effect of gases, water vapor, water droplets (clouds), and suspended solid particles (aerosols) that make up the atmosphere (see Fig. 2.12):

- a substantial reduction, as radiation is partly absorbed and partly reflected outwards;
- a variation in the spectral distribution, due to the selective behavior of some of the components of the atmosphere (O_2 , O_3 , CO_2 , H_2O);

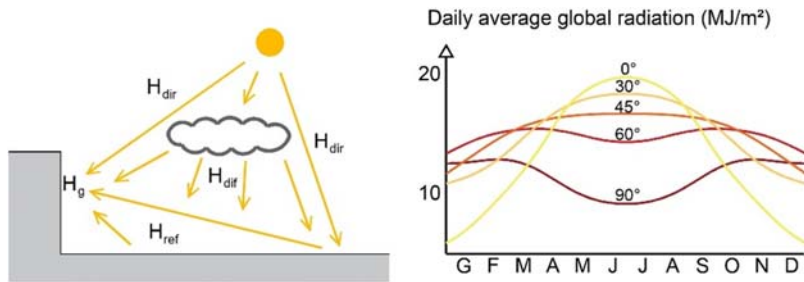


FIGURE 2.13 Composition of incident radiation (left) and density according to the angle of the surface (right).

- a dispersion in the atmosphere (scattering) due to the effect of multiple reflections, causing the radiation coming from the entire celestial vault to reach the ground (diffuse radiation) in addition to that coming directly from the direction of the sun (direct radiation).

The magnitude of these three phenomena depends on the thickness and composition of the layer of atmosphere crossed by the radiation. In turn, thickness depends on the altitude above sea level and on the position of the sun in the sky (dictated by latitude of the place, day of the year, time of day), all known and easily measurable quantities. The higher the sun position in the celestial sphere, the shorter the path that solar energy will travel to cross the atmosphere. Conversely, the lower the sun is on the horizon, the longer the path through which the atmosphere passes and therefore the lower the intensity of direct solar energy, due to increased scattering. As latitude increases, the elevation angle is reduced and, consequently, the layer of atmosphere crossed by sun's rays cross elongates, causing a decrease in the energy that reaches the ground. This is related to the decrease in altitude and, in particular, to the fact that the lower layers of the atmosphere are the most dense and difficult to penetrate. At the latitude of southern Europe or northern United States, in the absence of meteorological events, the solar irradiation available in summer is more than three times that in winter. As the latitude decreases this difference is reduced, at higher latitudes it is accentuated.

Concerning the composition of the atmosphere crossed by sunrays, it is difficult to evaluate as it is extremely variable both over time and with the location and is influenced both by meteorological conditions and by the presence of substances introduced as a result of natural and anthropic phenomena. At equal latitudes, in fact, more or less pronounced increases in the scattering phenomenon may occur on the basis of local sky conditions and, consequently, entail different contributions of the direct and diffuse components of radiation. Over the course of the year, global solar radiation can therefore be subject to significant daily variations, particularly in places where the variability of weather conditions is more pronounced (actual sunshine).

The power density incident on a surface (energy incident on the unit of area in the unit of time, W/m^2) also depends on the position of the plane to which the surface belongs (see Fig. 2.13). In particular, the direct component (or direct irradiance H_{dir}) depends on the angle of incidence (angle between the normal to the plane and direction of the radiation), being in maximum for a zero angle of incidence (normal radiation). The diffuse component (or diffuse irradiance, H_{dif}), in the hypothesis that it comes uniformly from the entire celestial sphere, depends only on the fraction of the sky seen by the surface, and therefore on its inclination with respect to the horizontal plane, being maximum for a surface horizontal which sees the whole celestial vault. In the case of a nonhorizontal surface, the component of radiation reflected by the ground (reflected irradiance, H_{ref}) must be added as a third component, which depends on the average coefficient of reflection of the ground (albedo) and, again, on the angle of inclination of the surface with respect to the horizon.

2.2.3.4 Sky conditions

Another important climatic parameter that needs to be investigated is that of the conditions of the sky over the course of the year in the intervention area, from which the natural lighting possibilities of interior spaces will derive.

Results from this analysis will provide inputs to optimize the choices on the location, orientation, shape and rooms layout of the building, the sizing and arrangement of openings and shading, the colors of the interior surfaces, the relationships with vegetation and with the urban context. The data collected on the availability of natural light will also be used in the final design for the verification of the minimum lighting levels of the internal environments required by relevant building codes.

Interiors daylighting comprises both a direct share and an indirect share. The first derives from the radiant energy in the visible spectrum ($380 \text{ nm} \leq \lambda \leq 780 \text{ nm}$) which comes directly from the Sun or is diffused from the celestial

sphere. The various wavelengths in the visible range define the various colors of light, with maximum sensitivity of the human eye in daytime vision obtained for wavelengths equal to 555 nm, corresponding to the yellow-green color.

Indirect lighting, on the other hand, is due to the amount of light that derives from the reflection of radiant energy on the surfaces. It varies mainly according to the color of the reflecting surfaces, being maximum for white and almost zero for black.

Differently from sun radiation analysis, the study of daylighting considers the celestial sphere as the primary light source instead of the sun. This is because the latter may cause glare phenomena with harmful consequences to sight (scotoma, blepharospasm, retinal lesions, etc.) and to work activities by penetrating inside the buildings. Much more suitable for human activities is the diffused light coming from the celestial sphere, expressed in terms of luminance, which determines a more uniform and less dazzling lighting; this source, of course, is affected by the latitude of the site, the season, the time of day, the current air purity, and the state of the sky (whether clear or cloudy).

Luminance is defined as the light intensity emitted in a given direction by a luminous or illuminated surface. In other words, it expresses the effect of brightness that a surface produces on the human eye, be it primary source (e.g., a lighting device) or secondary (e.g., a tabletop that reflects light). This magnitude is measured in candelas per square meter (cd/m^2). The luminous flux in turn is defined as the flux of light produced by a light source over the solid angle and is measured in lumens ($\text{lm} = \text{cd} \cdot \text{sr}$). The term illuminance, on the other hand, indicates the quantity of luminous flux that strikes a given surface and is measured in lux (lm/m^2).

A satisfactory illumination of an indoor space shall provide even a small amount of diffused light, which intensity will depend directly on the portion of the celestial sphere visible from within. Therefore, the amount of daylighting available inside is only a fraction of the outside lighting levels, filtered by the building envelope and by the surfaces inside the room itself, and depends on the following parameters:

- the luminance levels of the celestial sphere at different times of the year and day in relation to the possible sky condition;
- the frequency with which the different sky conditions occur (see Fig. 2.14): in Paris, for example, the sun is not visible for about half of the year;
- the levels of illumination on the horizontal plane placed in the observation site at different times of the year and day corresponding to the sky conditions themselves (in overcast conditions, the maximum level of illumination that can be expected on the horizontal plane is equal to at 50,000 lux);
- the visibility of the sky from the observation point, as constrained by any obstacles in front of it.

The determination and distribution of the luminance of the celestial sphere characteristic of a place (on which the levels of illumination in the area depend) is normally obtained by referring to the standard sky models, or types of sky, defined by the Commission International de l'Éclairage (CIE). There are five sky models divided into two main categories in relation to the visibility or not of the sun. Sun visible sky models include the “clear or blue sky” (no clouds) and the “intermediate clear sky” (partly cloudy with visible sun). The models without visible sun include the “intermediate overcast” and the uniform or variable luminance “overcast.” The fifth model is defined as “medium” and represents the situation in which the sky condition continuously changes from an intermediate clear sky to intermediate overcast sky. The overcast sky model is considered as the reference standard for calculating the average daylight factor of an indoor space in order to guarantee the necessary conditions of hygiene and health of the occupants.

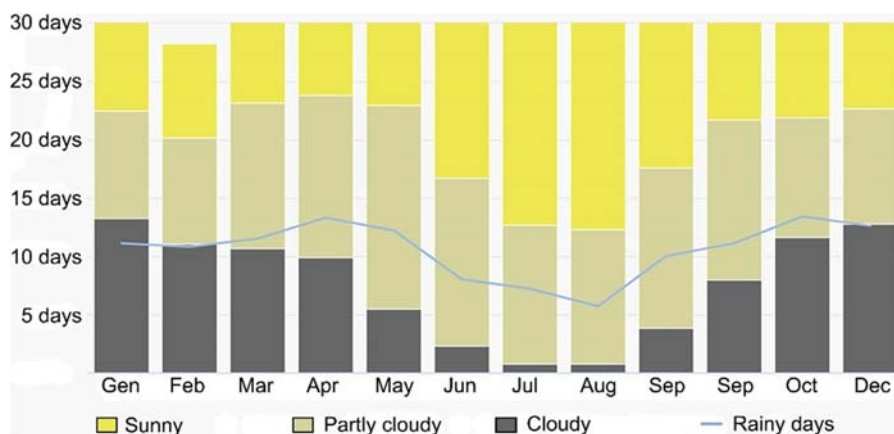


FIGURE 2.14 Sky conditions diagram for a given location (example).

With overcast sky conditions the luminance of the sky in the northern part is greater than with clear sky because the amount of light diffused by the atmosphere is greater. North-facing rooms, without direct lighting, are therefore more illuminated under an overcast sky than under a clear one. These spaces also benefit from more stable lighting, with minimal variations as the state of the sky changes. On the contrary, south facing rooms are brighter in clear sky conditions.

As for the study of sunshine, the evaluation of the visibility of the sky from the place of analysis requires to survey and characterize all external obstructions due to the orography of the terrain (embankments, hills, etc.), vegetation, surrounding buildings (existing or permitted by current urban planning).

2.2.3.5 *Extreme weather events*

A further phase of the climate analysis is assessing the potential risks and vulnerabilities to extreme weather events in the region and building site also taking account the climate change process underway. According to Working Group II on the IPCC Fifth Assessment Report (AR5), an extreme weather event is defined as an event that is rare at a particular place and time of year. In particular, an extreme weather event would normally be as rare as or rarer than the 10th or 90th percentile of a probability density function estimated from observations. Even if a pattern of extreme weather persists for some time, such as a season, it may be classed as an extreme climate event, especially if it yields an average or total that is itself extreme (e.g., drought or heavy rainfall over a season). The main categories of extreme weather events include pluvial flooding, fluvial flooding, windstorms, coastal flooding, droughts, heatwaves, hail, and snow. With the growing awareness and concern over extreme weather, measures shall be taken to design buildings in such a way that, when such events occur, the damage caused to the building structure and its occupants is minimized or avoided altogether and future potential climate change impacts can be mitigated by the adaptive capacity of the system.

The ISO 14091:2021 standard “Adaptation to climate change—Guidelines on vulnerability, impacts, and risk assessment” provides some guidance for evaluating the risks related to potential impacts of climate change by describing how to understand vulnerability and how to develop and implement a sound assessment for both present and future climate change risks. The main components envisioned for a risk assessment are: the hazard; the exposure of a given system to the hazard; the sensitivity of the system to the hazard; the (potential) climate change impact, that is, risk without adaptation; and the risk with adaptation (in the future).

The subject system may be a region, a community, a household, a supply chain, an economic sector, a business, a population group, an ecosystem, an infrastructure, and their components. The sensitivity of the system (e.g., land-use, age of the population) will determine the extent to which climate change hazards (e.g., drought, flooding, heat) affect it. Impact is a function of both the exposure and the sensitivity of the system to hazards. The adaptive capacity influences the degree to which the potential impact becomes a tangible risk, whereas the vulnerability of the exposed system can be expressed as a combination of an organization’s sensitivity and its lack of adaptive capacity. Nonetheless, though hazards are defined as sources of potential harm (e.g., heatwaves causing agricultural losses), they can sometimes lead to opportunities (e.g., higher temperatures leading to additional tourism opportunities).

Objectives of the climate change risk assessment can include the following:

- raising awareness of the consequences of climate change;
- identification and prioritization of risks to be addressed;
- identification of entry points for climate change adaptation intervention;
- if repeated over time, tracking changes in risk and monitoring adaptation.

To conduct the analysis, it is necessary to consider historical extreme weather events in the area and to consult any available risk maps, drought management plans, and river basin management plans. Site-specific factors include exposure to high wind speeds, excessive solar gain and UHI effects, proximity of mountainous regions, proximity of steeply sloped land masses, and proximity to the sea or watercourses. Public reports, weather databases, climate change projections, and insurance analyses can be valuable sources of information.

At the level of the single building site, some basic suggestions for identifying relevant risks are following:

- high-speed winds: factors include how exposed the site is, potential positive shielding by nearby hills, mountains, forests, and the surrounding built environment, how tall the proposed building will be, possible increased wind speeds at ground level caused by channeling of wind that impacts directly with flat built surfaces on large and tall buildings in the surrounding area;
- pluvial flood risk: factors in the surrounding topography include storm water drainage, presence of imperviously paved areas upstream and in the surrounding area, presence of stormwater drains combined with main sewers, positioning of overflows, records of recent flood events affecting the specific site;

- fluvial and coastal flood risk: factors include proximity of the building site to natural watercourses and records of recent flood events affecting the specific site;
- wildfires: in fire exposed settings, factors include the susceptibility of the surrounding area to droughts, the extent of vegetation, and recent relevant events. In cities, the focus would likely be on intake air filters performance.

European literature on potential changes to weather events includes the 2016 report as well as the “Urban Adaptation Map Viewer” produced by the European Environment Agency. Authoritative climatic projections for 2030 and 2050 are available as weather files for building dynamic simulations and modeling, to be based on the UN IPCC “mitigation” (SRES E1 or RCP 6.0) emissions scenario or, as a second worst case, “medium-high” (SRES A1B or RCP 2.6) emissions scenario. In the absence of suitable future projections at national, regional or local level, design reference weather files derived from extreme hot and cold weather events in the last 20–30 years may be used.

2.3 Holistic design strategies

In order to achieve the maximum environmental, social, and economic sustainability, the whole design process has to follow a holistic approach oriented toward the optimization and the best harmonization of the four main elements that characterized a building and that together concur in defining the quality of any built environment: geometry, envelope, systems, and people.

All design strategies and choices, articulated according to successive levels of technical analysis—concept, schematic, and detailed design—concern, in fact, the following aspects:

- typological (geometry), relating to the shape and orientation of the building, the positioning and sizing of the openings and the distribution of internal spaces;
- construction (envelope), concerning functional models, construction materials and products, and construction methods;
- technological (systems), relating to building equipment and renewable energy sources;
- management (people), regarding the monitoring, control, and maintenance systems of all building components.

It is evident that the final quality of the project can only arise from a correct balancing of the choices made in all the aforementioned levels through an integrated approach that is able to take into account from a methodological point of view the programmatic, requirement, planning, and environmental frameworks of the intervention.

Indeed, the design activity is not a straightforward task and there are many elements that need to be solved, some of which often conflict with others. All design choices must also consider the strategic objective of achieving a purposeful quality, meant both as the temporal duration of the associated characteristics and how that specific quality may or may not address effectively the needs of users and the characteristics of the context of intervention. Building design must in fact be based on principles of optimization in the use of materials and economic resources, and of easy maintenance of the envisioned performance over time. Therefore, each choice concerning technical and technological solutions must always respond to the need to meet the actual quality requirements expressed by the interested parties, in order to achieve an optimal level of performance in relation to costs.

Task of the designer is therefore to identify the specific technical solutions equipped with the technological specifications necessary to ensure that the various technological units, the environmental systems, and the building as a whole meet the quality expectations with reference to that specific environmental context. From this point of view, the numerous technical and technological solutions available today can allow not only higher performance but also the creation of new and ever more stimulating architectural languages (Luisa, Cabeza, & Marta Chàfer, 2020).

2.3.1 Building geometry

The geometry of a building and its orientation in space is generally the result of a complex design process in which different components interact: urban, esthetic, functional, ergonomic, technical, economic, and environmental.

The choice of the shape is a fundamental step for the quality of the building to be constructed, both in terms of architectural value and in terms of its well-being, efficiency, and economic competitiveness. Whereas the thermophysical properties of the building envelope determine the gain or loss of thermal energy, its shape determines the size of the exchange surface, and the orientation determines what areas receive direct solar radiation and which may be affected by the wind, in turn determining the potential use, or protection, of solar radiation and winds. Sustainability should therefore be primarily pursued through a design mindful of the environment context and aimed at architectural solutions in

which shape and orientation of the building, interiors layout, and placement of the windows have a profound effect on the energy behavior and indoor comfort, favouring natural lighting and ventilation, winter daylighting and exploitation of renewable energy, reducing energy losses in winter and overheating in summer (passive solar design).

In natural history, it is a universal rule that only those species that are in equilibrium with their habitat, and are endowed with an enclosure suitable to withstand all the internal and external forces to which it is exposed, are suitable to survive. That organic shape is the result of force fields in equilibrium.

In technique, all forms are instead derived from their intended use, starting from the first tools, such as the hammer or the plow, up to a modern turbine. Gradually, from experiment to experiment, the shape has developed through a long process of adapting the object to the needs dictated by its use, the nature of the material it is made of, and the tools used in the production process. The technical shape is the result of a collective effort aimed at obtaining maximum efficiency. Form follows function.

In architecture, form can become a work of art only if it is elevated by the creative instinct to a sphere in which it follows the rules of reason but acquires a further meaning beyond mere calculus. Within the current scenario oriented to the promotion of sustainable construction, the aim of the design must be to mediate between form, function, and efficiency in order to achieve the highest “building quality,” in a most contemporary sense of formal-spatial, technological, technical, environmental, maintenance, operational, and purposeful quality: form follows sustainability.

The ultimate performance of a building is strongly influenced by its shape and orientation because they dictate numerous interactions with the environmental components of the site. The microclimate of the context is in fact determined by local winds (characterized by their own intensity, directions, and periodicity), by the availability of solar radiation (linked to orientation, exposure, and to any natural and artificial barriers), by temperature and relative humidity (also variable in relation to anthropogenic factors). In addition, the influence on the internal environment of exogenous factors such as noise and atmospheric pollution can also be controlled through the geometry and orientation of the building.

A correct orientation, an appropriate shape of the building and a rational spatial and functional organization of the internal environments can allow substantial energy savings (30%–40%) without additional costs and to significantly improve the conditions of thermal, acoustic, and visual comfort and IAQ inside buildings, or in the most used spaces. Shape and orientation, along with the location, contribute to constitute a “building position income,” which is higher the more it ensures better conditions of well-being of the occupants, while reducing the environmental and economic costs of operation.

In relation to the possible advantages deriving from shape and orientation, the input elements to design essentially consist of the microclimate, sunshine, daylighting, natural ventilation, and the acoustic climate of the site.

In particular, the design choices at the typological level oriented to the reduction of energy requirements concern:

- the optimization of the ratio between the dispersing surface and the heated volume of the building, favouring shapes able to optimize the thermal exchanges with the external environment both in winter and in summer;
- the orientation of the building to maximize winter solar gain, reduce it during summer, favor natural lighting of interiors, promote the integration of renewable energy sources;
- positioning and sizing of the openings relative to the orientation of the facades and the intended use of the interior space, in order to increase winter solar gain, reduce it during summer and ensure a high level of daylighting and ventilation;
- the distribution of rooms and the layout of internal spaces in relation to the different orientations, in order to maximize the conditions for thermal and visual comfort;
- the choice of solutions for the improvement of the microclimate, such as green system, vegetable barriers, reduction of impermeable surfaces.

2.3.1.1 *Massing*

The shape of the building is primarily dictated by the territorial and urban context in which it will be built (size and shape of the lot, presence of other buildings, regulatory constraints, etc.). However, there are still numerous degrees of freedom that make the shape of the building a decisive design variable, capable of influencing its performance over the entire life cycle.

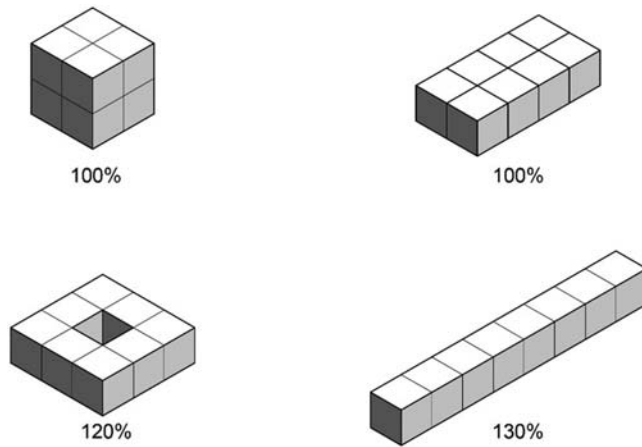
As regards, in particular, the relationship between the shape of the building and energy performance, it is necessary to make two preliminary considerations. First, there is no predetermined shape capable of optimizing performance: the optimal shape varies according to the climatic characteristics of the place (air temperature, solar radiation, ventilation). Second, for a given shape of the building, the dimensions and its orientation are equally important variables in the

TABLE 2.20 Massing ratios used for building optimization.

Name	Definition	Units
Aspect ratio	w/l	%
Shape factor	A_e/V_c	m^2/m^3
Rate of vertical exposure	A_{vs}/V_c	m^2/m^3
Rate of horizontal exposure	A_{hs}/V_c	m^2/m^3
Surface to floor ratio	A_e/A_c	%
Building porosity	V_c/V_{ev}	%
Building slenderness	A_f/h	m

Indices: w , width in m; l , length in m; A , area in m^2 ; V , volume in m^3 ; h , height in m.

Subindices: e , envelope; c , conditioned; vs , vertical surfaces of the thermal envelope; hs , horizontal surfaces of the thermal envelope; ev , building empty volume; f , building footprint.

**FIGURE 2.15** Shape factor values of different building configurations.

search for the best energy efficiency. Shape, size, and orientation therefore represent closely related variables that must be considered jointly within the design process. From the energy point of view, the goal is to identify design solutions capable of reducing winter heat loss and optimizing solar heat gains and natural ventilation, both in winter and in summer. Different form ratios are used in the optimization process of the energy performance of buildings (see Table 2.20).

Among these, the most commonly used is the surface-to-volume ratio, also called shape factor, defined as the ratio between the dispersing surface (A) of the envelope (given by the sum of the surfaces of the vertical closures and the upper and lower horizontal closures) and the overall volume (V) of the building ($F = A/V$). The smaller the value of the form factor, the lower the heat loss since the smaller the surface of the envelope in relation to the internal habitable space to be heated (see Fig. 2.15).

Equal values for the shape factor may correspond to numerous morphologies and different surfaces values of facades and roof. As winter and summer thermal gains due to solar radiation will vary according to the exposed surfaces, the shape factor must always be studied in close relation with the height and aspect ratio (width/length) and with the area of horizontal (A_{hs}) and vertical (A_{vs}) surfaces of the building in order to optimize the overall energy balance as a function of the climatic characteristics of the place (see Fig. 2.16).

Such optimization problems can now be effectively addressed, thanks to parametric modeling and generative design (see Section 6.4). The optimization of the form factor will also have to take into account the lighting needs of the interior environments. Normally, in fact, a shallower floor plate allows for deeper daylight penetration but determines an increase of the shape factor.

Another important factor to take into consideration, especially in hot-dry climates, is the ratio between full volume and empty volume, defined as porosity, which varies according to the presence of semi-open included spaces such as

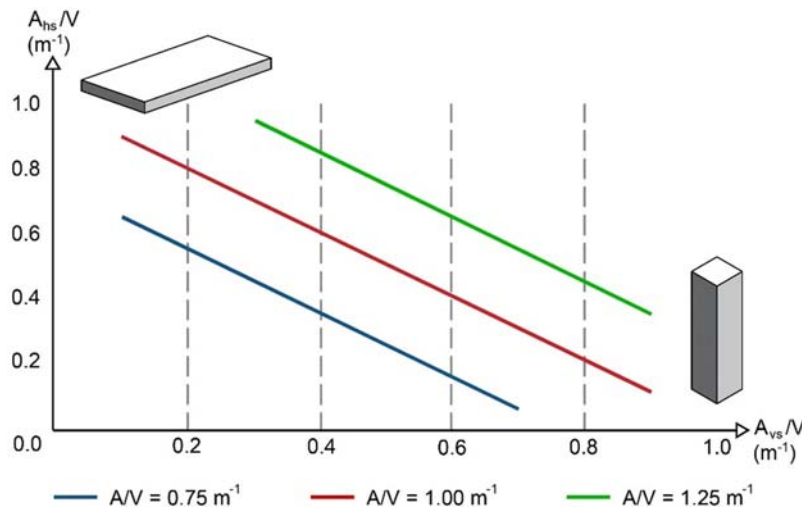


FIGURE 2.16 Inverse variation of (A_{vs}/V and A_{hs}/V) for geometries of equal (A/V) value.

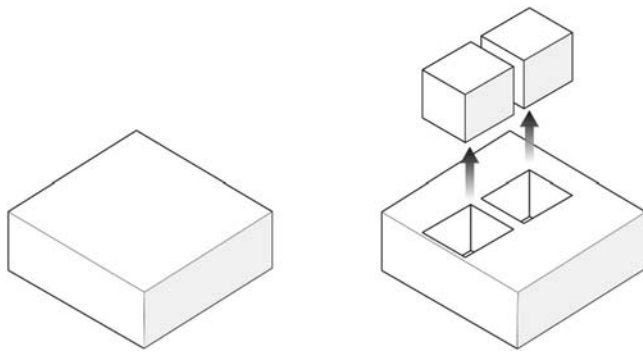


FIGURE 2.17 Definition of empty spaces within the building mass (porosity).

patios (see Fig. 2.17). With equal volume, a building with a high porosity has a higher shape factor, but nevertheless makes ventilation and lighting of the internal areas easier.

On the basis of these considerations, it is possible to formulate some general indications for determining the massing in relation to the local climate.

In hot and dry climates, forms closed toward the outside are to be preferred, with large shaded internal courtyards to promote natural ventilation due to the difference between external and internal temperatures. In such climatic conditions, in fact, the aim of the design must be to protect the external surfaces from the excessive incidence of solar radiation, to increase the level of humidity and to promote the ventilation of the interiors. The latter can be further favored through adequate openings capable of capturing refreshing winds and breezes. To favor the thermal dispersion of the accumulated daytime heat, domed or vaulted roofs are preferred. Porticos also allows for the creation of shaded areas, which are indispensable in hot climates. Most used rooms should be located in the internal area and protected by shading systems, where water pools, fountains, and other features can be functional choices to rebalance the humidity and reduce air temperature. Shielding openings with grates also responds to several environmental functions: control of the passage of light, control of the air flow, reduction of the temperature of the air flow, increase in the humidity of the air flow, protection of privacy.

In hot humid climates, the shapes of the building recall those used in hot-dry countries, but the need to obtain greater ventilation favors more elongated shapes in the East-West direction, articulated and raised from the ground. Use of vegetation close to the building is also advised, with the function of controlling the microclimate and protecting from excessive direct solar radiation.

In cold climates, the primary goal is to make the shape of the building as compact as possible to reduce the shape factor. To avoid the dispersion of internal heat, it is necessary to minimize the size of windows on the sides not facing south. At the same time, it is advisable to expand the building areas on the side most exposed to sunlight and thereby place most used spaces. Roof choice must avoid the accumulation of water and snow and favor pitched roofs, with

greater or lesser slope based on the calculation of precipitation. For the ground connection, having part of the building on the north side underground can further reduce heat loss.

In temperate climates, the lower environmental loads allow more freedom of forms. Nonetheless, slightly elongated shapes along the East-West axis are preferable, characterized by large windows which, suitably oriented, allow to exploit solar gain in winter. In summer, openings shall be suitably shielded in order to prevent overheating. To enjoy the temperate climate, external surfaces can be equipped with large openings and balconies.

Concerning high-rise buildings, such as skyscrapers, the choice of shape affects the aerodynamic resistance to wind load in addition to energy problems. Therefore, the boxy shape used until the end of the last century to minimize the costs of construction and maximize leasable area of the building has been replaced by tapered or twisted forms, or shapes characterized by large openings able to reduce resistance to winds and oscillations, with consequent savings in the use of structural materials. Indeed, the sharp edges of the conventional parallelepiped massing tend to detach wind vortices from the facades which may become self-sustaining and create substantial stresses on the building due to the imbalances of the forces at the basis of the structural calculation. More aerodynamic shapes can help reduce the phenomena of detachment of air vortices that can affect the stability of the tallest skyscrapers. For the Shanghai Tower by Gensler, CFD and wind tunnel tests allowed to identify the 120-degree torsion of the external façade as the most convenient, allowing a reduction in wind loads by 24% and savings on structural materials quantified in 58 million dollars. In The Bow skyscraper in Calgary by Foster & Partners, the rotation of the convex façade toward the prevailing wind allowed to minimize the structural load therefore reducing the amount of steel necessary for the construction of the diagrid system used for the building.

2.3.1.2 Orientation

As for the architectural shape, the choice of the orientation of the buildings depends on many factors: the local topography, any panoramic views, the solar radiation, the intensity and direction of the winds, the acoustic climate, the air quality, and the privacy requirements. The orientation and number of exposures can greatly influence the future performance of the building and the comfort of the interior spaces, therefore affecting the energy costs of management and, indirectly, the commercial value of the property. Indeed, the type of orientation dictates the thermal and luminous effects of solar radiation, the possibility of benefiting from natural ventilation, the quality of the acoustic climate of the indoor environments, as well as the possibility of fully exploiting the sun and wind for the energy production.

The choice of orientation is the result of an optimization of the various factors involved with respect to the characteristics of the place, the intended use of the building, and the objectives to be achieved in terms of well-being and energy performance. The orientation can be analyzed on three levels: whole building, building's zones, and glazed areas. This choice must be made from the very beginning and can now be supported through simulation and generative design tools that allow to optimize shape and orientation in relation to the building quality objectives set by the designer.

Orientation to the sun

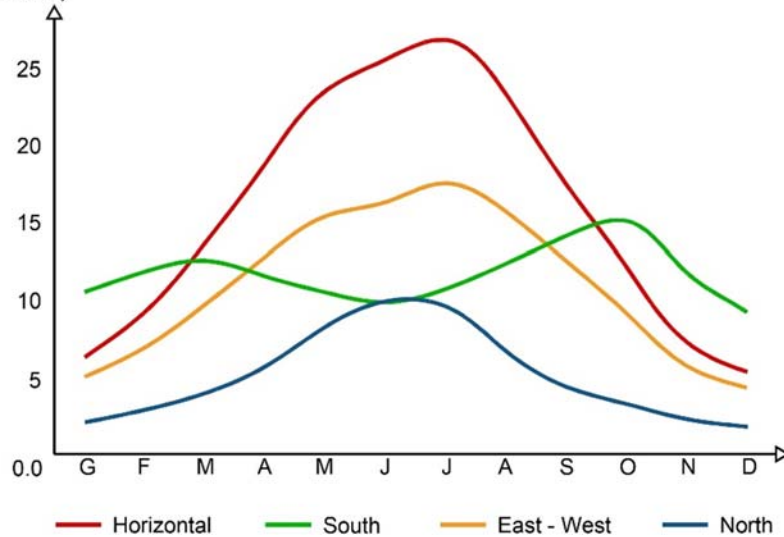
Right after the site topography, which establishes the geometric constraints, the first factor to consider in choosing the orientation of a building is certainly that of its exposure to direct solar radiation. The goal is to orient the building and arrange the rooms to exploit solar radiation to improve the conditions of thermohygrometric comfort, daylighting, hygienic, and psychological well-being, to reduce the energy needs of the building and to maximize the production of electricity and heat from renewable sources. The main aspects to be taken into consideration therefore concern:

- the hours of direct solar radiation on the roof and the different facades during the year according to the location and the presence of any obstacles;
- the thermal effects of solar radiation on the different facades during the year, also taking into account the temperature of the outside air at the time of insolation;
- the degree of penetration of sunlight into the rooms during the year.

In relation to the climate, the objective is to maximize solar gain in winter and to minimize it in summer, to avoid glare phenomena inside the rooms and to ensure uniformity of sunshine between the different facades in the case of double loaded corridor buildings. The amount of heat received by a given facade essentially depends on two factors: the duration of the insolation and the inclination of the incident sun rays at that time. In case of unobstructed insolation, sunlight duration depends on the latitude of the place, the day of the year and the orientation of the façade (see [Table 2.21](#)). In the Northern hemisphere, the South-facing facade receives the highest number of hours of sunshine

TABLE 2.21 Annual insolation values for central Europe.

Façade orientation	Annal insolation (h)	% of sunshine hours
South	3.740	83%
South-East—South-West	3.124	71%
East—West	2.224	50%
North-East—North-West	1.290	29%
North	756	17%

Daily average global radiation
(MJ/m²)**FIGURE 2.18** Incident radiation of facades of different orientation (latitude of Rome).

during the year (83%), followed by the South-East and South-West exposures (71%), while the Northern exposure receives the least amount (17%). Below are the hours of sunshine per year regarding the individual exposures for Central Europe expressed in absolute value and as a percentage of the annual total (4448 hours).

The energy of solar radiation per unit of surface is maximum in the case of rays incident orthogonally on the surfaces themselves, progressively reducing with the cosine of the angle formed with the normal to the plane. In the winter season in the Northern hemisphere, the sun has a lower elevation angle on the horizon compared to the summer season and will affect vertical surfaces orthogonally, maximizing its caloric intake per unit of surface. The opposite occurs in summer when the sun, high on the horizon in the central hours of the day, affects the facades with rays having a low angle of incidence, thus providing a limited caloric effect (see Fig. 2.18). This means that the facades facing South are those that make the most of solar radiation during the year, being the hottest in winter and the coolest in summer, while enjoying the greatest number of hours of sun overall. In winter, the South facade in fact exploits the entire daily solar radiation (from sunrise to sunset) which, low on the horizon, is able to provide an energy contribution that is more than double that of the East or West facades. In summer, on the contrary, when the sun's rays, high on the horizon, reach tangentially on the facade, the caloric intake is more than 40% lower than that of the East or West exposures. Furthermore, shielding of summer solar radiation with overhangs or awnings is easier in the South. For these reasons, the exposure to the South is ideal not only to ensure adequate thermal comfort, but also for the reduction of energy consumption through the exploitation of solar energy with passive or active systems.

East and West facing facades are instead cold in winter (when the sun rises in the South-East and sets in the South-West) and warm in the summer (when the sun rises in the North-East and sets in the North-West) because they are hit for several hours of the day by solar radiation with a very high angle of incidence with respect to the façade plane. Furthermore, as the sun is low on the horizon for many hours of the day, shading of the glazed surfaces is more complex (vertical screens must be installed).

The East and West exposures, although identical in terms of sunshine hours and calories received during the year, are quite different as regards the thermal effects of the air temperature. In the case of the eastern facades, the cooler morning air absorbs part of the radiant heat received from the wall; on the west-facing facades, however, the solar radiation received is aggravated by the warm afternoon air, making them particularly hot in summer. Furthermore, the summer heat received by West-facing walls during the afternoon is transferred inside at night, raising the internal air temperature and disrupting sleep if these spaces are bedrooms.

As for the other exposures, South-East and South-West facades present the greatest regularity of insolation over the year, with minimum variation in both the maximum daily intensity and the quantity of energy received in the day. On the other hand, North-East and North-West facades show the greatest fluctuations in maximum daily intensity as well as daily energy received during the year. These facades are cold from September to April. North-facing facades, finally, receive very little solar radiation, are often exposed to cold winter winds, and are more subject to heat loss from the building envelope. As regards the roofs, the amount of radiation received on the horizontal surface during the summer exceeds that received by all the facades; during the winter, this quantity is higher than that of the North, East, and West-facing facades but lower than that received by the Southern facades.

Therefore, for a single loaded corridor building, a rectangular plan with the main axis of the building oriented along the East-West direction is advised in order to maximize winter thermal gains and reduce energy inputs in summer, both in cold climates (where the goal is to maximize winter thermal gains) and in warm climates (where the goal is to reduce summer thermal gains) (see Fig. 2.19). This orientation allows to benefit from a large South-facing facade which, in addition to an improvement in the thermohygrometric climate of the environments, allows the possibility of exploiting incident solar energy through passive solar systems (in cold climates) and active solar systems (thermal or photovoltaic) to be placed on the facades or on the roof.

On the other hand, a rectangular plan increases the shape factor (S/V) compared to a square plan with the same volume, consequently increasing the heat exchanges through the envelope due to the differences in air temperature and the solar radiation. Even for more compact forms, the best orientation is still East-West. In certain local situations (morning fog, shadows brought by hills), it may be advisable to rotate from South to West of $5-10^\circ$. In general, rotation up to 15° does not lead to significant reductions in thermal gain and rotations up to 30° are still considered acceptable.

A solution to be absolutely avoided is that of a rectangular plan with the major axis oriented along the North-South direction. This orientation, in fact, implies the minimum energy intake in winter and the maximum intake in summer, making it unsuitable for both cold and hot climates. Narrow buildings with longitudinal facades toward East and West also require more energy for artificial lighting, due to the nonuniformity in natural lighting that can be found between morning and afternoon. The annual energy need for lighting is in fact minimum for buildings with a rectangular plan with the main axis oriented along the East-West direction and is further reduced the narrower the shape of the building is.

In coastal, sea or lake sites, the main axis of the building should be oriented parallel to the coast in order to take advantage of the sea and land breezes.

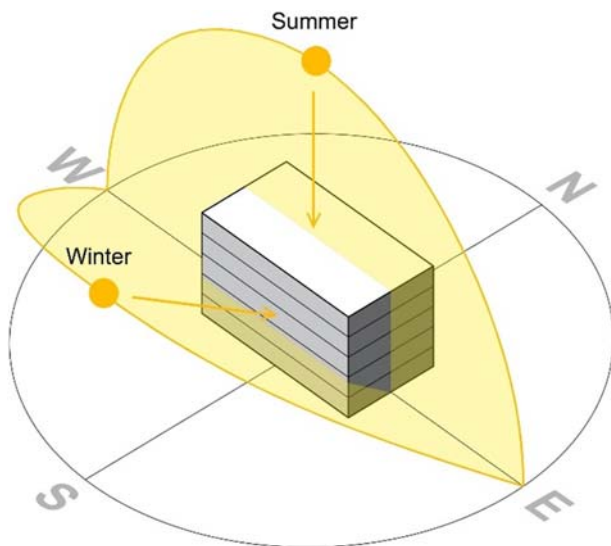


FIGURE 2.19 Ideal building orientation to the sun.

If, on the other hand, a double-loaded corridor building is envisioned, intended to accommodate several habitation units, the objective becomes to uniform sunshine on the different facades, in addition to the exploitation of solar energy. In this case, the best orientation is the one according to the equisolar axis, that is, the direction that goes from the point where the Sun rises in the summer solstice (E-NE) to the one in which it sets at the winter solstice (W-SW) (see Fig. 2.20). For the Northern latitudes between 40° and 56° , its inclination on the East-West direction is $32^{\circ} 24'$, equal to about 58° on the North-South one. By orienting a building along this axis, a more uniform distribution of both the hours of light and the quantity of heat is achieved.

At the most unfavorable moment, that of the winter solstice, the pair of facades facing east (NE and SE) receive more energy, while the pair facing west (SW and NW) can exploit a higher ambient temperature and, consequently, heat up more intensely.

Overall, the best exposures for a building space are South, South-East, and South-West, and worst ones are East and West (see Table 2.22). In the North latitudes between 50° and 35° , the North-East or North-West orientations are preferred to the East and West because they are cold in winter, but not too hot in summer. As regards the northern exposure, it is the one with the greatest regularity of illumination, even if it has the shortest duration of annual insolation and is often more affected by winds. Therefore, it is suitable for kitchens and other service rooms in residential buildings, as well as for work rooms where uniformity of lighting and glare control are recommended. To ensure adequate

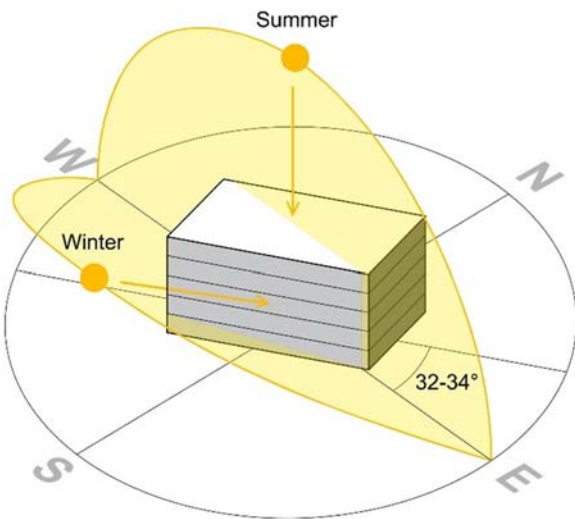


FIGURE 2.20 Building orientation on the equisolar axis.

TABLE 2.22 Recommended orientation for house rooms in latitudes between 50° and 35° North.		
Room	Recommended orientation	Suitable orientation
Rooms used at any time of the day or the night	South	South-East South-West
Bedrooms	South South-East	East North-East North-West
Study	North	North-East North-West
Kitchen	North North-East	Any but West
Bathrooms	North North-East	Any
Staircases, corridors, storage	North North-East North-West	Any

sunshine for buildings, building codes usually require that dwellings with only one external facade are not oriented toward the north, prohibiting the construction of housing units for which the angle formed between the facade and the east-west direction is less than 30° .

In the case of residential buildings, bedrooms and the rooms used in the afternoon benefit more from exposure to the East and South-East, because those to the West and South-West absorb heat from the afternoon sun and can be very hot in the summer season.

Natural ventilation

Another important factor to consider when determining the orientation of a building concerns the possibility of exploiting natural ventilation for summer cooling of interiors. Natural ventilation inside confined spaces is a complex phenomenon, significantly influenced by the prevailing winds in the area, by the characteristics of the context (morphology, vegetation, presence of other buildings), by the shape and orientation of the building, by the distribution of internal spaces, as well as the location, size, and characteristics of the openings (see Fig. 2.21). The forces that determine the air movements inside buildings are due both to the atmospheric pressure differences generated by the winds that hit the different facades (passing wind ventilation), and to the variations in the thermal gradient of the atmosphere which triggers vertical ascending and descending air (stack effect). Each can act alone, in combination, or in opposition to the other, according to the weather conditions and the configuration of the building. The horizontal distribution of the openings influences the cross-wind ventilation; the vertical distribution determines the movements by temperature difference.

Determining the size of the leeward region due to the presence of a building is important both for the influence that it can have on any downwind buildings, and for interiors ventilation (see Fig. 2.22). In particular, as the depth of the wake increases, so does air flow able to pass through the building and, therefore, the cooling potential for natural ventilation. To take advantage of natural ventilation, the openings must be suitably positioned and sized in relation to the direction of the prevailing winds.

Air currents that form around the building are determined by its massing and orientation and are independent of the air speed. In particular, the overall dimensions of the wake due to a building placed along a wind flow are not determined much by the absolute size, but rather by the relative dimensions: the size of the wake increases as the width and height of the building increases and decreases with its depth due to the greater friction of the air flow on the roof surface.

Fig. 2.23 shows the effects of the size of a rectangular building hit by an air flow in a direction orthogonal to its main axis. Of the 3D parameters, the height is the one that determines the greatest variations in the depth of the wake produced, therefore imposing greater constraints on the distances from other buildings.

The shape of the roof influences the air flows that hit the building as well. The greatest potential for natural ventilation is obtained with single-pitched roofs oriented toward the wind: this configuration increases and homogenizes the depression of the leeward facade.

The height being equal, different geometric shapes affect the overall dimensions of the wake according to their angle with the direction of the incident air flow.

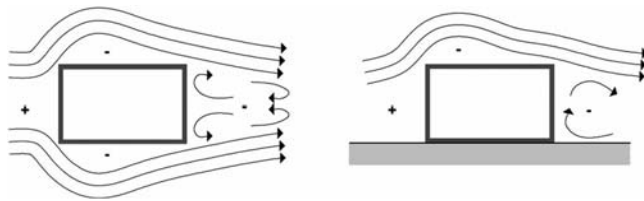


FIGURE 2.21 Airflow around a building.

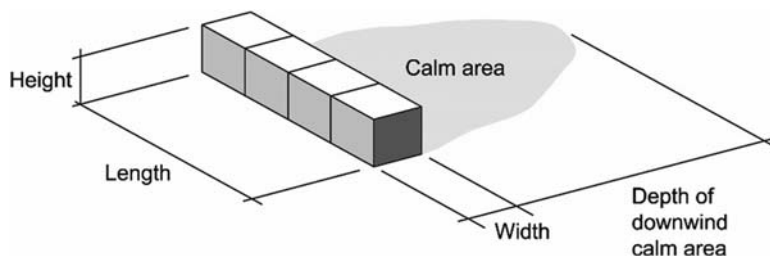


FIGURE 2.22 Influence on building's dimensions on downwind calm area.

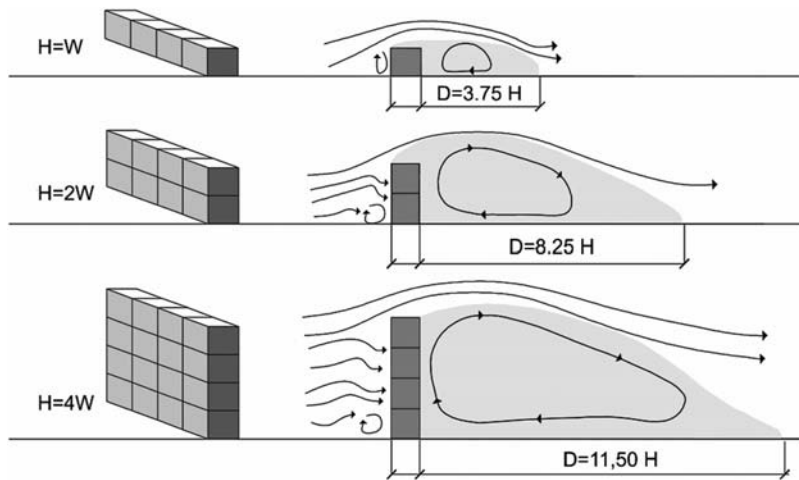


FIGURE 2.23 Influence of building's height on the depth of wind wake.

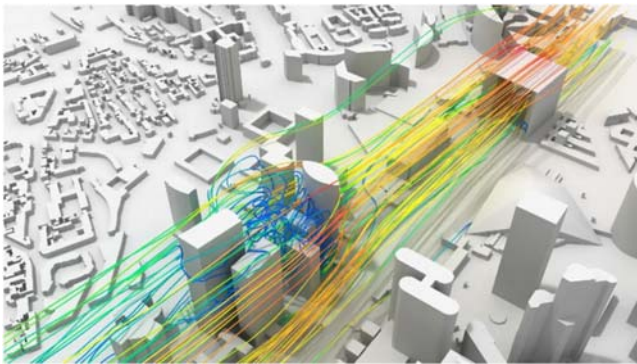


FIGURE 2.24 CFD analysis of wind flows around a building. Courtesy of SimScale.

Concerning the effects of wind deflection due to the shape and arrangement of the building on the neighboring structures and vice versa, spacing the rows of buildings at a distance equal to seven times their respective heights generally ensures a satisfactory effect of ventilation for each of them. Wind, however, has a tendency to fly over long parallel rows of buildings. Terraced buildings cause a shadow of the wind on leeward structures; this effect is reinforced by the tendency of the wind to channel itself through the open spaces and pass over the last rows. A quincunx arrangement with alternating units can take advantage of the bouncing path of the wind, having windward buildings direct the flow toward the leeward ones.

If the programmed building density does not allow to optimize the planimetric configuration to avoid an excessive reduction in wind speed, effective summer cooling can be obtained by varying heights between the buildings. In any case, situations that could cause discomfort conditions for pedestrians should be avoided, such as the excessive proximity of the buildings facades that may accelerate wind flow due to the Venturi effect.

Nonetheless, CFD analyses can prove useful in determining the wind movements in the intervention area as affected by the local topography, neighboring structures, and the building itself (see [Fig. 2.24](#))

Noise protection

Regarding noise protection, the building should be located as far as possible from the sources and the shielding effect of natural or artificial obstacles should be exploited, such as terrain reliefs, vegetation, or other buildings, lowering the areas to be protected in relation to the noise source.

If the intervention area faces a heavily trafficked road, the building may be better positioned either parallel or perpendicular to the street depending on the expected protection objectives. The perpendicular arrangement produces a different exposure in the various rooms as there is a progressive distancing from the source. In this case, the most exposed part must be protected with an adequate passive acoustic insulation of the facade. In a parallel arrangement, instead, the designer should locate buffer spaces in the facade most exposed, such as distribution or service spaces, and place

working, living, and sleeping quarters in the most protected one. Indeed, the difference in noise exposure between the two elevations can be as high as 30 dBA. It will also be necessary to integrate devices to contain the vibrations transmitted by traffic to the building through its foundations.

In general, it is advisable to avoid solutions that favor multiple reflections of sound waves between one building and another or parts of the same building, which increase the disturbing effect. Compact shapes that do not have concavities can avoid an uneven distribution of sound, echo phenomena, and acoustic distortions. Courtyard or terraced typologies are more suitable than isolated houses to create gardens protected from street noise; walls are significantly more effective than fences. Access to the garages must preferably be on the same side of the building subject to traffic noise and it is advisable to separate the pedestrian access from the vehicular access using two different gates.

Concerning, instead, the layout of the building and the presence of overhangs, balconies or terraces, their effects can be both positive and negative in relation to the shape of the facade, the absorption of the lower part of the overhang and the general direction of incident noise. Generally, a positive effect is due to the total or partial shielding of the facade by balconies or other objects. The negative effect is due, however, to additional reflections and a sound field that could be considered reverberant when a balcony forms a partial closure around the facade plane. The UNI 12354 standard reports the corrective coefficients to be applied in the calculation of the facade insulation according to its geometry. Thus, for example, having a balcony above a window causes a reduction in performance at low frequencies and an increase at highs, the insulation index being equal.

2.3.1.3 Openings

In addition to formal architectural reasons, the introduction of openings in the building envelope responds to the need to allow the entry of air, light, and heat and to enable vision and passage through. Openings inherently constitute an element of weakness within the building envelope in terms of thermal dispersion, excessive incoming heat, glare, and greater exposure to external noise levels; therefore, their positioning and sizing must be done with the intent to maximize the cost–benefit ratio (see Table 2.23). In particular, the energy balance between the energy lost due to dispersion and that gained through solar radiation must be adequately considered, as well as the possibility of providing adequate daylighting and natural ventilation of the rooms, and the need of protection from the external noise.

Energy balance

In the facades facing North, East, and West, the glazed surfaces should be sized to mainly guarantee sufficient daylighting and natural ventilation. For the North orientation, where solar radiation is almost completely absent, it is important to ensure a high thermal insulation and to limit the size of the window as much as possible to reduce energy consumption. In south facing facades, instead, the size of the windows should be larger than that strictly sufficient for daylighting to increase the benefit of solar gains in winter; in any case, windows should be equipped with shading systems to control the entry of solar radiation in summer.

TABLE 2.23 Table: Main parameters for building fenestration optimization.

Name	Definition	Units
Envelope transparent surface ratio	A_t/A_e	%
Envelope transparent surface to floor area ratio	A_t/A_c	%
Envelope transparent surface to wall ratio	A_t/A_w	%
Envelope transparent surface to building volume	A_t/V_c	m^2/m^3
South transparent surface to south wall ratio	A_{ts}/A_{ws}	%
South transparent surface to floor area ratio	A_{ts}/A_c	%
South transparent surface to building volume	A_{ts}/V_c	m^2/m^3
South transparent surface to envelope transparent area	A_{ts}/A_t	%

Indices: A, area in m^2 ; V, volume in m^3 .

Subindices: e, envelope; c, conditioned; t, transparent (glazing); w, wall; s, south.

As regards the penetration of solar rays into the building, the number of hours of sun penetrating increases with the width of the window, while penetration depth increases with the window's height. Other factors are the thickness of the perimeter walls, the presence or absence of outward frames and the presence of buildings or obstacles in the sun path. Even when the amount of sunshine is the same for two rooms, those exposed to the West receive low and deep rays, rich in heat radiation (infrared), while those exposed to the South receive rays rich in ultraviolet radiation.

In winter, the surface temperatures of a glass pane can be many degrees lower than the temperature of the air inside the room, creating environmental discomfort since it reduces the mean radiant temperature and may generate a radiant asymmetry that causes localized discomfort conditions. Air infiltrations associated with the presence of windows and convective motions (air descending over cold glass surfaces) can also contribute to discomfort. Finally, direct solar radiation is a source of both visual and thermal disturbance, mainly in summer, but in some cases also in winter,

Daylighting

Concerning interiors daylighting, the sizing, positioning, and shape of the openings shall guarantee, in addition to outside views, adequate visual comfort for users in relation to the intended use of the spaces, without glare phenomena due to direct solar radiation. The objectives are to maximize the useful contribution of daylight, ensure that light levels and distribution are appropriate, provide occupants with ability to tailor the amount of light to their individual needs and ensure suitable quality of electric luminaires as well. Potential trade-offs from excessive daylighting (e.g., glare, increased cooling energy) should also be considered as well as the design integration of shading devices.

It is therefore critical to ensure since the early stages of design that the amount of useful daylight available in the space is maximized by passive methods. At the conceptual design stage, the influence of building form and orientation on daylighting can be assessed as well as the supplementary electric lighting systems that will be necessary to provide the required illumination. At the schematic and detailed design stages, more accurate lighting plans as well as sequences of operations for lighting controls can be made based on calculations, simulations, and drawings to ensure that the lighting system is capable of meeting the required lighting needs. The analysis should extend to the as-built and in-use stages by including a walk-through preoccupation of the work/living spaces with in situ measurements to identify and address any performance gaps and to ensure that the commissioned luminaires and systems meet the design criteria. A post-occupancy evaluation could be also considered in order to understand the occupants' impressions of the lighting conditions and installations.

There are many factors that affect the amount of useful daylight that enters the building. These include the building massing (depth, orientation, fenestration, size/location) and the type of windows. In particular, the average lighting level of an interior space mainly depends on the incoming luminous flux and the characteristics of the environment.

The incoming flux depends mainly on the amount of light that manages to reach the center of the window (luminance and visibility of the sky), then on its size, shape, position on the wall, and the characteristics (type of glass, degree of soiling, frame size, size and position of shading systems). In particular, the illuminance available on the center of the window depends on the level of external illumination (i.e., the luminance of the celestial sphere characteristic of that place and variable according to the orientation of the window) and on the visibility of the sky in relation to the presence of any obstacles. Therefore, it is influenced by the presence of obstructions in the upper and lateral part of the window (balconies, canopies, screens), on the height of the window from the street level, on the distance, height, and reflection coefficients of any obstacles in front of the road, by the reflection coefficient of the outside space (generally negligible).

As for the influence of the orientation of the window on the incoming light flow, the southern exposure is certainly favorable because it receives light from the brightest part of the sky during all daytime hours; moreover, the sun, due to the height shift of its seasonal trajectory, penetrates deeply into the environment during the winter months, when it is appreciated, and very little during the summer months when it may cause overheating. Finally, the use of sun shading can satisfactorily limit direct radiation without compromising the lighting conditions. The north orientation is also favorable, both from the point of view of the amount of light available, and for the uniformity and quality of the light itself. East and West-facing orientations are less favorable since they imply significant variations over the course of the day, both in illumination and in thermal loads. In particular, a West-facing window will increase the solar heat gain in the afternoon hours in which the building is already at its peak for thermal load. Penetration of direct solar radiation may also be a hindrance for visual activities, affected by low and deep reaching sunrays, leading to the simultaneous use of both screening systems and artificial lighting systems despite exterior light levels being very high. Therefore, increasing glazed surfaces to the south and reducing those to the west can be one way to minimize the solar heat gain in the afternoon.

As the size of the window increases, so does the incoming luminous flux and, consequently, the average illuminance of the environment. If more daylight is required in the space, the easiest solution would be to increase the window-to-wall ratio (WWR), the area of window divided by the total exterior wall area for a particular space.

As for the shape, horizontal windows allow a better view of the outside, whereas vertical windows (i.e., taller than they are wide) provide a greater distribution of lighting in the environment, allowing to create deeper spaces. This is because the light coming from the upper part of the window is reflected on the ceiling, increasing the diffused light component. In general, the part of the window closest to the ceiling contributes to the internal lighting to a much greater extent than that next to the floor; in some building codes the area that is below 60 cm starting from the floor level is even excluded from the assessment of the size of the windowed area. Adjusting the height of the windows may change the depth of daylight penetration into the space but, depending on the season, time, and daylight component, it may also have the consequence of increasing solar gain, thereby creating a risk of overheating and an increased need for mechanical cooling.

Particular attention shall be paid to the choice of the windows frame, capable of significantly reducing the incoming luminous flux, as well as of the glass pane, in relation to its visible light transmission (VLT) factor. This parameter expresses the percentage of visible radiation allowed to pass directly in the range between 380 and 780 nm, the range of sensitivity of the human eye. Finally, it is necessary to take into account the cleanability of the window and the fouling factor. These can be improved by using self-cleaning glazing products, which impart dirt degrading and repelling capabilities on windows to ensure maximum light transmission and reduced environmental and economic costs of window cleaning. These are based either on superhydrophobic coatings that favor flushing of water droplets and dirt, or on superhydrophilic coatings with photocatalytic properties able to chemically decompose organic fouling with UV rays (see [Section 7.5.5.2](#)).

Concerning the influence of indoor space characteristics on daylighting, these concern, firstly, the dimensions of the room (floor area) on which the incoming light flow will be distributed. The greater the floor surface, the lower the average illuminance of an environment with the same incoming flow. Daylighting will also depend on the geometric characteristics of the environment, given by the ratio of the floor surface to the total surface (floor, ceiling, and walls), and the average reflection coefficient of the environment. In particular, illumination increases with the average coefficient of internal reflection of the walls and ceiling (light colors, reflective surfaces) and, for the same floor area, increases as the height of the environment and its total area decrease. Therefore, circular or square-shaped environments (which imply a smaller overall surface) guarantee greater illumination than rectangular rooms.

Control of incident solar radiation control can be implemented through the use of traditional static systems, consisting of solar protection glazing or fixed and mobile shading devices, or through dynamical systems, possibly integrated and coordinated with the BAS, consisting of automated shading devices or dynamic windows able to change their optical properties according to solar radiation (see [Table 2.24](#)).

Among the various shading systems, external shading elements, such as horizontal or vertical projecting louvers (*brise soleil*), shutters, blinds, or awnings, are preferable to internal ones because they block the solar radiation before it penetrates the building. Indeed, internal elements such as curtains, blinds, or shutters work primarily by reflecting and diffusing the radiation outward, although absorbing a share thus releasing some heat inside the indoor environment. These elements have anyway good efficacy in preventing glare.

Brise soleil also have a distinct architectural value and can therefore strongly characterize the external image of a building. It is important, however, to evaluate the behavior of such devices as their presence can significantly change the performance of the openings and therefore the ventilation coefficient of rooms. The presence of the screen, moreover, interferes with the visual enjoyment, natural lighting, natural ventilation, and the possibility of leaning out or passage offered by the window. If carefully designed, outer shading systems are able to provide a differentiated behavior over the year, excluding solar radiation in the summer while allowing, instead, the access during winter. The effectiveness of such systems must be verified through the use of shading masks or daylight simulation tools: the ideal screen blocks the sun path in the hours in which solar radiation is not desired. Parametric and generative design approaches are also suitable for solving this kind of physics-dictated architecture problems (see [Section 6.4](#)).

In general, the type and sizing of shading systems mainly depend on the latitude of the site, the orientation of the window, and the portion of the sky visible over the year.

For windows placed on South-facing facades, horizontal devices are the most effective. In summer, in fact, in the central hours of the day the sun is at its highest annual heights and therefore the vertical obstruction angle required to shade the window is relatively small and is a function of the height of the window. That same overhang in the periods of the year in which solar radiation brings a positive energy contribution does not impart any shading due to the lower elevation of the sun. However, this screen may affect daylighting levels, as it limits the portion of the celestial sphere seen through the window.

TABLE 2.24 Main advantages and disadvantages of traditional solar protection systems (Casini, 2018).

Solar protection systems	Advantages	Disadvantages
Static solar protection glazing	• Reduction of heat load in summer • Vision through • Limitation of glare phenomena • Lowest extra cost	• Reduction of energy harvesting during winter especially in the south facing facades • Reduction of natural light levels in the absence of direct solar radiation in particular for the east or west facing facades, irradiated for only half of the day • No privacy
Fixed shading systems	• Reduction of heat load in summer • Maintenance of energy harvesting during winter • Limitation of glare phenomena	• Risk of excessive reduction of inside natural lighting • Limitation of external vision • Possible unsuitability for energy retrofits of existing buildings • Medium extra cost of installation • No privacy
Dynamic shading systems	• Reduction of heat load in summer • Full energy harvesting during winter • Elimination of glare phenomena • Privacy • Direct control in relation to external daily environmental conditions and users' needs • Possibility of integration with HVAC, lighting systems, and BAS	• Limitation of external vision • Possible unsuitability for energy retrofits of existing buildings • Highest costs of installation, management and maintenance

The shading of surfaces exposed to East or West can instead be obtained with vertical devices that shield the radiation in the first and last hours of the summer day (North-East and North-West). However, if such devices are fixed, it is impossible to allow the sun to penetrate in the winter period as the shading mask necessary to shield the solar radiation in summer inevitably covers the winter solar path as well. The location, adjacent to the lateral edges of the opening, also impedes lateral vision, particularly when the user is close to the window; for further positions of the occupant, the disturbance is minimal and the effect of the screen is to direct the attention to the central area of the external scene (telescope effect). Given its position, these devices do not interfere with the possibility of leaning out the windows and are compatible with all types of opening.

With the increased diffusion of advanced BAS, especially in new constructions, dynamic shading systems are today able to change their geometric shape and optimize the amount of incoming solar radiation according to the climatic conditions (adaptive facades or kinetic facades) (see [Section 10.3.4](#)). Widely adopted in Europe, these systems are normally made using adjustable louvers or blinds integrated into a double-skin curtain wall.

Natural ventilation

To trigger adequate air circulation within an environment, at least two openings are required, positioned in such a way that one can function as an inlet and the other as an outlet for the air flow (see [Fig. 2.25](#)). In case of ventilation due to external wind, the amount of air circulation established by a pair of openings is proportional to the difference in wind pressure existing at the inlet and outlet, to their overall size, and to the dimensional ratio between them. The maximum air circulation occurs when the openings are located on the windward and leeward facades. In the case of wind perpendicular to the facades with the openings, these should be placed on opposing walls and staggered instead of directly facing each other. In the absence of opposite walls, the openings placed on adjacent walls, windward side and lateral side, provide adequate ventilation as long as the room is not too deep.

Opposite openings on the lateral sides of the building with respect to the façade directly exposed to the wind cause insufficient air flow. Openings located on the same wall are unable to generate the pressure differential necessary to trigger the movement of air, unless they are located at significantly different heights, such as to trigger an air flow due to the stack effect.

Indeed, the vertical positioning affects the cross-ventilation, modifying both the direction of the flow, when it is mainly generated by the wind, and the flow rate, when the flow is triggered by a stack effect.

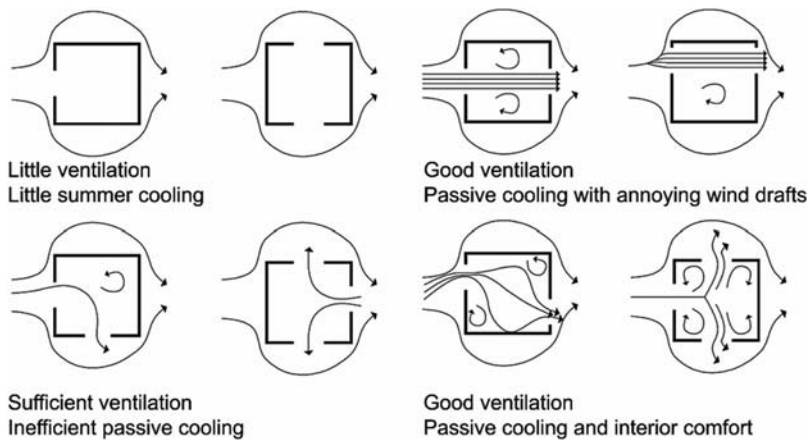


FIGURE 2.25 Influence of openings' position on interiors natural ventilation.

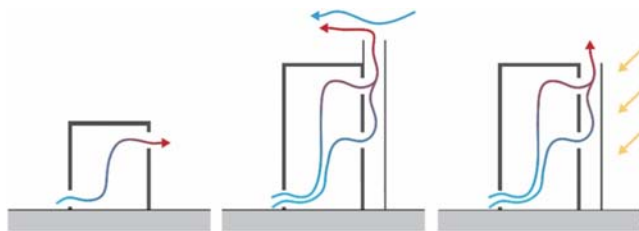


FIGURE 2.26 Stack effect ventilation.

Cross-ventilation In the case of cross-ventilation, the reciprocal vertical location of the air inlet and outlet openings is determined according to its specific purpose: if the goal is cooling the body, openings must be placed at eye level; if the objective is cooling the wall mass, the inlet opening must be positioned close to the mass to be cooled, that is, close to the ceiling or the floor.

As for openings size, air flow is directly proportional to the area of the opening, while the ratio between the inlet and outlet areas affects the internal pressure differential and, therefore, air speed. Since indoor air flow and velocity requirements may vary with the intended use of spaces (for body cooling) and/or with the envisaged convective cooling methods of the walls, a consistent design criterion is to provide types of closure with the maximum degree of variability of the opening area.

The ratio between the inlet and outlet opening areas influences the maximum flow speed rather than the average speed of the air inside the environment; therefore, it should be determined in relation to the intended purpose of natural ventilation, considering that:

- an inlet area smaller than the outlet area determines, all other factors being equal, an increase in the maximum speed of the internal air flow compared to that of the wind outside the opening (Venturi effect);
- an inlet area greater than the outlet area determines a decrease in the speed of the internal air compared to external wind speed;
- an inlet area equal to the outlet area determines the smallest difference between internal and external air speed and also the smallest difference between maximum speed and average internal speed; for these reasons, this configuration is recommended in most cases.

Stack ventilation Stack effect typically occurs in the presence of narrow vertical spaces, connected with the outside through inlet and outlet openings placed at either end, as the upward movement of warmer internal air draws colder air from the outside (e.g., inside the flues of fireplaces) (see Fig. 2.26).

Stack effect can also occur in rooms of a certain height in the presence of openings near the floor and ceiling, respectively. The air flow that is generated is directly proportional to the difference in height between the inlet opening and the outlet opening, at least 3 m in residential spaces and 4.6 m in commercial spaces, and to the temperature difference between inside and outside air, which should be at least 1.7°C. The larger the distance between openings, the greater the volume of air displaced. In shorter buildings, the chimney effect is usually negligible; on the contrary, within the stairwells of high-rise buildings, substantial ascending or descending air currents can be generated in relation to the

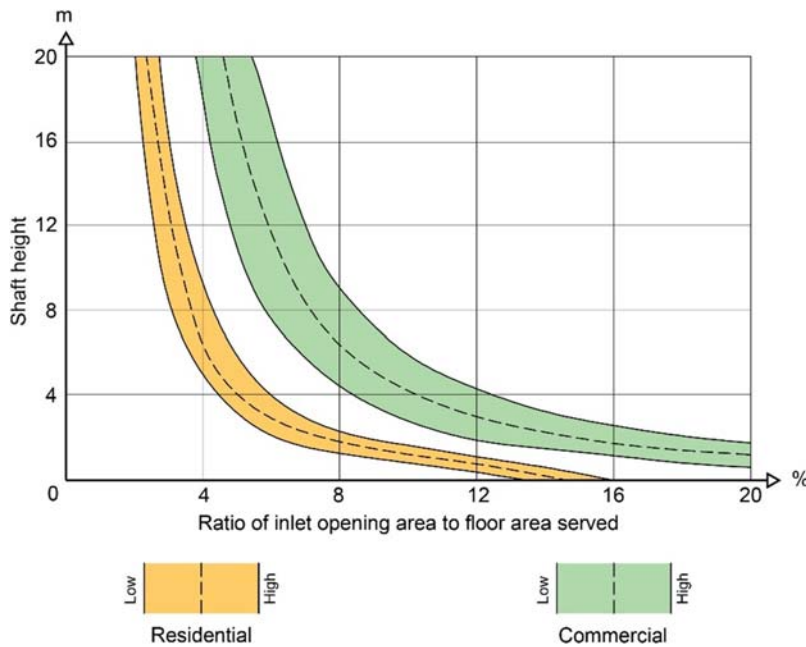


FIGURE 2.27 Stack ventilation capacity for a temperature difference of 1.5°C.
Redrawn from (2030 Palette - Stack ventilation).

thermal gradient between exterior and interior. The size of the inlet opening areas as a percentage of floor area served (%) can be determined with dedicated graphs based on the difference in height from the outlet (shaft height), according to the amount of heat to be removed from space and its intended use (see Fig. 2.27).

It is also possible to induce stack effect through the use of solar chimneys or stack ventilation shafts. Solar chimneys, also known as thermal chimneys, consist of narrow vertical spaces exposed at least on one side to solar radiation in order to heat the internal air and generate upward air motions. Stack ventilation shafts are attached to the building with the purpose of augmenting the building own air movement and feature their own shaft inlet opening, to be located as high as possible within the space to be ventilated, preferably on the ceiling, and outlet opening on the opposite side of the shaft and at the highest possible position. The total amount of heat removed from a space is proportional to the height of the ventilation shaft. The higher the shaft, the greater the volume of air displaced.

As regards the combined cross ventilation from wind and stack effect, it is necessary to avoid that the two factors conflict with each other by placing the highest opening, the outlet of the flow, in a leeward position with respect to the prevailing wind direction. A synergistic action is obtained by locating the outlet at the ridge of the roof to exploit the Bernoulli-Venturi effect; this induces a depression zone near the opening, increasing the suction effect of the flow.

The overall geometry of the building and the presence of protruding elements, capable of intercepting the wind, also affect air motions inside the rooms. In the absence of wind, the shaded areas on the external walls (due to overhang and loggias) create masses of cooler air, and therefore modest depressions that can be exploited to trigger movements of air inside. In the presence of wind, the protrusions and obstacles on the external walls divert the air flows creating areas of pressure and depression, which can be used to increase the air movements inside the rooms as well.

In residential buildings, single internal spaces with more than one exposure are rare, and ventilation is usually obtained by involving several rooms of the house. The extent and path of air flows therefore depend on the overall characteristics of the layout and on the position of all openings, both those in direct communication with the outside and those of internal communication between the rooms. To avoid reduction of the air flow rate, the partitions between the different rooms should not obstruct the path that the air would follow in their absence.

Air movement implies the transport of fumes, vapors and odors produced within the environments during the performance of the activities; since the circulation of large masses of air generally involves several rooms inside an apartment or building, it is necessary to avoid that the probable path of the air flow goes from malodorous environments (kitchens and bathrooms) toward clean rooms. In residential buildings, living rooms and studios should be placed on the windward side, while kitchens and toilets should be placed on the leeward side.

The typological characteristics of the openings and screens, finally, determine the possibility of obtaining at the same time the exclusion of direct sun radiation and the introduction of the substantial air flows necessary for summer cooling.

2.3.2 Building envelope

The envelope of a building represents both its spatial boundary and its architectural language. For this reason, the building envelope has always played a fundamental role in communicating to the public and mediating between the collective interest, the needs of interior spaces, and the conditions of the context, as well as between esthetic motives and technical-economic reasons. Nowadays, the building envelope has acquired a leading role in the formal and technological qualification of architecture, as it performs as an urban catalyst and a diffuser of quality, more than any other architectural element, and at the same time plays a strategic role in the energy and environmental performance of the building, significantly affecting the levels of indoor comfort. The building envelope consists, in fact, in a complex system of environmental barriers and filters, potentially able to not only regulate the flows of heat, solar radiation, air, and vapor, but also to convert solar, wind and mechanical energy into heat and electricity.

In view of this vast range of environmental loads and performance requirements, a predetermined optimal building envelope solution does not exist, but rather a repertoire of technological solutions is available, to be employed in an appropriate manner in relation to the type of users, the complexity of the building, the environmental (heating or cooling dominated), economic (or developed undeveloped), and local cultural context and whether it is a new construction or a retrofit intervention. More and more importance in the design choices pertains the relationship with the site and the need to consider the building system no longer only as an energy consumer, but also as a producer by adopting envelope configurations capable of exploiting the surrounding microclimatic characteristics, both passively and actively, to meet the energy needs of the building with the least impact on the environment.

Design choices shall relate to the optimization of the thermo-hygrometric characteristics of the building envelope, concerning both the opaque and transparent components. Regarding opaque closures, the resistance to the passage of heat, measured through the thermal resistance (or its inverse, defined thermal transmittance), and the ability to store heat, measured through the thermal capacity, are the characteristics that have the greatest influence. In fact, thermal resistance entails the possibility of reducing unwanted thermal flows between inside and outside, both in summer and in winter; thermal inertia implies the possibility of avoiding interiors overheating in hot climates or in summer periods as a result of high direct solar radiation.

For hot climates, just as important is solar reflectance of roof and walls in order to reduce absorption of solar radiation and its transmission as heat toward the interior of the building. In this picture, integration of vegetation in buildings for the realization of living walls or green roofs is increasingly widespread, to make plant species an actual technological component of the building envelope. In summer, vegetation allows to reduce heat flows entering through the envelope, thanks its shading and to the absorption of the radiant energy needed for photosynthetic and evaporation-transpiration processes, in addition to the greater thermal inertia offered by the mass of the potting soil. These benefits add to the improvement of air quality, thanks to the action of dust filter operated by the plants, the reduction of the visual impact of walls or roofs, and the use of vegetation as a natural habitat for the development of biodiversity (Blanc, 2012; Cantor, 2008; Susca, 2019).

Concerning the transparent closures, in addition to a high resistance to the passage of heat, they must have adequate optical capabilities to ensure the entry of visible radiation (VLT) and contain, where not necessary, the infrared component of solar radiation (solar heat gain).

In particular, the envelope design choices aimed at improving internal comfort and energy performance of buildings concern:

- high levels of insulation in walls, roofs, and floors to reduce heat losses in cold climates, optimized using LCA and LCC analyses;
- high levels of thermal inertia and highly reflective surfaces in roofs and walls to reduce summer overheating in hot climates;
- high-performance windows with low thermal transmittance and climate-appropriate solar heat gain coefficient (SHGC) or solar shading systems in order to favor solar gain in winter and reduce it during summer;
- properly sealed structures to ensure low air infiltration rates with controlled ventilation for fresh air (air sealing alone can reduce the need for heating by 20% to 30%);
- minimization of thermal bridges (components that easily conduct heat/cold), such as discontinuities in insulation and structural members.

Building codes and voluntary green building certification systems have become more demanding in terms of the thermal performance of the envelope (see Table 2.25). Passive house standard requires that all envelope building components must be very well-insulated with a heat transfer coefficient (U-value) below 0.15 W/m²K for opaque closures

TABLE 2.25 Recommended maximum U values according to heating and degree days.

Climate zone	Parameters		U (W/m ² K)		
	Heating degree days	Cooling degree days	Wall	Roof	Windows
Zone 1	<1500	>1200	0.38	0.27	2.60
Zone 2	<1500	800–1200	0.26	0.22	1.67
Zone 3	1500–3000	400–800	0.23	0.20	1.30
Zone 4	1500–3000	<400	0.22	0.19	1.00
Zone 5	>3000	<400	0.20	0.17	0.90

TABLE 2.26 Most effective advanced technologies for smart buildings related to climate and type of intervention (Casini, 2016).

Climate	Smart envelope materials and technologies	
	New construction	Retrofit
Hot	• Very low-SHGC glazing or dynamic glazing • Dynamic shading systems • BIPV shell and photovoltaic glazing • Cool roofs • Phase change materials (thermal inertia) • Green roofs and walls • Self cleaning glazing and surfaces • Ventilated roof and walls • Adaptive skin facades • NEMS	• Very low-SHGC glazing or dynamic glazing • Solar control films for windows • Cool roofs and reflective coatings • PV shading systems • Ventilated walls • Green walls • Phase change materials (thermal inertia) • Self-cleaning glazing and surfaces
Cold	• Advanced insulation glazing • Glazed double skin facades • Dynamic shading systems • Antireflective glazing • Light redirection and optical systems • Heating glazing • Bioadaptive glazing • ETFE envelope • BIPV shell • Self-cleaning glazing and surfaces • Transparent insulating materials • Phase change materials (passive solar gain) • Advanced insulating materials for thermal bridges correction and Equipment insulation • Adaptive skin facades • NEMS	• Advanced insulation glazing • Dynamic glazing • Antireflective glazing • Suspended film glazing • Light redirection and optical systems • Heating glazing • BIPV/BAPV shell • Self cleaning glazing and surfaces • Advanced insulating materials for interior or exterior insulation and equipment insulation • Phase change materials (passive solar gain or in case of internal insulation) • Green walls • Reflective thermal coatings for interior walls

and below 0.80 W/m²K for windows. All edges, corners, connections and penetrations within the envelope must be designed and constructed with great care to prevent or minimize thermal bridges as far as possible. Uncontrolled infiltration through envelope gaps must be smaller than 0.6 of the total house volume per hour during a blower door pressure test at 50 Pascal (both pressurized and depressurized). For hot climates like UAE, the Estidama PEARL code prescribes—at its lowest rating—maximum roof and wall U-values of 0.14 W/m²K, and 0.32 W/m²K, respectively.

Current available solutions for the construction or renovation of high-performance building envelopes, both opaque and transparent, are numerous and derive from the profound evolution that materials, products and construction systems have undergone over the last decade spurred by stricter energy efficiency and environmental protection objectives (see Table 2.26). Moreover, recent years have seen the introduction in the market of advanced materials and nanotechnology products with physical and mechanical properties greatly exceeding those of conventional materials, as well as the

availability of active components and devices, called smart materials, able to change their characteristics in relation to different operating conditions determined by climatic elements or users, and of materials and products of vegetal or animal origin able to provide excellent performance with a greatly reduced or even positive environmental impact (see [Chapter 7](#)). Such innovative products and systems may be used for the thermal insulation of the building, enabling superior performance with extremely reduced thickness, for glazed components allowing dynamic performance, for the surface treatment of building materials improving their characteristics or introducing new ones, for facade systems allowing for adaptive behavior and maximum integration with building equipment.

Most advanced products and technologies available on the market for improving the building envelope energy performance in both new construction and retrofit interventions include (see [Section 7.5](#)):

- advanced insulating materials (fiber reinforced aerogel blankets, VIPs) with extremely reduced thickness, able to allow architectural integration, minimal encumbrance, thermal bridges reduction, and piping application;
- transparent insulating materials (TIMs) to combine daylighting with energy efficiency;
- phase change materials (PCMs) to raise thermal inertia of the envelope or of internal partitions and provide thermal heat storage for solar passive heating without increasing building mass;
- reflective coatings to increase thermal insulation or reduce solar radiation overload (cool roofs);
- self-cleaning and antireflective glazing to maximize luminous transparency;
- advanced thermal insulation glazing and heating glazing to reduce thermal loss from windows in cold climates and improve thermal comfort;
- dynamic glazing to allow continuous control of solar radiation and BAS integration, in order to guarantee maximum visual comfort and solar gain management in both hot and cold seasons;
- PV glazing to reduce incoming solar radiation and at the same time produce electricity;
- living green walls and roofs to reduce incoming heat flow during summer and improve urban air quality.

Ultimately, the objective is to obtain a “smart” building envelope that acts in analogy with skin in the human body, being able to fully adapt to the environmental conditions and ensure, in full synergy with the systems and equipment, an efficient continuous and automatic management of all matter and energy flows in accordance with climate, user behavior, and market conditions of energy. Such envelope would not only be capable of offering better performance compared to a traditional building shell, but also to fulfill new functions (power generation, light emission, image projection, air purification, ability to self-clean and self-repair, etc.) and to adapt its characteristics in response to changes in external conditions (from transparent to opaque, from solid to liquid, from waterproof to permeable, etc.).

This adaptive behavior (climate adaptive building shell) may comprise both the macroscale, with the presence of moving mechanical parts, that the microscale, through a change of physical or chemical properties of the envelope materials. The first case regards the kinetic envelope, and the dynamic response primarily covers sun shading systems, natural ventilation or solar energy capture systems, capable of orientating, opening or closing automatically according to the need. The second case regards more properly an intelligent skin, and the response to environmental stimuli involves the internal structure of materials able to modify their optical, electrical or thermal properties, their geometry or to convert energy from one form to another (smart materials).

The adaptive behavior of the building envelope can then be passive, self-powered but without the possibility of direct control by the users, or active, with manual or automatic control, or a combination of the two. These variations of the characteristics of the building envelope can be fully integrated into advanced BAS and coordinate with HVAC, lighting and other buildings systems to adjust automatically their operation in relation to the materials and energy flows actually entering the building (smart building).

2.3.3 Building systems

Within the design process, the systems engineering is not an independent phase but is characterized by a continuous interaction with the architectural design activity. This interactive process can play a positive role and therefore enrich the work as a whole or, on the contrary, turn into conflicts capable of penalizing the expressiveness of the design. For this reason, it is essential that the engineering of the systems follows the architectural design hand in hand and, therefore, begins at the very moment in which the work is conceived and the client’s needs are compared with the constraints and resources. Plant engineering choices can offer different solutions, which, in order to achieve the highest building quality, must integrate perfectly with the architectural choices and provide a concrete response to needs that building construction alone is not able to satisfy completely.

Design choices shall aim at identifying systems solutions capable of allowing the best conditions of interiors comfort and, at the same time, of maximizing the reduction of primary energy needed to satisfy all requirements (winter and summer air conditioning, domestic hot water production, ventilation and lighting) by increasing the efficiency of all equipment systems and using renewable energy sources. The goal is to realize positive energy buildings able to self-produce on-site more energy than is needed to meet the different needs.

Architectural choices, system engineering choices, and economic feasibility are closely intertwined: each architectural choice entails a construction cost and a cost of operation that can vary considerably. In choosing the most appropriate building technologies, architects, and system engineers should discuss, already in the concept design phase, to verify the energy and economic effects of these choices. Through dedicated BPS software it is possible, in fact, to simulate the behavior of the building-plant system and verify in real-time different technological choices (materials, fenestration, orientation, types of shading systems, renewable sources, HVAC and lighting, etc.) (see [Chapter 5](#)). More advanced design methods further allow automated modeling of systems and equipment according to the architectural choices via parametric and scripted design tools (i.e., automatically placing lighting fixtures or water sprinklers according to room surfaces), up to the application of AI and generative design techniques to identify the best solutions among thousands of alternatives according to the engineers requirement (see [Chapter 6](#)).

Plant engineering choices, obviously, will have to take into account a careful cost-benefit analysis (LCC): higher initial investments must be justified by savings during operation and maintenance, by greater thermohygrometric well-being and, in any case, by a significant reduction of environmental impacts. One well-known procedure to evaluate the maintenance costs of a building is value engineering (VE), also known as value/cost management, a systematic technique to evaluate the value of building services based on the ratio of function to cost ([JRC, 2021e](#)).

The design of the technical systems is based on the one hand on the results that emerged during analysis and programming regarding the needs to be met, the legislation to be respected, the characteristics of the environmental context, and the performance to be provided, on the other hand on the architectural and technological solutions identified jointly with the other actors involved in the project (shape and orientation of the building, inclination of the surfaces, characteristics of the structure and envelope, materials, layout of the rooms, depth and height of the rooms, orientation, size, and arrangement of openings and shadings, etc.).

The first objective is the definition, with the greatest possible degree of precision, of the electrical, thermal, and refrigeration needs of the building both from a quantitative and qualitative point of view. Once this information is known, the evaluation of the best technological and plant solution for improving the energy performance of the building will take into account the following main aspects:

- primary energy savings achieved with the proposed solution;
- reduction of the environmental impact resulting from direct (fuel consumption) and indirect (electricity consumption) atmospheric emissions with particular reference to CO₂ (the main climate-altering gas produced in energy transformations);
- economic profitability of the proposed solution (LCC) using the known parameters of the net present value (NPV) and the internal rate of return (IRR);
- architectural integration;
- durability and ease of maintainability.

Informed decisions include the types of plant to be adopted; the physical quantities and sizes of the system (thermal and electrical powers, flow rates, etc.), the quality standards of materials (pipes, valves, channels, electrical cables, lighting fixtures, sanitary appliances, insulation, etc.). In particular, main technological elements able to maximize indoor environmental quality and reduce energy consumption and environmental impacts include:

- renewable energy sources integrated into the building to cover both thermal and electrical needs;
- high energy efficiency class equipment, with particular reference to electrical heat pumps for space heating, cooling and hot water production, focusing on the latest heat pump technology using CO₂ as working fluid and on combined heat and power (CHP) and combined cooling heat and power and cooling (CCHP), along with the introduction of variable flow systems;
- energy recovery systems (condensing boilers, heating recovery ventilation systems, dual compressor heat pumps);
- thermal storage including sensible (hot water, underground storage), latent (ice storage, phase-change materials) and thermo-chemical storage;
- electricity storage systems (lithium ion batteries, fuel cells);
- flow regulator power systems to reduce energy consumption of electrical installations through the adjustment and stabilization of the energy flow;

- hybrid natural cooling systems to precool ventilated air through ground pits, air exchange, water and night sky radiative cooling;
- low temperature conditioning equipment, such as floor, wall or ceiling radiating panels integrated with thermal solar, heat pumps or condensation boilers;
- highly efficient lighting systems (LEDs, OLEDs, QLEDs) and building appliances equipped with connectivity features;
- MERV and HEPA rated air filtration for IAQ.

Detailed systems design is finally completed by the description of the operating, regulation, and control characteristics of the plants, the maintainability of the system components, as well as the maintenance programs and the related operating costs.

Nonetheless, to best ensure optimal operation, all building parameters shall be adequately controlled and monitored (see Table 2.27). It is fundamental to provide interoperable energy control, monitoring, and automation tools for efficient HVAC, domestic hot water production, lighting, shading, energy storage and generation, transportation, and other building services while ensuring high levels of indoor environment quality.

Suboptimal control of energy-consuming systems such as heating, cooling, ventilation, and lighting is in fact endemic in existing buildings, having spaces heated when it is not necessary, lighting left on, ventilation operating continuously at maximum capacity, etc. As a result, large quantities of energy are wasted, and thus, a considerable potential for savings is presented. Building automation technology and control systems (BAT/BACS, or BAS) are indeed identified by several studies as a missing link for the successful implementation of zero energy buildings. BAS can improve the use of renewable energy sources and increase overall grid stability by providing buildings with demand side load shifting and storage management capabilities. By integrating demand response enabling elements into BAS, it is

TABLE 2.27 BAS main control functions (JRC, 2020).

Heating and cooling

- Emission control (e.g., individual room temperature control with BAS including schedulers and presence detection can lower the general heat demand);
- Control of distribution pumps in networks (e.g., switching off circulation pumps when not required);
- Heat generator control for combustion and district heating (e.g., reducing the return temperature based on load forecasting to increase boiler efficiency by condensation);
- Heat generator control for heat pump (e.g., controlling the exit temperature base on load forecasting);
- Heat pump control system (e.g., inverter driven variable frequency compressor depending on the load);
- Other functions: Sequencing of different heat generators, thermal energy storage, control of thermo active building systems (TABS);
- Interlock between heating and cooling to avoid simultaneous heating and cooling.

Domestic hot water (DHW)

- Reduce standby losses in hot water storage tanks (if any) with automatic on/off control based on forecasted demand;
- Control of DHW pump (if any).

Air supply or ventilation

- Demand-driven variable outside air supply;
- Heat recovery unit, icing protection;
- Free air night time cooling mechanical by automatic opening windows and/or operating the ventilation unit;
- Humidity controls (if any).

Lighting

- Occupancy control for indoor lighting;
- Control artificial lighting power based on daylight levels.

Dynamic envelope

- Window open/closed and solar shading control.

Electricity

- Storage of (locally generated) electricity;
- Optimizing self-consumption of locally generated electricity;
- Control of combined heat and power plant (CHP);
- Support of (micro)grid operation modes;
- EV charging grid balancing.

TABLE 2.28 BAS Reporting functionalities.

System Domain	Reporting functionality
Heating, cooling, domestic hot water, electricity	Central or remote reporting of performance evaluation including forecasting and/or benchmarking, also including predictive management and fault detection
Controlled ventilation	Real time monitoring and historical information of IAQ available to occupants plus warning on maintenance needs or occupant actions (e.g., window opening)
Dynamic building envelope	Position of each component, fault detection, predictive maintenance, real-time, and historical sensor data (wind, lux, temperature, etc.)
Electricity	- Real-time feedback or benchmarking on appliance level with automated personalized recommendations - Central or remote reporting of real-time energy use per energy carrier, combining building systems of all main domains in one interface (monitoring and control) - Reporting information on current, historical and predicted demand side management (DSM) status, including managed energy flows (monitoring and control)

possible to achieve the best building energy system interaction, and to optimize at the building level, the energy consumption, production, and storage considering the availability and price of energy supplied via the grid.

Assessments based on EU Standards and official Cost Optimal Building Performance requirements show how intelligent controls and BAS technologies produce consistent energy savings in residential dwellings and in commercial buildings, in which energy consumption reductions up to more than 50% are also reported.

Main BAS functions include (EN 15232–1:2017 and EN 16947–1:2017):

- set point management, for example, web operated heating/cooling temperature set points (20°C/26°C) with frequent resetting to default values where relevant;
- run time management, for example, predefined schedule (e.g., a night time set back temperature) with variable pre-conditions (e.g., no presence in the room);
- management of local renewable sources or CHP to optimize own consumption and use of renewables;
- control of thermal energy storage of heat recovery (if available);
- smart grid integration;
- detection of faults in building equipment;
- reporting functionalities—this includes reporting on performance, temperatures, and energy consumption, as well as reporting on maintenance, fault detection and fault prediction (actual values and logged trends).

BAS can today take advantage from recent advancement of IoT technology that allow sensing and computing capability to be integrated in all energy consuming equipment (air conditioning systems, electrical switches and outlets, lamps, appliances, plumbing, etc.) or in building envelope elements such as doors and windows, offering users the possibility to optimize energy efficiency, microclimatic conditions, safety, and security. Integrated with pervasive and unobtrusive wireless networks of IoT sensors and powered by powerful AI and predictive control systems, most advanced BAS allow integration and interoperability between all building subsystems and empower the user with direct control and reporting on a wealth of building services via natural human interfaces such as face and gesture recognition and voice control (see [Chapter 10](#)).

The transition toward more efficient and smart buildings requires also a change in user's behavior with respect to the uptake of energy efficiency solutions and the increasing use of renewable energy sources. It is therefore essential to provide building occupants with purposeful and easy to grasp information on the environmental conditions and building services status and consumptions (see [Table 2.28](#)). Data collection and analysis is also important for automated and predictive fault detection and diagnosis, which has the potential to significantly improve both the energy performance, by identifying inefficient operation, and the maintenance of the building.

2.3.4 Building integrated renewable energy

To meet global energy and climate goals, renewable energies must make a significant contribution in covering the energy needs of buildings. Buildings can facilitate the greater uptake of renewables in many different ways, such as

self-production (with photovoltaics, solar thermal and geothermal) or by interoperating in a smart district where a number of buildings optimize the use of renewable energy (through a district heating system, micro grids or using waste heat).

Among the different possible sources of nonfossil energy (wind, solar, aerothermal, geothermal, hydrothermal, tidal, hydropower, biomass, landfill gases, residual gases from purification processes and biogas), those that can more easily be applied in today architecture are undoubtedly solar technologies, vertical axis wind technologies, biomass, and energy harvesting systems such as in-pipe mini-hydro systems and piezoelectric and electromechanical systems for pavements.

Renewable energy can be used in various forms in thermal systems, such as through the capture of solar heat gains for space or water heating, the use of biomass for heating, or heat pumps (thermal, geothermal, or hydrothermal) for space and water heating as well as for space cooling. Electricity can be produced by photovoltaic, wind, mini-hydro and piezoelectric and electromechanical systems. The use of cogeneration (CHP) or trigeneration (CCHP) systems using gas, biomass, or hydrogen with fuel cells, allows to combine the production of electrical and thermal energy ensuring greater conversion efficiencies compared to separate production. District heating and cooling systems driven by energy from renewable sources are also viable.

All these technologies shall be accurately mixed, integrated, and operated according to the specific climate and local conditions, including cost and incentives. Hybridization can achieve better results both for thermal energy production and for power generation. The integration of energy storage systems is also an increasingly recommended strategy to maximize the utility of integrated renewable energy sources.

Indeed, since electrical systems require to balance supply and demand over time, the use of renewable energies means a growing challenge to the operation of electrical systems due to the variability and uncertainty of such energy sources. In this picture, the storage of both thermal and electrical energy could balance daily and seasonally varying energy supply and demand, and would lead to a reduction of expensive peak-energy supply. Storage possibilities will facilitate change in consumption over time through load shifting and peak shavings, ensuring demand-side flexibility in response to availability of renewable sources, needs of the occupants and grid requirements (see [Sections 12.2 and 12.3](#)). Electricity storage in buildings mainly employs batteries (including lead acid and lithium-ion ones); thermal storage includes water tanks, ice chillers, PCM tanks, PCM slurries, and sorption thermal energy storage. Plug-in hybrid and electric vehicles can also be integrated into the shared energy concept as V2B and V2G, serving as both electrical storage and load management devices, but also providing backup power during emergency situations such as natural disasters.

In new constructions, the objective of integrating renewable energy sources entails important implications at the design level in terms of location, shape, and orientation of the building, inclination of the absorbing surfaces, location and size of technical rooms, buffer zones, geotechnical engineering (geothermal heat pumps). On the other hand, the choice of the most suitable technology to meet the energy needs will have to consider, in addition to the availability of the source itself, also the actual energy needs and peculiarities of the building itself. The choice of the best technology to install must include, in addition to an estimate of the total energy consumption (thermal and electrical) and their temporal distribution over the year, also a thorough assessment of the vocation of the place to use renewable energy, as well as an examination of the technologies actually available on the market, of the regulatory, financial, contractual, tariff, and interconnection to the electricity grid aspects. This study will result in a careful cost–benefit assessment aimed to identify the technical, economic, and environmental advantages of the chosen solution.

With regard to the energy availability, the potential of the site will be evaluated in terms of:

- access to electricity produced from renewable sources supplied by the supply company and indication of the maximum percentage that can be supplied;
- exploitation of solar energy, in relation to the climate and the layout of the site, for the production of hot water for sanitary or heating uses (thermal and thermodynamic solar panels) or electricity (photovoltaic solar panels);
- exploitation of wind energy in relation to the annual availability of wind;
- exploitation of any watercourses as an electromotive force;
- exploitation of biomass (produced by local agricultural processes or wood processing waste) and biogas (production of biogas included in agricultural production processes);
- amount of heat extractable from the ground by geothermal probes for powering heat pump systems for the production of thermal energy;
- possibility of installing microcogeneration and district heating systems.

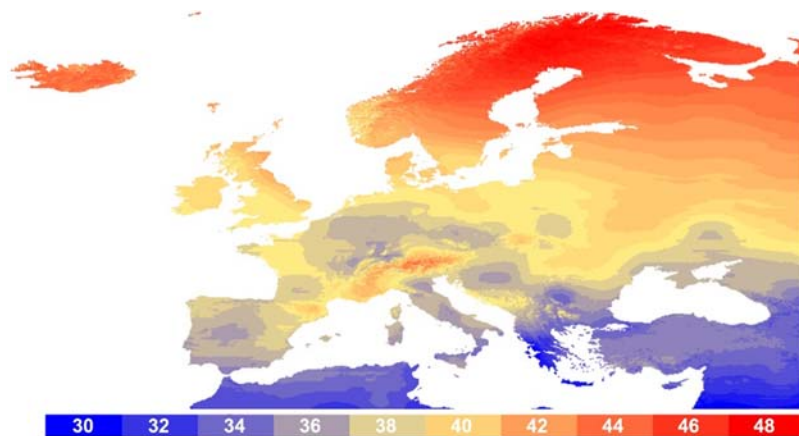
Therefore, it emerges that the quantity of energy available for conversion is a local quantity strictly connected to the characteristics of the site, both through the geographical parameters (solar radiation) (see [Table 2.29](#)), and through the general climatic conditions and specific microclimatic conditions (windiness, rainfall, and morphology of the ground).

TABLE 2.29 Average global horizontal solar radiation at different latitudes (Photovoltaic Geographical Information System PVGIS).

Lat. N	Annual global horizontal radiation (kWh/m ² year)
10 °	3250
20°	2500
30°	2200
40°	1700
50°	1000
60°	975

TABLE 2.30 PV energy production for different orientation and inclination of modules.

Orientation	Energy production (South 30° = 1.00)			
	0°	30°	60°	90°
East	0.93	0.90	0.78	0.55
South-East	0.93	0.96	0.88	0.66
South	0.93	1.00	0.91	0.68
South-West	0.93	0.96	0.88	0.66
West	0.93	0.90	0.78	0.55

**FIGURE 2.28** Optimum tilt angle of PV panels to maximize incident radiation (Šúri, Huld, Dunlop, & Ossenbrink, 2007).

Building integrated photovoltaics (BIPV) systems are a promising solution for clean electricity at building level and new technologies now allow full architectural integration for any type of building and surface.

For a given surface available and PV technology, the energy that can be produced depends on the latitude, the local climatic conditions (sky condition, atmospheric pollution, temperature and winds, albedo) and the solar access of the absorbing surfaces (orientation, inclination, shading phenomena) (see Table 2.30). For a given location, the greatest contribution of solar radiation on an annual basis is normally obtained with panels oriented to the South (North for the southern hemisphere) with an inclination of 5–10° lower than that of the latitude of the place (see Fig. 2.28).

Particular attention must be paid, however, to determining any shading phenomena caused by external bodies (buildings, antennas, chimneys, trees, etc.) capable of reducing the yield of the solar system. In this sense, in the case of development areas, it is also essential to evaluate the local urbanization policies envisaged to avoid that, after the system is

installed, the panels may end up shadowed by a new building that has since been built. If a panel is fully shaded, the power output will be close to zero, but partial shading can also have a big impact not only on panel efficiency, but also on the whole system efficiency. Strings of panels are connected in series and shading one panel can affect the whole string. For example, slight shading can reduce panel power output by 50% or more, which in turn can reduce the entire string power by 20%–30%. Add-on devices known as optimizers and microinverters can reduce the negative effect of shading, especially when only a small number of panels are shaded. The same problem may be reversed in case the intervention is programmed in areas where neighboring buildings with solar technology systems are present.

Concerning the conversion of wind energy, the new generation of vertical axis turbines capable of exploiting the wind from any direction, including the updrafts typical of urban centers, allows promising integration with buildings in replacement or in addition to photovoltaic systems. With a height from 2 to 10 meters, small wind turbines can be placed on rooftops, on streets or in gardens, have relatively little visual impact and are able to produce energy even from modest wind flows (2 m/s). The identification of the turbines position must however be preceded by a thorough analysis of available winds, because turbulences or areas of calm, generated by surrounding buildings or different obstacles located on the roofs (air conditioning systems, antennas), could lead to an energy production significantly lower than expected. At the same time, it is possible to benefit from the interaction between the wind and the built environment in order to channel air currents to very specific areas where wind turbines can be installed. Turbines able to exploit the concentration of wind power due to the shape of the building are known as building augmented wind turbines (BAWT) and their different configurations include positioning close to the building, on the rooftop or along the sides, between buildings or inserted in air conducts through buildings (see [Section 12.3.1.2](#))

2.3.5 Landscape and vegetation

Landscaping and vegetation elements can strongly connote the context of a building and its environmental quality, with direct effects on the building itself. Trees, bushes, and herbaceous species can, in fact, perform an important function in controlling the local microclimate, on which thermal, light, and acoustic comfort depends. This occurs both for their function as a barrier to solar and light radiation, noise pollution, and prevailing winds, and for the phenomena of evapotranspiration that influence the temperature and humidity of the air.

The solar control function performed by vegetation barriers essentially derives from their ability to intercept direct solar radiation, absorbing it before it hits the building, and to limit the component reflected by the ground by casting shadows on it. The shade of trees depends on variable factors depending on the species considered, including the geometry, dimensions, and height of the crown from the ground, which vary according to age and growth; the shape, size, and density of the leaves, which affect the permeability of the foliage to solar radiation; and the seasonal vegetation cycles, which distinguish the tree species into evergreen and deciduous.

In general, deciduous plants are preferred for the solar control function. Vegetation periods, relating to the fall and germination of the leaves, shall be checked to evaluate shading in each season. The percentage of shielding of a deciduous tree varies seasonally and consistently with thermal comfort demands, being reduced in winter and reaching maximum values in summer. Moreover, it adapts to seasonal variations of the foliation cycle, delaying the germination in cold spring periods, and the fall of the leaves in warm autumns. Placed near the building, these tree species can reduce the incident solar radiation during the summer period, without excessively interfering with the winter solar gains. The position in which to place the trees varies according to the exposure of the facade to be protected and therefore to the grade of the rays that are projected on it. Since the sun in the morning and late afternoon is low on the horizon, the plants perform best on the East-Southeast and West-Southwest sides. When the sun is low, it casts long shadows that can be used effectively to protect the sides of the building. In the central hours of the day, the sun is high thus its rays shall be intercepted by means of a horizontal projection; trees placed on the south side of the building give poor performance, casting the shadow only near their base.

In the presence of high levels of noise in the external environment, it is possible to resort to appropriate shielding systems by creating morphological remodeling of the building close to critical areas using special plant-type noise barriers. For these plant barriers to effectively contribute to the attenuation of noise levels, it is necessary to carefully evaluate the density of the foliage, the periods of foliation and defoliation, their size, shape, and growth. Due to sound diffraction, the attenuation power of vegetation is generally very small, worth a few decibels. To obtain appreciable effects, very dense vegetation with leaves of great circumference for great distances is required; for instance, to obtain a reduction of 8 dB (A), a high density tree barrier at least 30 m wide is required. Better results can be obtained with specific, slender embankments constituted by metal scaffolding and soil pouches in organic fabrics. These screens are sown with vines which cover their vertical surfaces and create a sound-absorbing layer of leaves and flowers.

To improve indoor and outdoor air quality, possible design solutions concern the positioning and shape of the building, the reduction of pollution sources within the site and the use of protective barriers. Building layout and shape must favor the removal of pollutants rather than their stagnation, by placing open spaces upwind the polluting sources and away from the “channels” of flow of pollutants and orienting the buildings parallel to the dominant air currents. Although less effective, the only viable strategy is often the use of the perimeter areas of the site as protection from polluted air flows, for example, by morphological remodeling the terrain close to critical areas, with the introduction of natural or artificial elements acting as a barrier to air flows carrying polluting substances. Plant belts arranged in the perimeter areas of the site should be composed of tree and shrub species suitable for absorbing the substances: contrary to what happens for noise protection, vegetation is more effective than artificial barriers as it acts as an air pollution filter by separating the source from the target and absorbing pollutants.

The impact of vegetation on the free diffusion of air varies according to specific characteristics such as: wood impact surfaces; leaf area; interstitial spaces between leaves, physical and chemical surface characteristics of leaves, the stomatal density. The interception of solid particles may occur by sedimentation, by impact under the influence of air currents, by deposition through precipitation. Vegetation is less effective in removing gaseous pollutants, acting through physical and chemical mechanisms, which occur on the outside of the leaves and in the plant tissues. The choice of trees resistant to pollutants, especially in an urban environment, is an important factor for environmental quality; it must ensure an effective filtering action and, at the same time, the survival of the trees themselves. Evergreen species are preferable, as they are also effective in winter when urban pollution levels are usually highest; nonetheless, deciduous species maintain a partial filtering function even in winter as a result of the impact of dust on the branches and the stem.

The vegetation, which has an absorbing effect on environmental pollutants thanks to the photosynthesizing action, must be arranged as a windbreak with respect to the direction of the prevailing winds, in relation to the source of pollution, with attention to the height, species, density, and shape of the plant materials used. Protected area results from the height of the plant barrier, which reduces the wind speed in the leeward area by an extension equal to approximately 20 times its height. The most effective barrier should have about a third of voids in its density and would be composed of evergreen species for about 50% of its constitution and 50% of deciduous species to ensure permeability. The barrier will be structured by aggregating trees with bushes, which will occupy the median body located between one tree and another, and with a polyphite lawn at the base, consisting of a greater number of leguminous species for better rooting of the major species. Particular attention should be paid to the arrangement of the rows of trees so as not to compromise the crossing of the sun's rays in winter and the circulation of summer breezes.

Regardless of their intended use, new plant species must be chosen taking into account not only their performance, but also their specific requirements in relation to the climate, the type of soil, and the need for irrigation and pruning. A method for determining water demand for landscaping plants is set out in ANSI / ASABE S623.1: Determining landscape plant water demands.

In particular, the choice should preferably be oriented toward native species, which demonstrate a good adaptation to the environment in which they are inserted and which are resistant to the typical pollutants of the place. Especially in areas with low annual rainfall in general, xeriscaping principles should be applied.

Furthermore, it is important to evaluate how some species may be incompatible with certain functions envisaged for the specific external space. For instance, the insertion of plant essences inside parking areas will have to evaluate the aspects related to the possible production of viscous substances, or to the possibility that certain trees drop fruits or berries, causing damage. The degree of resistance to winds must also be evaluated, to prevent the branches from breaking, as well as the posture and characteristics of the crown for evaluating the shading potential.

2.3.6 Design for construction and deconstruction

The stage of building construction is an extremely important phase within the environmental sustainability of the building's life cycle. The construction site activity in fact involves the following main processes:

- reclamation of the area, earth movements, definition of the roads;
- preparation of the construction site barracks and of equipment and machinery;
- transport, storage and processing of building materials;
- excavation operations for the construction of foundations and underground parts;
- construction of the building (foundation and elevation structures, vertical perimeter walls, roof, internal partitions, systems, external fixtures, external and internal finishes);

- storage and transport of construction site waste;
- arrangement of external areas.

Each of these activities implies the consumption of raw materials and energy and the release of byproducts into the environment, in greater or lesser quantities according to the characteristics of the area, the size and type of work to be carried out, the type of construction systems adopted (dry or wet), the type of materials used (weight, workability, etc.). These aspects concern in particular:

- land use and contamination;
- use of natural resources and raw materials (including energy);
- reduction, recycling, reuse, transport, and disposal of solid and other waste, especially hazardous waste;
- emissions into the air;
- water discharges;
- goods and employees transport;
- risk of environmental accidents and potential emergency situations;
- effects on biodiversity.

Compared to other industrial sectors, moreover, the construction activity generally involves problems that directly affect the surrounding population during the period of operation of the work site. These include noise, dust, the movement of vehicles, and the limitations of mobility within the construction yard and also in neighboring areas.

The contractor shall correctly manage these aspects, including relations with the public, right from the design stage, and shall have already considered the conditions for the restoration of the affected areas at the end of the works. The main difficulties lie in the fact that, while for an industrial site the activities are always similar over time, in a construction site they change both according to the type of building and in relation to the place and construction phase in which they take place. Construction companies will therefore have to implement an environmental control system of those basic processes that are repeatedly carried out on site, and plan environmental criteria for selecting the raw materials used, delegating to specific environmental analyzes the control and minimization of the impacts of each single construction site and the verification of the relationships with the spatial, social, and environmental context in which the transformation takes place.

Adequate training must therefore be provided to the workforce, which is often temporary as well, in addition to the development of recovery plans to improve the environmental conditions of the area at the end of the activities, if necessary. Great importance must be given to communication with the interested parties, in order to adequately inform the resident population in the area and the local authorities on the important environmental aspects associated with the work plan and the relative solutions identified. Communication to local communities must cover all information that is useful for understanding the commitment of the organization and the possible dangers to health. There is in fact an increasing demand from the population to know what is happening inside the construction sites, how the urban physical space is being transformed and what visual and functional effects the transformations will bring to the perception of that same area.

2.3.6.1 *Design for lower impact in construction*

Design for a more sustainable and efficient construction process implies the implementation of numerous strategies, mainly aimed at reducing the quantity of materials used and waste produced on site and at reducing the environmental impacts deriving from the transport and construction phases. These strategies add on top of those aimed at reducing environmental impacts in the product stage, which concern in particular the use of products with lower environmental footprint and the design for an efficient building shape and form.

From this perspective, the first strategy to be implemented certainly concerns the possibility of reusing and possibly reconverting an existing structure, through the practice defined as adaptive reuse. Across the world, there are in fact several thousands of unused structures, such as factories, office buildings, shopping malls, train stations, etc., that offer an opportunity for creating a new space without actually constructing new buildings from scratch. For instance, in New York City around 20% of the 14,000 properties managed by municipal agencies are not being used, and overall city building stock is home to a 6% retail vacancy rate, which accounts for hundreds of abandoned storefronts.

Adaptive reuse projects are generally faster, more cost-effective, and more sustainable to construct than new buildings by reusing materials and avoiding demolition. Reuse projects can cut embodied carbon by up to 70% compared to demolition and reconstruction (JRC, 2021c). In terms of economic benefits, studies suggest that compared with a new construction, adaptive reuse and restoration can be 16% cheaper in terms of construction costs and take 18% less

execution time. Moreover, many local governments, such as in California, provide incentives for adaptive reuse through increased flexibility in zoning requirements and building codes related to construction, height, parking spaces, setbacks, and tax breaks. In the UK, the Department for Communities and Local Government has extended permitted development rights, so that change of use from office to residential no longer requires a formal planning application, with some exemptions such as listed buildings and ancient monuments. This is intended to “support an increase in housing supply, encourage regeneration of offices and bring empty properties back into productive use.”

Furthermore, adaptive reuse is an important part of cities redevelopment over time and allows to extend the useful life of buildings as societal and technological needs evolve, to preserve architectural and cultural heritage, to transform urban decay phenomena into sparking social change by revitalizing the businesses around abandoned buildings and so restoring economic confidence in a region.

There are more and more examples of adaptive reuse of buildings in the world, and in the next decade 90% of real-estate development is expected to focus on the renovation and re-use of existing structures. For instance, numerous interventions carried out so far concern old suburban malls built in the latter half of the past century repurposed into mixed-use developments that include apartments, collaborative office spaces, retail and entertainment spaces, and some civic amenities, or converted for diverse uses such as medical centers, churches, and public spaces. Best known examples of adaptive reuse certainly include the High Line Park in New York City (see [Fig. 2.29](#)), the raised urban park of 2.4 km once the site of an elevated railway line that carried food along the west side of the city, now home to hundreds of native plants, and the 2019 conversion of the iconic TWA Flight Center terminal, designed in 1962 by Eero Saarinen, to a boutique hotel. The 512-rooms hotel has meticulously preserved the former terminal character and features guest rooms with floor-to-ceiling noise-insulating windows.



FIGURE 2.29 High Line Park, NYC .
(photo by the author).





FIGURE 2.30 Zeitz Museum of Contemporary Art Africa.
Courtesy of Arup.



FIGURE 2.31 California Academy of Sciences.
(photo by the author).

Other notable examples are the Victorian gas holders in King's Cross, London, built in 1860 and converted in 2018 into apartments, or Cape Town's grain silo built in 1924 and converted in 2017 into the Zeitz Museum of Contemporary Art Africa, a 6000 m² exhibition space hosting 80 galleries, a rooftop sculpture garden, bookshop, restaurant, bar and reading rooms, along with storage and conservation areas (see [Fig. 2.30](#)).

Nonetheless, adaptive reuse is not the answer in every case and priority constraints have to be considered at the early stage of planning: condition of the existing building, availability of archive information, floor to ceiling heights, wall conditions, depth of the building, internal space, layout and access (including vertical circulation), historic listing, building structure, load capacity, redundancy, and foundations. As all new developments, including refurbishments, must comply with the latest safety standards, lifts, escape routes, and travel distance are fundamental aspects that often do align with existing building layouts. In particular, lifts and alterations to cores, which often provide stability to the building, are among the most expensive structural interventions. Building digital twin and generative design are innovative tools that can support architects in rethinking and redesigning layouts that best use the space available.

When adaptive re-use is not practicable and existing buildings must be demolished, the second strategy to be taken into consideration is to proceed with a demolition as selective as possible in order to recover materials to be reused in the project or recycled. A well-known example in this sense is the Academy of Sciences in San Francisco (see [Fig. 2.31](#)), United States by Renzo Piano Building Workshop, which construction works allowed to recycle 90% of demolition materials from the 12 buildings that previously stood at the site. In particular, 32,000 tons of sand from foundation excavation were applied to dune restoration projects in San Francisco, 12,000 tons of steel were recycled and went to Schnitzer Steel; 9,000 tons of concrete were reused in Richmond roadway construction; 120 tons of green waste were recycled on site.

The procedures to follow and the degree of separation that can be achieved depend on the following main aspects:

- the potential of the materials that make up the building to be sent for recovery and/or recycling processes;
- the construction techniques with which the building was built;
- the availability of spaces in the demolition site for the collection of waste and recovered materials;
- the distance of the site from other buildings and recovery plants;
- the road system.

The deconstruction plan shall also consider regionally available facilities and processing equipment, which in turn will be influenced by national and regional WMP. It should identify and address how to deal with safety, security, and environmental issues, including, as a minimum, a distinction about how to deal with hazardous and nonhazardous wastes on site. Ideally, the deconstruction plan makes provision for the separate collection of different types of demolition waste as a function of planned treatment options, which may include:

- cleaning for reuse (e.g., contaminated soil);
- reuse (e.g., structural steel, metal sheet, bricks, and roof tiles);
- recycling in the same application (e.g., metals, paper, glass, asphalt);
- recycling/material recovery in another application (e.g., bricks to aggregates, wood to particleboard);
- energy recovery (e.g., wood, plastics, certain insulation materials);
- disposal (e.g., landfill or thermal destruction without energy recovery).

From an operational point of view, today it is possible to leverage LiDAR and BIM techniques to create a so called MP, that is, a document containing a complete description of all products (staircases, windows, furnaces, etc.), components (iron beams, glass panels, etc.), and raw materials (wood, steel, etc.), that are present in the building, facilitating their most effective reuse. Better understanding of older or heritage sites allow to reuse the core of existing structures or make recycled materials central to a new project's design. By proceeding with the separation at the origin of the different categories of waste, it is possible to process not only the typical construction materials such as brick, concrete, and mixed rubble, but also wood, plastic, glass, and metals that can be transferred to the respective recycling or energy recovery channels. Selective demolition not only allows to recover almost all of the waste produced, but also allows the production of high quality secondary raw materials for construction by recycling homogeneous waste (see [Table 2.31](#)). Cladding boards, tiles, timber, bricks, stones, architectural elements, doors, windows, and iron elements all have a good potential for reuse: after a process of cleaning, repair, and adaptation they can be re-employed in their original function. If they are in a bad state of conservation, they must be dismantled in order to recover the individual constituent materials (e.g., wood, glass and iron) to be sent for recycling.

The metal parts should be reused as much as possible, but the high value of the waste makes their reintroduction into ordinary production processes possible and convenient. Metals such as steel, copper, and aluminum are recyclable over and over again, maintaining the same chemical-physical and technological characteristics of the primary materials, without limitations of use or decrease in value. The recycling of metals also allows a considerable environmental and economic advantage by reducing the consumption of resources and energy compared to the primary manufacturing process.

Concerning plastics, PVC is one of the most easily recyclable materials from a technical point of view. Recycled PVC can be reused for the same initial function, because it retains many of its physical-mechanical properties unaltered and provides excellent results even if traces of other plastic materials remain incorporated in the material. For recycled PVC there is a market with a growing demand, especially in the sector of rigid products, from pipes made entirely of recycled PVC to multilayer ones (with the main layer—equal to 60%—in recycled PVC), from injection molded accessories to formed profiles, from floors to sweaters, from footwear to bottles for nonfood products.

Although concrete cast in situ cannot be physically reused, it can be recycled to replace aggregates in the preparation of new concrete (up to 20% of natural aggregates) or used in road embankments. Materials resulting from the treatment of the aggregates and the bituminous conglomerate resulting from the scarification of the road surface, defined as “recycled aggregates,” find the following possible re-uses:

- embankments of civil engineering earthworks;
- substrates for road, railway, airport, and civil and industrial yards;
- foundation layers of transport infrastructures;
- environmental recovery, landfilling, and filling;
- accessory layers for pavements (having an anticapillary, antifreeze, draining function, etc.);

TABLE 2.31 Reuse, recycle and recovery potential of main construction materials (JRC, 2021d).

Material	Alternative 1 (preparing for reuse)	Alternative 2 (recycling)	Alternative 3 (recovery)
Concrete	Re use of precast concrete blocks with large environmental benefit especially due to avoided need for cement.	Crushing for use in concrete production, ideally on site (recycling). 40%–50% of waste concrete is acceptable (uncertain for bricks, etc.). Main benefit is avoided demand on virgin material quarries.	Crushing for use in road construction or backfill (recovery). Up to 75% of waste concrete is acceptable (uncertain about bricks, etc.). Main benefit is avoided demand on virgin material quarries.
Bricks, tiles and ceramic	Reuse of bricks, tiles, and ceramic, with large environmental benefit due to avoided need for firing.		
Bituminous materials	In situ recycling can accept up to 100% of waste asphalt. Main benefits are reduced need for bitumen binder, virgin material quarries, and transport.	Recycling in a stationary plant. 30%–80% of waste asphalt can be accepted. Main benefits are reduced need for bitumen binder and virgin material quarries	Material recovering as aggregates. Up to 41% of waste asphalt is accepted. Main benefit is the reduced need for virgin material quarries.
Wood	Pieces of solid wood (e.g., floor-boards, beams, etc.) to be manually removed, sanded, cut to size if necessary and varnished accordingly.	Recycling into derived timber products. Around 33% of waste wood can be accepted. Benefits of prolonging the presence of wood in the value chain and reducing demand for virgin wood and avoided methane emissions in landfill.	Energy recovery. Up to 100% of waste wood is accepted. Benefits of “renewable” electricity and heat destruction of any harmful organic compounds present, and avoided methane emissions in landfill.
Gypsum		Use in manufacture of plasterboards. Up to 30% of gypsum waste is accepted. Benefits are avoided need to quarry virgin gypsum and avoided hydrogen sulfide emissions from landfill.	Use as an additive in cement. Uncertain how much waste gypsum could be used this way. Avoids the need to quarry virgin gypsum and hydrogen sulfide emissions from landfill.

- concrete with resistance class $R_{ek} \leq 15$ Mpa, in compliance with the harmonized standard UNI EN 12620: 2004 and in accordance with the indications of the UNI 8520–2 standard.

Through a process of vibro-compacting under vacuum, mineral materials such as marble, granite, limestone, and siliceous stones can be combined with portland cement and a limited amount of water to form agglomerated stones for internal and external floors and walls (each tile containing about 75% of natural stone).

Remarkable examples of reuse of materials in new constructions include the Kendeda Building of the Georgia Institute of Technology in Atlanta, United States (2021), which features several salvaged materials in its structure and on its grounds, including wooden beams from dismantled movie sets that were repurposed as panels for floor decks, and the 6 Bevis Mark office in London, UK, that in 2018 won a sustainability award from “Ground Engineering” magazine for its innovative approach to piling, which enabled 66 of the piles from the previous building to be reused.

A third important strategy is to use advanced building construction methods and techniques such as prefabrication and modular construction, off-site and on-site construction automation, robotics and additive manufacturing, which are oriented to improving quality, safety, productivity, and sustainability of construction industry. Such methods are widely considered as a way to ensure, among the other benefits, lower environmental impact of the final construction site because of reductions in material waste, air and water pollution, dust and noise, and overall energy costs (see Chapter 8). In addition, engineered massive timber systems such as CLT are emerging in response to the need for more efficient and greener construction methods ensuring maximum flexibility in the construction phase and the minimum production of waste produced by work on site (see Section 7.5.2).

2.3.6.2 Design for deconstruction

Buildings have traditionally been valued based on their floor area, the location and land area they sit on, architectural features, and the use that can be made of the building. However, there is also a residual value that is locked into a

building via the components and materials it is made of. This locked-in value (often viewed solely as a future demolition and disposal cost) is maximized when these components and materials can be adequately retrieved at the end of life of the building for reuse.

In particular, one of the main strategies within circular economy is urban mining: this new approach toward recycling promotes the systematic reuse of anthropogenic materials from urban areas, of which a substantial amount is incorporated within buildings and infrastructures. This stock shows large resource potential that can eventually become available at the end of the lifetime (Honic, Kovacic, Sibenik, & Rechberger, 2019).

The main barrier to design for deconstruction is the separation between decisions made at the design stage of a building and those that may be made several decades later when the building reaches the end of its life. Studies of demolition and deconstruction practices have identified four main barriers to material reuse and recycling (JRC, 2021c):

- building designs: most current construction methods and materials do not facilitate the recovery of materials, with issues including contamination with hazardous materials, entanglement of services in structural elements and the use of composite steel and concrete systems;
- demolition processes: main schedules and practices do not support the recovery of materials in a useable state, for instance by using shears to cut steel sections because of welded joints, or are subject to excessively strict time limits;
- logistics: reclaimed materials require extensive space for storage up to their reuse, for example reclaimed steel sections have to be stored and often modified at a price before a new construction project needs that specific elements;
- market: there is a lack of demand for reclaimed materials, mainly caused by the limited supply and variability in sizes of elements or sections, caused by changes in standards and specifications over time, versus those which may be currently required, as well as by uncertainty about material properties and use history.

To promote the buildings as material banks (BAMB) concept and the circularity of materials in construction, two main actions should be encouraged (see Table 2.32):

- building information: information about the building should be passed on during project handover and include as-built drawings, the MP (which describes characteristics of materials and products valuable for recovery and reuse)

TABLE 2.32 Main strategies of design for deconstruction.

Scope	Actions
Building information	• Develop a deconstruction plan during design phase • Ensure as-built drawings are available • Establish feasibility of element reuse • Include information on deconstruction techniques • Think about early in design process (scheme and design development) • Train all team members on design for deconstruction
Design stage actions	• Avoid use of hazardous materials • Avoid use of resins, adhesives, and coatings • Design in tie offs for deconstruction • Do not use structural grout with precast elements • Ensure elements of the building are independent and separable (structure, envelope, services, fit out) • Ensure post-construction ease of access to fixings • Permanently mark materials with their properties • Reduce number of materials and components • Reduce use of concrete in situ • Size components for manual handling • Use components made of singular materials • Use durable materials • Use lime-based mortar with masonry • Use noncomposite floor systems • Use prefabricated and modular elements • Use reversible mechanical/nonchemical connections • Use standardized elements

and a deconstruction plan, as well as the conservation and update of BIM and digital twin models during the building's operating life;

- design stage actions: specific design decisions should favor the future separation of materials and elements.

By choosing elements and components that can be disassembled, and by providing clear instructions about their correct disassembly via building MP, the possibility to reuse that material or element is maximized. The level of information for each product could include the product features, reuse/recycling potential and visual details of the building element or material. In fact, the compiled MP serves both as design-optimization tool and as an inventory of embedded materials, thus representing an essential aid for the implementation of so-called urban mining strategy. The MP consists of qualitative and quantitative knowledge of the material composition and distribution within a building structure and gives the possibility to evaluate the embedded materials of a building according to their mass, recycling potential and environmental impacts. To maximize benefits of the MP, it should be compiled in early design stages, where changes with a high impact can be conducted at low cost (Honic et al., 2019). MP, LCA, and therefore BAMB approaches are complimentary with BIM and can slot into the building model and related documentation.

An interesting demonstration of design for deconstruction is the Urban Mining & Recycling unit prototype, designed under the direction of architect Werner Sobek within the NEST (Next Evolution in Sustainable Building Technologies) laboratory of ETH Zurich. Researching new joining technologies, nothing built into this unit was glued or coated, ensuring materials can eventually be recycled or composted as part of the building-material cycle.

2.4 Conclusion and future trends

There is little doubt that the current way of designing architecture, that has already significantly changed in the last 10 years, is destined to evolve even more profoundly following the new demands of contemporary society and the new innovative digital tools available, which were unthinkable only up to a few years ago.

This reflects the fact that architecture is a frontier art that closely mirrors society and is contaminated by other disciplines, and architects are tasked with continually redesigning themselves as well. It is a trade poised between art and science that necessarily uses the tools and materials of its time to express, in spatial and technical terms, the will of the current era. Moreover, architecture consists in a wonderful synthesis process in which hundreds of people are involved, that is fertilized by a multitude of factors: history, society, the emotions, hopes and expectations of people, geography and anthropology, climate, culture, and, again, science and art.

The substantial changes taking place concern the methodological approach, the objectives, the relationship with the context and with stakeholders and the analysis and design tools used.

The new and urgent needs of sustainability, comfort, and energy efficiency require a holistic approach to design, based on “life cycle thinking” and able to take into account the environmental, social, and economic effects of design choices on the entire life cycle of the building, from the identification of the site, to construction, to management, up to the disposal and recovery of materials (“from cradle to cradle”).

As for the objectives to be achieved, the requirements of indoor environmental quality and efficiency in the use of resources have become increasingly important, along with new objectives of adaptability, smart readiness, adaptation and resilience to climate change, and safe human interaction in response to global health issues. In this context, the adaptation of the building to the context has become absolutely central to the project. The challenge calls for an architecture that maintains or improves the quality of life of all stakeholders, in harmony with the climate, culture, traditions, and environment of the site, using energy and resources in a rational way, recycling or reusing materials, and, generally, reducing the release of harmful substances in the local and global ecosystem during its entire life cycle, bringing value to all involved actors. The design activity is perceived today more and more as a point of balance between collective needs and individual needs, within an open dialectic between the environmental context and the building in which the envelope, as the central element of mediation between the various interests at stake, constitutes the technologic and dynamic response to the environmental demand, capable of assuming the triple role of diffuser of urban quality, provider of comfort, and producer of energy.

Buildings shall be science-based, able to connect energy consumers and generators (prosumers), cost-effective, safe and healthy, and service-oriented to meet the sustainability demands of the populations served. They need to be performance-based as well and cognizant of the whole value chain, taking account of the amount of energy consumed to produce building materials for more accurate calculation of energy efficiency. Low-carbon and low-energy technologies shall be employed to encourage clean and renewable energy utilization and lower greenhouse gas emissions. A

lower water footprint can be achieved by adopting innovative rainwater harvesting and wastewater reuse/recycling technologies.

Therefore, both conception and delivery of buildings must be holistic and integrated, data-driven, based on energy models that reliably predict actual building performance, made using sustainable materials, equipment, construction methods, and management practices, always recognizing that buildings and their environment are part of a system. Due consideration shall always be given to passive building design where practicable.

In this scenario, digital design has begun its transition from CAD to BIM and in recent year's analysis and simulation tools (BPS tools, LCA software tools) have been integrated in standard workflows to pursue knowledge-based and data-driven design from the very beginning. In the coming years, the development and diffusion of new destructive technologies such as LiDAR, drones, virtual and mixed reality, cloud computing, and generative design through artificial intelligence will allow even greater possibilities both to explore design alternatives and to optimize them in a conscious way, involving all the actors concerned right from the start.

Finally, the wealth of data made available by construction sites and buildings equipped with IoT sensors will be collected and analyzed to obtain important insights on times, costs, and performance that will further improve decision support toward the construction of more and more sustainable buildings and an increasingly competitive construction industry. This step inevitably requires new and important skills from the designers concerning both physics of the building, new materials, and circular economy, and the use of digital tools with particular reference to the more innovative ones such as parametric and generative design, VR/AR, and digital twins.

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Chapter 3

Building digital revolution

3.1 Construction 4.0 technology drivers

The concept of digital transformation (DT) refers to the profound changes that are currently underway in both the economy and the society as a result of the pervasive uptake and integration of digital technologies in every aspect of human life. Indeed, digital technologies have already become the foundation of all innovative economic and social systems, and the transformation that results from their adoption is in turn affecting all sectors of the industry and services economy. It is a cross-sector global transformation with both positive and negative effects. In addition to directly transforming entire economic sectors, digital technologies are having increasing impacts on general population as well, changing the way people communicate, interact socially and, ultimately, live. Digital technologies and services have already transformed vehicles, transport infrastructures and the traditional concepts of mobility, are improving the security, affordability, stability and sustainability of the energy supply, are providing new options to deliver public services and interaction with citizens, and are changing the way an ever growing amount data is continuously generated and processed (IEA, 2017, 2019; IRENA, 2019a; JRC, 2019a). In this picture, DT is expected to be a strategic policy area for all countries in the next future.

Even the construction sector, which has always been reluctant to embrace Information and Communication Technology (ICT) and digital innovation compared to other sectors such as the manufacturing industry, has finally embarked on the DT path, which in this case concerns not only the design phase, already well reliant on digital tools (e.g., computer-aided design, structural analysis programs as well as budget and resource management software), but also in the construction and management phases that until now have particularly lagged behind (Autodesk, 2016; Boston Consulting Group, 2016; ECSO European Construction Sector Observatory, 2021; Frost & Sullivan, 2021; JRC, 2019a; McKinsey, 2016, 2017a, 2017b, 2018b; PEEB, 2019; Roland Berger, 2016, 2017, 2018; WEF, 2016).

This revolution in the architecture, engineering, construction and operation (AECO) sector, which is leading to the Construction 4.0 (C4.0) model, is due to the contemporary and synergistic development of key technologies, that have created the conditions for this change and in turn have triggered the development of further new technologies (see Table 3.1) (Qi, Razkenari, Costin, Kibert, & Fu, 2021).

All together, these are capable of disrupting the future of construction due to the advent of both smart buildings and infrastructures and of novel design and construction processes as well as innovative business models. Technology areas, work processes, businesses, and supply chains that were previously unrelated are becoming interconnected, digital and physical assets are blending together, and a growing range of actors is being involved in the process. In particular, IT companies are entering the construction sector in forces, having recognized the untapped potential of digital technologies in this industry.

In the construction sector, the convergence of digital technologies is accelerating exponentially, substantially improving the productivity, competitiveness, and efficiency in the use of resources over the entire value chain, from investment programming to the design phase, to construction (including procurement, labor, supply chain, site management) up to the operation and maintenance phase (asset, property, and facility management) and the final decommission of the structure. These effects are achieved both by streamlining the design and production processes by providing more efficient data handling, and by introducing new data acquisition technologies (e.g., 3D measuring systems, and drones) and novel production and construction techniques [e.g., additive manufacturing (AM) and automated construction] that could not exist without the extensive contribution of digitalization.

The full digitalization of real-world structures through building information modeling (BIM), along with the availability of unprecedented amounts of data from sensors and connected devices [Internet of Things (IoT)] together with georeferenced data [i.e., implementation using geographic information system (GIS)], are allowing an ever increasing number of analysis services to improve productivity in the construction process as well as in real estate, commerce and services.

TABLE 3.1 The digital world of AECO industry.

Construction 4.0 technologies	Key technologies						
	BIM	Cloud and edge computing	IoT	5G	AI and ML	Big Data and analytics	Nanotechnology
3D mapping and scanning	■	■		■			
Additive manufacturing	■						■
Advanced materials					■		■
Autonomous vehicles	■	■	■	■	■		
Blockchain	■	■					
Building automation system	■	■	■	■	■	■	■
Building energy storage							■
Building integrated PV							■
Building performance simulation	■	■	■		■	■	
Common data environment		■		■			
Connected construction site	■	■	■	■	■	■	
Digital fabrication	■						■
Digital twin	■	■	■	■	■	■	
Extended reality (VR/AR/MR)	■	■		■			
Generative design	■	■			■	■	
Machine vision		■	■		■	■	
Mobile Internet		■		■			
Parametric design	■	■					
Predictive maintenance	■	■	■	■	■	■	
Real-time 3D visualization	■	■		■			
Robots in construction	■	■	■	■	■		
Smart grids		■	■	■	■	■	■
Smart home		■	■	■	■	■	
Smart objects		■	■	■	■		
UAVs	■	■		■	■		
Virtual assistants		■	■	■	■	■	
Wearable technology		■	■	■	■	■	

As data science and analytics become crucial to interconnect all of the innovative technologies in this sector, the production of valuable and abundant data during building construction or operation will lead to significant improvements and transformations in the way work is performed. Data collation from the site and its matching to complementary databases and data sources will entail remarkable added value.

Finally, digital technology paves the way for the advent of smart buildings and infrastructures, which will extend the benefits of interconnectivity from single structures to contribute and interact in the context of collaborative neighborhoods, smart grids and smart cities.

3.1.1 Building information modeling

At the base of the digital transition that is affecting the AECO sector there is, first of all, the adoption of BIM, increasingly identified by policymakers and investors as a decisive strategic factor for the full control of all phases of the building process and for the achievement of quality and cost reduction objectives (ECSO, 2019, 2021; European Commission, 2019; JRC, 2019a; WEF, 2016, 2018).

Namely, BIM is a collaborative process in which all parties involved in the project use 3D modeling applications which integrate geometry with additional information about assets' scheduling, cost, sustainability, operations and maintenance. This way, BIM ensures information is shared accurately and consistently throughout assets' life cycles. Differently from 2D and 3D CAD modeling, in fact, BIM allows to virtually construct the building, before its actual erection, simulating its performance, construction times and costs and thus providing essential information for achieving the set objectives. The term BIM in fact indicates "the use of a shared digital representation of a built object in order to obtain a reliable basis for decisions that can facilitate the design, construction and management processes" (ISO 19650:2019). As a process, BIM involves the generation and management of digital representations of both physical and functional characteristics of an asset, producing models rich of information that become shared knowledge resources to support decision-making in relation to a facility from the earliest conceptual stages, through building design and construction, its operational life and its eventual demolition (Borrmann, König, Koch, & Beetz, 2018).

The BIM workflow entails a virtual information model to be handed from the design team (architects, surveyors, civil, structural and building services engineers, etc.) to the main contractor and subcontractors and then on to the owner/operator and to the appointed facility manager., with each professional figure adding their discipline-specific knowledge to the single shared model. This reduces information losses that traditionally occur when a new team takes "ownership" of the project, and provides more extensive information to owners of complex structures.

By leveraging increased and cheaper computing power, over the past 10 years BIM has shown the potential to increase the efficiency of the construction industry by automating non-value adding and repetitive tasks, even complex ones, and by providing a collaborative platform for generating, sharing and reusing information throughout the construction life cycle to more effectively plan, design, build and manage the physical infrastructure. The diffusion of cloud computing and virtualization, and the increasing countries mandating BIM use in public-sector projects worldwide, are ushering BIM into the era of "connected construction" to become the default design and collaboration platform for the business (Autodesk, 2016, 2021; Boston Consulting Group, 2016; ECSO, 2021; Roland Berger, 2017).

Through BIM virtual modeling, it is possible to go beyond the mere 3D representation of the object and instead associate in real-time the formal architectural solution (3D) with the effects in terms of processing times (4D), construction costs (5D), energy and environmental performance (6D), thus controlling the entire architectural project, up to the construction site, also from a technological, economic and environmental point of view. The same BIM model of the building created can then be used for the management and maintenance of the building itself through advanced facility management (7D) software.

A model authored in BIM can contain, in fact, any information regarding the building or its parts, from the geographical location, to the geometry, to the properties of the materials/components/systems and of the technical elements (including technical data sheets of the products, costs and procurement times), to the construction phases, to maintenance operations, up to instructions for final disposal (Borrmann et al., 2018). BIM optimizes asset design, eases scenario testing and decision-making, verifies constructability, enables clash analysis, improves project and investment planning, ensures project control and stores information for preventive maintenance, among other functions. The parametric modeling of the objects in the BIM model also allows to establish reciprocal relationships between the different elements so that any change made during the design phase corresponds to a real-time update of the entire model. The 3D representation in a single model of all the components of the technological system (structures, systems, building envelope and partitions) also allows to identify on time any interference between the various elements, significantly reducing variants and reworks, thereby construction times and costs. In a BIM process, fewer change requests are

typically made due to more time being upfront in planning, and those are transparent and can be appropriately and quickly priced and integrated into the design without unexpected repercussions. BIM can also bring important environmental benefits thanks to better control of the quantity of materials used and waste produced as well as due to the ability to simulate and optimize the energy performance of the building. During construction, BIM significantly reduces activity and equipment conflicts in both time and space sequencing, thus improving worker safety, increasing efficiency and reducing schedule variability and cycle times. Facility managers can use BIM to better visualize the building and so manage it more effectively, reducing its operating costs, maintenance and repairs downtime and overall increasing its value. In the longer term, BIM's greatest potential may be in optimizing building operations and management, and capturing operations data, so that lessons learned can be quickly and easily incorporated into the next round of designs (Boston Consulting Group, 2016; Roland Berger, 2017).

In the last decade, BIM adoption has risen all over the world, pushed by BIM mandate from more and more governments on all public projects and by the availability of convenient, cloud-based BIM software-as-a-service solutions within reach of even smaller AECO enterprises (ECOSO European Construction Sector Observatory, 2021; NBS, 2020).

The strategic importance of BIM in the construction sector lies not only in bringing an operational improvement in all phases of the construction process, but also in constituting an enabling technology for the digitization of the entire AECO sector, favoring the application and development of numerous other technologies, tools and methods such as simulation software, parametric and generative design (GD), 3D real-time visualization and Extended reality, prefabrication and AM, robotic construction, digital twin and advanced analytics (see Fig. 3.1) (Boston Consulting Group, 2016; Roland Berger, 2017).

In particular, BIM constitutes a shared digital platform of information that can be augmented by several digital technologies and in turn feed technologies that can take advantage of the structured data within the BIM model. In fact, BIM design allows the digital acquisition of geometric data through laser scan and 3D photo reconstruction, also through the use of drones or autonomous robots, both for the preparation of the digital model and for its rapid and precise verification and possible update (advanced surveys). The availability of a BIM model of the building during the design phase allows to carry out seamless, real-time simulations of energy and environmental performance, to optimize shape and performance through parametric and GD methods, to take advantage of a real-time 3D visualization and to use tools of virtual reality (VR) and augmented reality (AR) for a more immersive experience, to facilitate the future direct digital fabrication of even highly complex elements. During the construction phase, the BIM model can allow data exchange with project management and construction monitoring tools, it can constitute a digital input to prefabrication and AM methods and for automated and autonomous construction equipment. Furthermore, during the operation phase IoT devices in the construction site provide the status information of workers, tools, vehicles and building components, and their positional information can be linked with the BIM model so that the spatial relations and real-time statuses can be displayed simultaneously (Tang, Shelden, Eastman, Pishdad-Bozorgi, & Gao, 2019). Once construction is complete, the as-built BIM data is transferred to the owner or operator and used to organize and optimize facility management. This function becomes even more capable with the use of new, real-time data coming from building sensors, equipment and services robots that provide detailed information on conditions. Indeed, BIM is the base component for the building digital twin, the digital replica of the built environment that is continuously informed by live data collected from sensors within the real structure it replicates, that opens unprecedented potential for optimizing operation and building maintenance and improvement (Opoku, Perera, Osei-Kyei, & Rashidi, 2021). Cloud-based analytics can be used to better understand all the data provided by the BIM model and the digital twin, and the results are fed back into the system so that it optimizes itself.

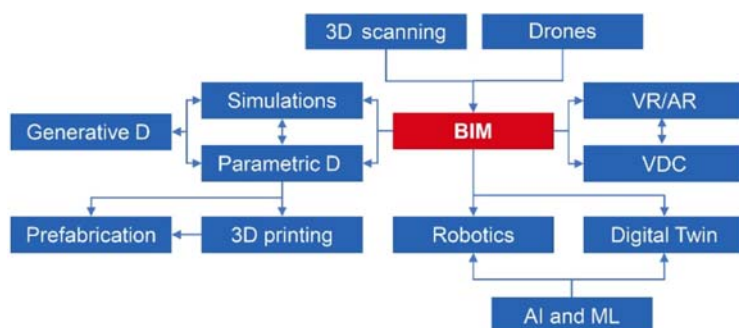


FIGURE 3.1 The strategic role of BIM.

3.1.2 Cloud and edge computing

Another technology that is giving a significant boost to the digitalization of the construction sector is Cloud computing, which use by design studios and companies is steadily expanding. Eighty-five percent of construction contractors used or planned to use cloud-based solutions in 2017, from only 16% in 2012 ([The Associated General Contractors, 2018](#)). United States National Institute of Standards and Technology (NIST) defines Cloud computing as “a model for enabling convenient, on-demand network access to a shared pool of configurable computing resources (for example, networks, servers, storage, applications, and services) that can be rapidly provisioned and released with minimal management effort or service provider interaction” ([Mell & Grance, 2011](#)).

After deeply evolving various industrial sectors in the last years, cloud-computing technologies are making their way into the construction sector as well due to the numerous benefits they can bring in all phases of the construction process, from design, to construction, to management and maintenance ([Bello et al., 2021](#)).

Cloud services come in three main models: Infrastructure-as-a-Service (IaaS), Platform-as-a-Service (PaaS) and Software-as-a-Service (SaaS) ([Elazhary, 2019](#); [Yousefpour et al., 2019](#)).

The IaaS model makes hardware resources available via the internet for storing, backing up and restoring data, for hosting websites and apps and for carrying out computational activities that require large computing capacities. IaaS allows customers to avoid the upfront expenses of purchasing, configuring and managing a local data center and allows rapid and cost-effective flexibility and vertical scalability for the creation of development and project management environments.

The PaaS model provides a web platform that, in addition to including the hardware infrastructures (server, storage and network) of the IaaS solutions, also provides users with middleware, development tools, business intelligence (BI) services, database management systems and more, allowing users to avoid the upfront expense and complexity of separately purchasing these tools and managing them. Examples include Amazon Web Services (AWS), Microsoft Azure or Oracle PaaS platforms.

Finally, the SaaS model offers programs on the cloud which perform their tasks through Internet connections rather than working locally on computers following installation (with all the security risks that could pose). Both apps and data are stored on private cloud services and accessed through a virtual desktop environment. This allows users to access the application from anywhere in the world and from any device connected to the internet and to work jointly on a single centralized document. SaaS examples include email services, calendars, and productivity tools, such as Microsoft Office 365, Google Documents, or Adobe Creative Suite, as well as new, industry-specific tools for design such as BIM cloud (BIM 360), for project management (Primavera, Oracle Financials, Procore, SmartnetBid) or other business applications such as customer relationship management (CRM), enterprise resource planning (ERP), and document management.

Cloud computing constitutes a paradigm shift in the way hardware and software resources are managed and used. Cloud services in fact are always accessible regardless of time and location via any device on the Internet and allow many users to share the same computing infrastructure remotely while maintaining a guaranteed level of individual privacy and security. Cloud adoption rates have been rapidly growing in the last decade, and have been further accelerated by recent sanitary emergencies such as COVID-19 which showed the necessity, and then the benefits, of remote working: in the second quarter of 2020 alone, investors pledged nearly \$3 billion to fund cloud-computing deals ([Castellanos, 2020](#)), and the cloud-computing market is expected to be worth \$623.3 billion by 2023 ([Elias, 2020](#)). Cloud-computing technology offers affordable and scalable processing capabilities using a pay as you go pricing model, thereby eliminating the upfront costs of acquiring, installing and maintaining IT facilities, both hardware and software, that have always been a barrier to the adoption of ITC in the construction sector, especially by SMEs.

The various functionalities provided by cloud services are particularly interesting for the AECO sector, which is characterized by the presence of numerous actors involved in the process, with different skills and roles, often located in different offices and sites, who must collaborate closely with each other on the same project ([Bello et al., 2021](#)). Moreover, design activities and the management of the project life cycle require a high computing power, in particular for advanced functionalities such as building performance simulation, GD or artificial intelligence (AI) and machine learning (ML), and involve the processing and analysis of a large amount of data, images and documents, often of considerable size, which must be securely stored, readily accessible, searchable and updatable from the construction site and from anywhere in the world on any device. The construction sector is in fact an industry with a high intensity of data, which continuously generated and updated as the project progresses. The use of emerging technologies such as LiDAR and aerial photogrammetry, 3D Real-time visualization, extended reality, 4D–5D BIM and IoT, is also contributing to the sheer increase of volume and size of the data produced. The integrated management of such data and

information is a determining factor for the overall coordination of the project. However, such data are normally stored in different silos (team server or desktop, individual desktop, laptop, smartphone, etc.), are not readily available and their sharing among the stakeholders involved is often difficult, with consequences in terms of incorrect planning, unnecessary project variations, delays in project delivery and increased costs.

In addition to removing hardware limitations in terms of computing power, data storage capacity, and IT security as well as significantly reducing ICT costs, cloud services allow to have total accessibility to data and documents, to create collaborative work environments and take advantage of value-added services such as AI and ML, improving the efficiency of all phases of the construction process.

Through the cloud, construction professionals are able to access project drawings, models, and other information and collaborate in real-time without being in each other's presence, avoiding unnecessary travel and accommodation for meetings. Any project information can be uploaded to the cloud, accessed, edited, and saved back to the cloud for conservation. Indeed, connecting teams and project information in a centralized data environment in the cloud can improve productivity, reduce rework, streamline approvals, and accelerate project delivery. Tradesmen or professionals on site can access or contribute to project information without waiting to get back to the office. On-site supervisors can discuss issues with in-house staff a lot clearer and faster, without the need of meeting face to face. SaaS platforms like Pro Crew Schedule can provide a real-time view into the construction site and can connect with team members through the communication platform available on the software and share file with them. Cloud services support contractors in easily keeping track of each of their worksites. Project managers can more effectively monitor what everyone is doing and what are the contractors assigned on, to provide work assistance as needed. Project and construction data stored in the cloud allows to take measurements, compare plans or obtain useful information and insights on any device, from any location.

SaaS also allow to implement the maximum level of BIM maturity (so-called level 3) allowing the design team to work together on a single centralized model that is updated based on the contributions of each without the need to report the changes made on the different project models (see [Section 4.5](#)). By working on the same cloud environment, specialists from different disciplines can avoid time wasted on uploading, syncing, transferring or waiting on large files. Each modification to the model is in fact automatically synched by the system on all the architectural, structural, systems and economic drawings, allowing complete control of the project. Through cloud integration, the various architectural, structural, plant engineering and economic components interact in a single model, with a reduction in design times of over 70% compared to conventional CAD systems ([Autodesk, 2016, 2021](#)). Cloud-based BIM provides a collaborative outlet for these teams, whether they are working remotely from home, in the office or on site.

Moreover, a large number of SaaS solutions focus on the construction industry, including providers like Plangrid, Procore, Unearth, and HCSS. These programs cover almost every construction task, with the most popular areas being daily reporting, plan management, and project management. Indeed, cloud-based real-time project performance monitoring and reporting systems allow all stakeholders to be involved and contribute to every stage of the project delivery process. The use of cloud platforms to track project progress can prevent delays and block leakages arising from inaccessible information, allowing project progress to be monitored more openly. Transparent monitoring can also help in resolving disputes in a timely manner, directly addressing one of the biggest financial drains for project contractors. As disputes commonly arise as a result of conflicting or unavailable evidence for a clear conclusion, having as-designed and as-built evidence readily available on cloud storage can result in more amicable settlements of disputes rather than spending money and time on litigations.

Furthermore, cloud-computing services are naturally suited for connecting all sorts of IoT devices. Such an integration has great potential to transform the whole AECO sector, allowing to easily process and leverage a large amount of data collected on site or from the building. Nonetheless, this rapid rise of data creation poses infrastructure and convenience challenges for its timely and efficient transportation to and from the cloud. To improve the processing of these accumulated data, partial analytics can be carried out already at the device level, before sending data to the cloud. Such emerging paradigm goes by the name of Edge computing ("computing at the edge of network"), which describes a computing topology in which information processing and content collection and delivery are placed closer to the sources of this information ([Elazhary, 2019](#); [Sittón-Candanedo, Alonso, Corchado, Rodríguez-González, & Casado-Vara, 2019](#); [Yousefpour et al., 2019](#)).

Rather than send every piece of information collected by cameras, scanners, handheld terminals, or sensors to the cloud to be processed, edge devices carry out some or all of the processing themselves, at the very source of data. Edge computing technology can effectively complement and extend cloud processing, thereby enhancing bandwidth efficiency, reducing response time, decreasing network pressure, and minimizing energy consumption. Multiple IoT

devices can be connected through an edge gateway where collected data are processed locally, and services are available as needed, which enhances performance, privacy, and security (Zhang, Li, & Chen, 2021).

Edge computing saves time and bandwidth of data communication and transmission and can significantly reduce the latency of data processing, which is quite important to real-time applications such as autonomous vehicles and robots, smart city and smart home. Moreover, processing data at the edge of network can also help prevent private information from being compromised. Important data of personal messages can in fact be preprocessed at the edge server before sent to cloud centers. The data can be extracted and encrypted during this procedure to ensure that only the most necessary data is sent outside in a safer means.

3.1.3 Internet of things

A significant trend within the current digital revolution is that the cyber and physical environments are becoming more and more interconnected at different levels due the diffusion of IoT, the infrastructure of devices and objects that are connected to the internet and can gather and transmit data on their particular state which can be collected for monitoring, control, statistical analysis and decision support (IRENA, 2019c).

IoT has already been widely immersed into various domains in the industry and is considered one of the key enabling technologies of Industry 4.0. By 2025, 75 billion devices worldwide are expected to be Internet connected, providing a wealth of information to consumers, manufacturers and utility providers (Statista, 2018). In turn, the growth of the IoT paves the way for the rise of AI, powered by Big Data, as it provides the granular information needed to feed ML algorithms. IoT is expected to have significant impacts on building construction, operation, and management, as well as on smart grids and smart cities, by facilitating high-class services, providing efficient functionalities.

The architecture of IoT allows to equip all objects with identifying, sensing, networking, and processing capabilities: these “smart objects” become able to exchange and share information and develop advanced services over the Internet. Interconnection of the distributed IoT network can facilitate deeper insight of complex systems and provide dynamic, context-aware decision-making capabilities and intelligent autonomy (Goyal, Sahoo, & Sharma, 2021).

The wide application of sensors and wireless communication technologies to objects, machines and people is allowing to generate real-time information on their particular state which can be collected for monitoring, control, statistical analysis and decision support both in construction, operation and maintenance phases of the building, up to the possibility of creating a digital replica of the building (building digital twin). Information sharing can take place directly machine-to-machine, allowing devices to communicate and interact even without human intervention (e.g., by automatically programming the repair or maintenance of an equipment based on its state of use or its performance).

IoT architecture consists of different technologies articulated on multiple layers: hardware devices (perception layer); networks and gateways (network layer); middleware, data storage and analytics, and IoT applications (application layer) (Jia, Komeily, Wang, & Srinivasan, 2019; Sethi & Sarangi, 2017).

The hardware technology is comprised of various devices, including sensors and actuators. Sensors capture data and process signals from the environment in real-time, while actuators transform electrical signals into tangible actions to influence the environment. Examples of IoT sensors include wearables, which provide reliable information about human activity, or environmental sensors designed to collect measurements of different factors such as temperature, humidity, pressure, air quality, length, time, speed, movement, and heartbeat. The IoT network layer collects the great mass of unprocessed data, converts it into digital streams, filters and preprocesses it so that it is ready for analysis. The application layer, finally, is represented by edge devices and centralized computing units responsible for processing and enhanced analysis of data, also using AI and ML technologies, and for presenting the data to users and programs for further services.

Over the entire AECO sector, IoT can bring numerous benefits (Woodhead, Stephenson, & Morrey, 2018). In the construction phase, IoT allows the creation of connected yards that can greatly improve the performance of operations and the management of all activities. With IoT, it is possible for interested parties to obtain and manage in real-time the large amount of data and information daily generated from construction site activities related to employees, machines, processes, materials and environmental risks, thus increasing management efficiency and effectiveness, while improving the site environment and human safety (Tang et al., 2019). Sensors can be embedded into personal wearing devices such as helmets, vests, or other items, to identify and locate the worker and to determine their action and vital status. Furthermore, IoT applications can collect information about the inventory and consummation status of materials, check the delivery schedule of supplies, monitor the operating conditions of connected equipment, control abnormal situations, and issue alerts for timely repair or maintenance in advance.

IoT technologies are also at the basis of the creation and diffusion of smart buildings and smart homes (Daissaoui, Boulmakoul, Karim, & Lbath, 2020; Froufe et al., 2020). IoT devices can in fact be integrated into all systems and equipment inside buildings (electrical distribution, air conditioning, water system, lighting, data network, access control, elevator control, fire and security systems, renewable energy and energy storage, electric mobility, home appliances, etc.) or in building envelope elements such as doors, windows or shielding systems, contributing substantially to save energy, improve comfort and safety conditions and promote more sustainable users' habits and choices (see Sections 10.2.3 and 10.6). By analyzing the collected environmental and activity data and using predictive models, the building's IoT network allows the building automation systems (BASs) to take into account the external climatic conditions, the energy costs of the network, the actual presence of users and their preferences, thus maximizing the conditions of comfort and at the same time reducing the energy consumption of the building.

Thanks to IoT, everyday objects become self-recognizable and acquire intelligence due to the ability to communicate information about themselves and gain access to aggregate information from any other device. An alarm clock may anticipate in the event of traffic, irrigation systems can self-schedule according to soil sensors and weather forecast, smart thermostats track the occupancy and users' habits to adjust the temperature when necessary, smart lighting can switch on after a prolonged absence for security purposes, windows close autonomously when it rains or outside air is too polluted, the bed adjusts the temperature according to our sleep cycle, turns the lights off and in the morning commands the coffee pot to prepare coffee.

IoT is also particularly useful to manage building power consumption in a more rational way (Jia et al., 2019). All connected devices can talk to each other, interact with the network and generate information on the amount of energy they are consuming. Smart appliances, for example, could independently make decisions on when to start their cycle based on when more energy from renewable energy sources is available, or when the grid cost is lower. IoT allows to extend remote control devices to doors, by installing smartphone-controlled locks, and monitor licenses and electronic keys distribution with dedicated systems, or to windows with remote controlled actuators, with programmable opening in coordination with the HVAC systems.

Equally important is the role that such systems can play in bridging the information deficit of users and inducing virtuous behavior in the management of house equipment by the inhabitants due both to a smart human interface (visualization with intuitive dashboards on touchscreens and mobile devices, voice and gesture recognition) and to the continuous information on house status and performances enriched with suggestions and alerts to manage energy consumptions and comfort levels in an efficient and conscious way.

The IoT also makes it possible to improve the maintenance of structures and systems by favoring preventive and predictive maintenance thanks to continuous monitoring of the equipment and real-time detection of any anomalies, with a consequent reduction in intervention times and costs (see Section 11.2). Embedded IoT technologies can also be used to continuously monitor the physical and environmental conditions of structures, such as vibrations and deformations, tensile and compressive stresses, to check the damage of structures after earthquakes or to estimate the structure health and its service life, thus increasing the building's safety and reducing maintenance costs.

Furthermore, the IoT is a pillar of smart grids, as it increases the visibility, reliability, flexibility, responsiveness, and security of the resources connected to the grid, and favors the development of new services and business models thanks to the intelligent integration of actions of all users (utilities, centralized generators, consumers and distributed renewable energy sources).

The use of IoT-powered smart meters to connect, aggregate and control industrial and residential loads can allow them to participate in demand-response programs and provide balancing services to the grid (see Section 12.2). Furthermore, the automation of loads can further improve operations, paving the way for fully self-sufficient energy networks such as micro-grids. In this way, the system can respond more effectively to intermittence from industrial-scale renewable plants and from a smaller distributed generation, using existing resources. IoT allows the rapidly controllable two-way flow of both electrical power and information and even automatic system dispatch on an economic basis.

IoT technology is also at the base of smart city models and functioning, as it enables many innovative services in terms of energy, environment, transportation, health, and security (Ahad, Paiva, Tripathi, & Feroz, 2020; JRC, 2019b; McKinsey, 2018c). A smart city is in fact equipped with different electronic elements employed by several applications, like street cameras for observation systems, or sensors for weather, pollution, transportation systems, and can exploit the diffused usage of individual mobile devices (see Section 12.1). Data can be collected, monitored and analyzed for traffic surveillance and management applications, intelligent parking management, water and waste management, air pollution and noise control, risk assessment, security, etc. IoT can also play an important role at the national level regarding to the policy decisions (like energy saving, pollution decrement, etc.), remote monitoring, and required

infrastructure. On this basis, the IoT will help to provide more efficient, economic and secure operation of the system based on different aspects, such as energy saving policies, economic considerations, reliability levels, etc.

Finally, IoT also allows to create a digital replica, called digital twin, of any physical entity, be it a process, a product, a building or an entire city, which allows to simulate entity behaviors, monitor the ongoing status, detect abnormal patterns, reflect system performance, and predict future trends to optimize operations (see [Section 11.4](#)) (Jones, Snider, Nassehi, Yon, & Hicks, 2020; Opoku et al., 2021; Ozturk, 2021).

3.1.4 5G network

The term “5G” broadly indicates the fifth-generation technology standard for broadband cellular networks that began deploying worldwide in 2019 in substitution of the current 4G network introduced in 2009 (Andrews et al., 2014; Mitra & Agrawal, 2015; Wang et al., 2014). While earlier transitions to next generation networks, from 1G to 4G, mainly boosted cellular communications mostly by speeding up service and increasing bandwidth, the current transition to 5G promises an even greater impact on society by providing a key platform for cutting-edge applications for industry 4.0 and smart city, way beyond faster smart phones.

The main advantages of the new 5G cellular networks, compared to the 4G standard, is that they present greater bandwidth, giving higher speeds (with theoretical values from 1 up to 10 Gbit/s in download compared to the 300 Mbps–1 Gbps of 4G LTE), a lower latency time (only 8–12 ms), the ability to manage a greater quantity of devices per unit of surface area (approximately 1,000,000 devices/km² against 1000–100,000/km² of 4G), a significant reduction in consumption energy (90% less than 4G for each bit transmitted), as well as the ability to support even devices in motion at very high speeds (approximately 500 km/h) (see [Table 3.2](#)) (Allam & Jones, 2021; Tang et al., 2021).

The increased speed is achieved in part by using higher-frequency radio waves than previous cellular networks. Higher-frequency radio waves have a shorter useful physical range, therefore 5G geographic cells are smaller and will require multiple, compact antennas that can be sited anywhere (lamp posts, roofs, vehicle tops, etc.) to connect the larger extents. For wide service, 5G networks operate on up to three frequency bands, low (600–700 MHz), medium (2.5–3.7 GHz), and high (25–39 GHz). The most widely used is medium band 5G, which allows speeds of 100–900 Mbit/s with each cell tower providing service up to several miles in radius. These speeds are over 10 times higher than those of current 4G networks which are between 15 and 75 Mbit/s real depending on the operator and the degree of coverage of the network.

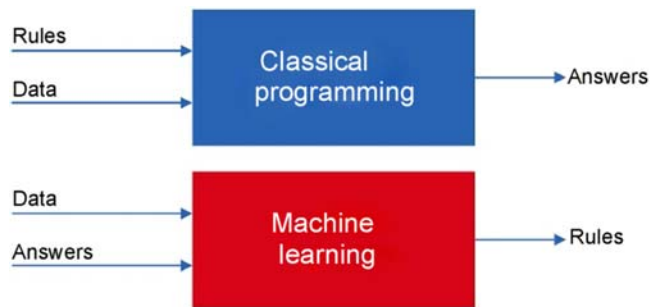
The characteristics of high speed, high-reliability, low-latency, high connection density and security, typical of the 5G network, make this technology crucial for the creation of increasingly smart and connected construction sites and for the full application of advanced construction tools and methods (see [Table 3.3](#)).

TABLE 3.2 Comparison between 4G and 5G network features.

Features	4G	5G
Year of introduction	2009	2018
Technology	LTE, WiMAX	MIMO, mmWaves
Access system	CDMA	OFDM, BDMA
Network	Packet Network	Internet
Frequency	800–2600 MHz	600 MHz–39 GHz
Maximum speed	300–1000 Mbps	1–10 Gbps
Latency	20–30 ms	1–10 ms
Mobility	200 km/h	500 km/h
Connection density	1000–100,000 km ²	1 million/km ²

TABLE 3.3 Advantages brought by 5G to digital technologies in AECO sector.

Digital technologies	Device density and data volume	High data rate	Ultra-low latency	Energy efficiency	Reliability	Security
IoT real-time monitoring	■		■		■	■
UAVs		■	■	■	■	■
VR/AR/MR		■	■	■		
Virtual consultation	■			■	■	
Robots, autonomous vehicles and teleoperated machines		■	■		■	■
Data analytics and repository		■			■	■

**FIGURE 3.2** Classical and ML approaches to programming.

To improve quality, efficiency and safety of construction, there is a growing need to leverage the new digital technologies of virtual design and construction (VDC), XR, AI and advanced analytics, cloud computing, image capturing and teleoperated machines which, however, require a fast and reliable transmission of a large amount of data.

From the BIM model to images taken by drones or robots, 5G enables the acquisition, analysis and real-time update of all relevant data and information directly on the construction site for continuous monitoring of the progress of the work, thus supporting and simplifying, also with the support of AI and ML, operational workflow and decision-making. The high transmission speed and low latency also allow full use of VR and mixed reality (MR) on site and virtual tele-presence collaboration.

Furthermore, all data coming from the IoT network for the control of machinery, equipment, for real-time asset tracking, and for the management of personnel and safety can be managed with maximum efficiency thanks to the ability of 5G to maintain connections among a high density of devices. Finally, the extremely low latency makes it possible to make remote control of construction vehicles much more reliable, even from thousands of kilometers away.

3.1.5 Artificial intelligence and machine learning

AI is referred to the area of computer science that focuses on the creation of intelligent machines which operation is inspired by human cognitive processes. At its core, AI encompasses a series of systems that act intelligently, using advanced algorithms to recognize patterns, draw inferences and support decision-making processes through their own judgement.

Crucial to this process is ML, which is the ability of AI to learn from data and get better at interpreting them over time without being explicitly programmed (Hastie, Tibshirani, & Friedman, 2013).

In particular, ML is the process of using mathematical models of data to help a computer learn without direct instruction (Soofi & Awan, 2017).

Contrary to traditional logic programming, in which input data is processed according to explicit rules to output the desired answers, in ML the rules are inferred by the system itself by identifying patterns between input data and the associated output answers (see Fig. 3.2). The result is a data model that can produce valuable answer on other problems

within the same domain, as long as it is provided with similar/compatible input data. Through ML, AI gives machines the ability to carry out a wide range of humanlike processes, such as visual recognition, writing texts, speaking naturally or even actions such as driving, flying or executing complex tasks (autonomous vehicles and construction robots), and even predict future outcomes based on what they learn from data (McKinsey Global Institute, 2016).

In the last decade, ML techniques have advanced rapidly and their application field expanded, extending to the AECO sector, thanks to the availability of three key technologies (Darko et al., 2020; Hong, Wang, Luo, & Zhang, 2020; McKinsey, 2018a; Yan, Yang, Peng, & Ren, 2020).

First, with the rapid advancement of IoT technologies and cheaper infrastructure for data storage, an unprecedented amount data is being collected and stored, and is thereby available for research, development and industrial use. Second, ML-oriented chips such as Graphic Processing Units and Tensor Processing Units have been designed and produced, which provide people with better access to powerful and affordable computational resources. Third, more advanced ML algorithms have been developed and validated, such as artificial or deep neural networks (Hong et al., 2020).

Nonetheless, the multiple opportunities provided by AI and ML should not be embraced uncritically, as several questions and concerns are still being addressed as the technology is developed. In particular, the black box characteristics of most AI techniques make them opaque even to specialists. Moreover, AI application is still limited to narrow and well-defined tasks, and as a technology based on training it may inherit imperfections from its human creators, such as the well-recognized bias effect present in data (JRC, 2018).

Today, AI and ML can be used in all stages of the building life cycle, including design, construction, operation and maintenance (Akinosho et al., 2020; Pan & Zhang, 2021).

In particular, as regards the design phase, AI and ML can support design choices from the initial phases both by predicting the performance of the building in the operational phase in relation to the possible formal and technical alternatives, and by allowing the optimization of design choices according to the project objectives through GD methods. In fact, normally 20% of design decisions taken at the early design stage affect around 80% of the subsequent design choices, therefore models that can provide rapid and accurate results are necessary. ML offers the possibility of developing surrogate models that provide rapid and sufficiently accurate building performance predictions even at the early stages of conceptual design, whereas traditional building performance simulations tools are effective only in later stages when most decisions have already been taken and changes become time and cost consuming. Conversely, GD based on AI allows project teams to explore effortlessly a much wider range of design alternatives than what is manually achievable thanks to the automatic generation of design ideas based on the specified design targets, an approach that facilitates more variability in the design workflow. AI analyzes thousands of blueprints as source material for a project, then designs its own concepts with this new knowledge. ML has recently started to be used to identify potential errors and incompatibilities linked to variations in the design. In fact, software has been developed to perform, following modifications to the original parameters, massive automatic checks of the conformity of all kinds of computable rules and interferences, including mechanical, electrical, and plumbing plans, without direct human control, thus significantly reducing the time required by public administrations to approve construction projects.

Moreover, AI and ML tools can be particularly helpful in retrofit projects, in which they can leverage vast data on building stock and comparable interventions to support the identification of retrofit potential, the evaluation of different energy conservation measures and the characterization of buildings to intervene on.

As regards the construction phase, AI and ML are the basis of the operating functions of robots and autonomous vehicles, allowing the automation of both off-site and on-site processes. AI-powered software tools can moreover bring numerous advantages in construction management activities supporting site planning, activity scheduling, labor workforce and subcontractors management, fleet maintenance, material procurement, safety and security management. Main benefits include optimization of both resources and time, identification of current or potential management issues and their characterization based on priority, prevention of accidents, identification of solutions and strategies to be implemented in management (see Section 9.6). Historical data such as planned start and end dates, bill of quantities or cost logs are used by the project manager to feed into predictive models to envision realistic timelines for future projects and predict cost overruns based on factors such as the project size, the type of contract, location, etc. ML can be effectively applied to predict construction costs with a sufficient degree of accuracy, which is notoriously difficult at the planning or early stage when the project information is limited and could help project managers identify potential problems, adopt response strategies, and better control project costs. On site, AI-powered machine vision can oversee video footage from cameras and drones to identify objects and people, with useful applications in monitoring tasks and performances, performing security surveillance, helping wayfinding and recovering of materials, power tools or vehicles, as well as supporting safety monitoring by recognizing accidents and potential hazards such as incorrect use of personal or

collective protective equipment. AI can also be used to predict construction waste generation and, during works, automatically sort it when combined with appropriate sensors (e.g., infrared). The first applications of AI in the construction phase demonstrated a potential for up to 40% increase in labor productivity and project completion, saving more than 10% of the budget (Schober, 2020).

Regarding building's operation and maintenance, several common problems difficult to be solved with traditional programming, such as predicting occupants' behavior and learning their preferences, or forecasting energy demand and peak periods, can be effectively addressed using AI and ML, allowing optimal control and operation of BAS for maximum energy efficiency and comfort, and costs reduction (see Section 10.4). In such applications, IoT sensors constantly monitor environmental parameters and detect the presence of people, then AI-based tools adjust HVAC and electricity consumption not only on the basis of real-time data but by analyzing the building's usage statistics to adapt and anticipate needs.

In facility management, AI allows predictive maintenance and diagnosis strategies of equipment with benefits in terms of reduced downtime and lower management costs. Cloud-based ML trained with structured and unstructured data can help to identify maintenance issues and to schedule interventions before they become problems. A ML algorithm can process the visual data, revealing problems like a patch of wall gradually darkening with moisture which may signal a leak. AI can assess structural damage (e.g., detecting structural damage after earthquakes) or perform continuous structural health monitoring (e.g., identification of damage and nonlinearities in wind turbine blades based on a pattern recognition technique). Overall, this allows more proactive stewardship of built environments, saving money and resources and sustainably extending the usable life cycle of the building.

Finally, at the level of infrastructures and network services on an urban and district scale, AI and ML allow, among others, to maintain electric grid stability and reliability, to optimize energy storage and distribution and to improve wind and solar generation forecast.

3.1.6 Big Data and advanced analytics

The term "Big Data" refers to the exponential explosion in the amount of data being generated and stored any moment in this increasingly digital age, while "advanced analytics" refer to the ability to automatically work with and generate insights from these data (Buyya, Calheiros, & Dastjerdi, 2016; McKinsey Global Institute, 2011, 2016).

Advanced analytics involve using AI and ML to automate analytics processes, including gathering data from raw data sources, preparing and cleaning that data, building unbiased analytics models, and generating and communicating relevant insights to those who request them (IRENA, 2019b).

The sheer volume of data created every day, and the rate at which it is accelerating, is so vast that 90% of the data available in the world today was generated in the last 2 years (IDC & Seagate, 2018). The amount of available data doubles every 2 years and, according to the market intelligence company IDC, could grow from 33 zettabytes in 2018 to 175 zettabytes in 2025.

The established model of Big Data has three defining attributes, referred to as "3 V," namely volume (terabytes and petabytes of data); variety (heterogeneous data formats like text, sensors, audio, video, graphs); and velocity (continuous streams of the data) (Beyer & Laney, 2012; Buyya et al., 2016).

These attributes are apparent in construction data that are typically large, heterogeneous, and dynamic. Over time, they have been joined by a fourth attribute, veracity, which refers to the reliability index of the data processed, followed a fifth, value, which refers to the possibility of actually transforming into value the huge amount of data collected and analyzed. Big Data can come from a variety of sources, with data classified accordingly into:

- Human generated: Produced directly by individuals mostly through their interaction with the web: click streams from websites managed through cookies, social networks, blogging, multimedia, or e-commerce portals.
- Machine generated: Produced from sources such as global navigation satellite systems (GNSS) sensors, IoT, RFID, weather monitoring stations, scientific instruments, consumer and professional software such as trading systems for financial markets, biomedical devices and others.
- Business generated: All those data, both human and machine generated, produced internally by a company (payments, orders, production data, inventory, sales, financial data, etc.).

The ability to process large amounts of data and to extract useful insights from there has had a huge impact on society, with applications for a wide assortment of industries, including the construction sector. The construction industry already deals with large volumes of heterogeneous data, which is expected to increase exponentially as technologies such as sensor networks and IoT become more common. However, while the application of data analytics in the

construction industry is not new, the adoption of Big Data technologies is still lagging behind the broader uptake of these technologies in other fields.

The construction industry is dealing with significant data arising from diverse disciplines throughout the life cycle of a facility. BIM is envisioned to capture multidimensional CAD information systematically for supporting multidisciplinary collaboration among the stakeholders. With the advent of embedded devices and sensors, facilities have even started to generate massive data during the construction operations and maintenance stage, eventually leading to more rich sources of Big BIM Data (Lu, Lai, & Tse, 2019).

As stated above, construction data is voluminous and heterogeneous and includes design, operational and financial data, photos and videos, conversation and text data, as well as sensors, RFIDs, and BAS data. Although such unstructured wealth of information is challenging to analyze, exploiting it to optimize construction operations is the next frontier of innovation in the industry. Currently, in fact, 96% of all data in the AECO industry goes unused (Snyder, Menard, & Spare, 2018). The purpose of advanced analytics is to extract value in the form of knowledge from Big Data by examining the huge datasets available to discover correlations, trends, patterns and further statistical indices hidden therein. Specifically, analytics is the systematic computational analysis of data or statistics, and is used both for the discovery, interpretation, and communication of meaningful patterns in data and to apply discovered data patterns toward effective decision-making. Analytics relies on the simultaneous application of statistics, computer programming and operations research to quantify performance. Analytics can be performed on structured, semistructured, and unstructured data, including:

- *text analysis*, which consists in the extraction of information and knowledge from unstructured text contained in documents, emails, web pages as well as blog and social networks posts. Also known as text mining, it mainly employs Natural language processing techniques, ML and statistical analysis to develop algorithms for the recognition of topics (topic modeling), the search for the best answers to a question (question answering), the identification of user opinions on certain news (opinion mining) and other purposes;
- *multimedia data analysis*, which employ ML algorithms to extract low- and high-level information useful for the semantic description of the content of images, video and audio, including indexing (multimedia indexing) and recommendation algorithms (multimedia recommendation) based on automatic annotation using textual labels (multimedia annotation) and on the extraction of visual or sound features (feature extraction);
- *web analysis*, which automatically analyzes web pages and hyperlinks to obtain information and knowledge on the contents, structure and use of the web, by employing both textual and multimedia analysis and reconstructing the topology using crawling algorithms that follow hyperlinks to reveal relationships between pages or websites.

For the construction sector, the possibility of analyzing an ever increasing amount of structured and unstructured data and information, both historical and in real-time, coming not only from the construction site, but also from previous construction projects, meteorological reports, roads, local communities, or from machinery and equipment manufacturers databases, allows to discover patterns and relationships that were previously unknown and to better predict future outcomes, and make smarter and more informed decisions at all levels (Bilal et al., 2016).

Big Data analytics offer insights that traditional systems simply cannot, providing helpful indications concerning accurate budget estimates, risk levels associated with thresholds for alerts, the scheduling of the optimal time to start works, the best combination of equipment purchase and rental, how to use fuel more efficiently to reduce costs and environmental impact, and more.

In order for construction Big Data to be available for analytics, however, some efforts should be made at the industry and at company level, as currently most data, either structured or unstructured, is dispersed among servers, devices, different companies, and projects teams. Indeed, with various home and field offices all requiring access to the same data for different purposes and at different frequencies, it is easy to unintentionally compartmentalize data in disconnected siloes in which data is downloaded and analyzed on an ad hoc basis, with copies being made and saved locally. New data entries are added manually, and the most up-to-date documents only exist as localized copies. Therefore, central data repositories for and sets of standards that govern data storage are recommended to ensure all relevant information is accessible and to prevent duplicates and unrelated data from polluting analysis results. In this picture, the integration of CRM systems and ERP platforms in the organization's data strategy, as well as a more extended emphasis on BIM processes, are prerequisite tools to harness the potential of Big Data analytics.

Nonetheless, the effectiveness of Big Data in improving construction quality and productivity cannot be measured just by how large the volumes of accumulated data are; it is the specific use cases or industrial problems that dictate the usefulness of these technologies. Therefore, researchers or domain experts are required to highlight domain-specific problems that are the subject of Big Data, as many organizations are either unprepared for or overwhelmed by the

magnitude of information and understanding which data can be useful and how it translates into BI requires strategic planning and a clear understanding of each company's overall goals and vision. As with other innovative technologies, Big Data may not be the driving force itself, but rather a tool with which the AECO sector can lead the innovation by solving its topical issues in new more effective ways.

3.1.7 Nanotechnology

Nanosciences constitute a whole new approach at research and development, aimed at controlling the structure and fundamental behavior of matter at the atomic and molecular level. In particular, nanotechnology is defined as the application of scientific knowledge to manipulate, control and synthesize matter in the nanoscale (from approximately 1 to 100 nm). The nanometer (nm) equals to 10^{-9} or a billionth of a meter, a dimension tens of thousands times smaller than the thickness of a human hair and correspondent to the length of a small molecule. In this order of magnitude, in fact, new properties and phenomena dependent on size and structure can emerge, distinct from those associated with individual atoms and molecules or with bulk materials, giving the possibility of exploiting the new properties provided by nanomaterials. Bulk properties of materials, such as strength, electrical, chemical, and optical characteristics, may indeed change dramatically when miniaturized to nanoscale dimensions: at this scale (<100 nm) they do not depend anymore on chemical composition only, but also on size and form.

By operating at the molecular level, nanotechnology opens up new possibilities in material design. In a world where quantum physics rule, objects may change color, shape, and phase much more easily than when in the macroscale. Fundamental properties like strength, surface-to-mass ratio, conductivity, and elasticity can be designed to create dramatically different materials. For instance, normally opaque substances become transparent (e.g., copper); inert materials become catalysts (e.g., platinum); stable materials turn combustible (e.g., aluminum); solids turn into liquids at room temperature (e.g., gold); insulators become conductors (e.g., silicon). Composites made from ceramic or metal nanoparticles can suddenly become much stronger than predicted by existing macroscale materials-science models: metals with a grain size of around 10 nm can be as much as seven times harder and tougher than their ordinary counterparts with grain sizes in the hundreds of nanometers.

Today, nanoscience and nanotechnology are already bringing innovation and transformation in several industrial sectors and their potential is increasingly recognized, as confirmed by the government funding allocated in this area. Hundreds of products based on nanoscience and nanotechnology are currently in use across many industries, with a world market worth \$76 billion in 2017 and expected to grow to €125 billion in 2024 ([Global Nanotechnology, 2018](#)). In fact, nanotechnology is proving able to help solving many issues of contemporary society, allowing the creation of products and processes for more specific uses, with higher performance and lower environmental impact throughout their entire life cycle, with applications ranging from medical applications to information technology, from aerospace to automotive industry, from building construction to energy production and storage or environmental protection. For these reasons, nanoscience is often referred as a “horizontal,” “key” or “enabling” discipline since it can connect different scientific fields and benefit from interdisciplinary and converging approaches.

Main applications of nanotechnology in the various sectors are as follows:

- the creation of nanostructured materials by the addition of free or embedded nanoobjects within the composition of traditional materials and products, both solid (nanocomposites) and liquid (nanosuspensions), such as cement, metals, ceramics, plastics, textiles, paints, adhesives and lubricants, as well as the modification of their internal structure to make it nanocrystalline;
- the use of nanocoatings for the surface treatment of traditional products such as glass, wood, ceramics, textile materials, or photovoltaic cells;
- the modification of the surface structure of traditional products to make it nanostructured;
- the creation of new nanoporous materials (insulating materials, nanofilters, nanomembranes, etc.);
- the development of nanodevices such as nanoelectrical and mechanical systems (NEMSs).

In the construction sector, the use of nanotechnology can bring many benefits by improving energy and environmental performance of buildings, with application potential in all technical elements, from structures, to opaque and transparent closures, internal partitions, to systems and appliances ([Casini, 2016](#); [Pacheco-Torgal, Diamanti, Nazari, & Goran-Granqvist, 2019](#)).

Several solutions are already available to increase the mechanical, physical and chemical properties of materials, products and equipment, as well as their durability over time, with the aim of improving environmental comfort, safety, energy efficiency of buildings and at the same time reduce operating and maintenance costs and environmental impacts

(see Section 7.1). Nanotechnology finds application in all main construction materials, elements and systems of buildings including: structural materials as steel, wood or concrete (see Section 7.4.1); plasters and screeds; construction ceramics; plastics and polymers; insulating materials (see Section 7.4.3); glazing (see Section 7.4.4); paints and coatings (see Section 7.4.5); adhesives; lubricants; energy storage systems; renewable energies (see Section 7.4.6); lighting systems; air and water depuration; building and environmental monitoring and control systems. Within these construction materials, elements and systems, nanomaterials can be integrated in the form of solid nanocomposite materials, solid materials enhanced with nanocoatings or characterized by nanostructured surfaces, nanoporous materials and fluid nanodispersion as nanopaints, nanoadhesives or nanolubricants.

Moreover, nanotechnology is finding application in extending AM in construction, helping to ease the manufacturing process and enhance the properties of products, especially in the fabrication of intricate structure and complex shapes. In the past few years, there have been a lot of advancements in the integration of nanomaterials in AM for various applications. The usage of nanocomposite materials (such as Nylon 6, SiO₂ and Ag nanoparticles, carbon nanotubes, nanoclays, among others) is a fast-growing market for allowing generating lightweight products with many improved characteristics such as mechanical, thermal, and electrical properties, fire resistance and biocompatibility (see Section 8.3).

Regarding the energy sector, nanotechnology can provide important benefits throughout the entire supply chain, from production to distribution (power transmission and heat transfer), storage (batteries, supercapacitors, phase change materials and adsorptive storage with nanoporous materials), up to end use (thermal insulation, lighting and appliances), including the development of renewable energy, hydrogen generation, fuel cells and smart grids with nanosensors for intelligent and flexible grid management capable of managing highly decentralized power feeds. In particular, concerning renewable energies, nanotechnologies can improve:

- photovoltaics, with nanooptimized cells (polymeric, dye sensitized, quantum dot, thin-film, multiple junction) and antireflective coatings;
- wind energy, with nanocomposites for higher and stronger rotor blades, protection from wear and corrosion, nanocoatings for bearings and power trains, etc.;
- geothermal energy, with nanocoatings for wear resistant drilling equipment;
- hydro-tidal power, with nanocoatings for corrosion and oxidation protection;
- biomass energy with nano-based precision farming (nanosensors, controlled release and storage of pesticides and nutrients).

With regard to the environment protection sector, aimed at the protection of water, air and soil from pollution, nano-based technologies offer sensible help in achieving environmental objectives and targets, by improving many conventional processes or introducing altogether new approaches. In particular, benefits provided by nanotechnology regard the environmental monitoring of pollutants, processes for water and air cleaning and purification along with water desalination and soil remediation methods. Chemical sensors based on nanotubes and nanowires have already proven effective, as have NEMS serving as sensors, controllers, analyzers and communication devices allowing uses in many situations where bigger scale devices were not viable.

3.2 Digital building life cycle

Construction 4.0 model allows to match the building life cycle with a “digital twin building life cycle” capable of interacting in a bi-directional way with the real world (see Fig. 3.3). In other words, it allows to create a perfect digital replica of what is intended to build, what is actually being built and what has been built and is currently in operation, providing a new method of using data to deliver built environments with higher total performance at lower total cost. Such method takes the long view of a building’s life cycle, thus enabling efficiencies, proactive maintenance, and predictive operations, and maximized investments—through data.

This allows to anticipate the physical construction of the building with a perfect digital replica, containing both geometric data and technical parameters and information (BIM) with which to simulate and optimize performance, environmental impacts and construction costs, plan the sequence of construction and give input to the manufacturing of components or to the automation of on-site activities (robots, etc.). During construction, progress can be monitored and compared with respect to digital planning and perform trend analysis, risk prediction, corrections, optimizations, etc. After delivery and handover of the project, the constructed building can be monitored through the collection of its operational data to optimize its operation and maintenance with predictive analyses, etc. Results of the data analysis can

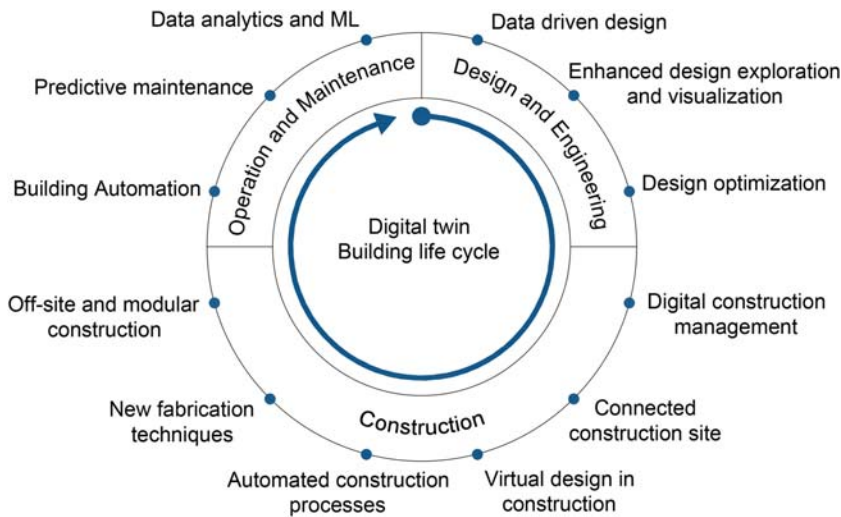


FIGURE 3.3 Digital twin building life cycle.

then serve as input for the design of new buildings, closing the information loop according to a circular model oriented toward continuous improvement.

Construction 4.0 tools then enable users to expand their scope to the physical, social, and digital environments, by accumulating critical datasets from each life-cycle phase and refining them into information that is applicable for the next users. For instance, preplanning the end of the building's technical life cycle allows to turn waste into reusable or recyclable resources.

Specifically, a digital twin is a common data reference that is created during a project-planning stage then spans every phase of an asset's life cycle, from design to manufacturing and construction to operation and maintenance, until its future decommissioning or reuse (Opoku et al., 2021).

Unlike static data models, digital twins are dynamic, living entities that evolve in real-time. They continuously update and communicate with their physical counterparts by exchanging data throughout the asset's life cycle using IoT technologies. Leveraging AI, ML and dynamic simulations, users of these virtual twins can predict problems before they happen, explore new opportunities, and plan for the future.

In a new construction, the digital twin is created at the outset of a project, as AECO teams and owners work together to define performance goals and desired outcomes. As the project proceeds, data is continually collected and mapped to the model, even during construction. When the asset is finally handed over to the owner, the virtual twin then collects operational data that can be used to fine-tune performance and manage maintenance over the long term, as well as support decommission and future reuse. Digital twins can be integrated into built structures as well, using LiDAR or 3D photo reconstruction to create a 3D point cloud with a high degree of accuracy. This was recently used to create a digital twin of the Notre Dame cathedral in Paris to assist with renovations following the 2019 fire.

From a workflow standpoint, digital twins can unlock data that is traditionally trapped in noncommunicating silos or in paper files and make it available for sharing in common data environments. As a result, all project stakeholders can be connected throughout the entire life cycle of a project, from design to decommission. By integrating static data such as component specifications and maintenance schedules with dynamic data such as occupancy rates and environmental conditions, digital twins enable more informed decisions that maximize the performance and life cycle of the asset.

This digital building life-cycle method supports data-driven decision-making in all stages of the construction process. Virtually building, simulating, and analyzing projects during the design and preconstruction phase can avoid costly mistakes. The overall performance of different design options can be compared, analyzed, cost-engineered, and optimized. For instance, different building materials can be assessed during design for how they affect the working environment in terms of acoustics, indoor comfort, space usability, safety, to identify the optimal solution to the project requirement brief.

During construction, digital fabrication and digital supply chain management support the implementation of the physical artifact, while machine-readable data supports the increasing practice of off-site construction. Robotic machines are able to turn digital design data directly into physical action, autonomously and safely. As a consequence, automated and unmanned operations are already taking place at, for example, mining sites, and are mature to enter the more challenging environment of the construction yard.

Worksite data analytics can deliver insights on how different workspaces are performing, and thus what should be changed to improve productivity and safety on the job. Processing cradle-to-grave building data can allow to discover the most effective ways to disassemble the physical structure into recyclable and reusable resources at the end of its life cycle, in terms of cost, safety and circular economy potential.

Digital twins shall be directly integrated into the BIM process to give everyone better insights in a standardized environment. Furthermore, the value of these insights can extend beyond the single project and can be fed back into the planning and design phases of new projects, applying data learning to continually improve them in a closed loop of information.

With data-driven BIM, total cost analysis and performance simulations can be performed to allow owners to know precisely how their project is expected to perform, and the value they will get for the investment, right from the programming stage. Furthermore, every stakeholder can have access to the same data and contribute to balancing a building's performance, budget goals, and other project requirements. Rather than being based on past experience, habitual choices, or rule of thumb, design, engineering, and budget decisions can be informed by reliable, unbiased data and a clear understanding of the tradeoffs. By implementing a full digital building life cycle, any project can meet the goals of its current and future stakeholders, while digitally delivering the optimized technical building life cycle.

A final aspect of the architecture is Big Data and analytics, which the construction industry is beginning to use beneficially. Data mining methods based on AI and ML methods allow to process the huge amount of heterogeneous data generated by construction projects and their environments, and to exploit that data to enhance building design, facilitate real-time decision-making, increase the accuracy of predictions, and support systematic improvement.

3.2.1 Augmented digital design

Due to the peculiarities of the construction sector, the design activity assumes a specific relevance for the purposes of the management and assurance of the final quality of any intervention. It plays an intermediary role in ensuring, through a system of information and instructions, the compliance between the explicit and implicit needs of the customer and the performance of the future product, by ensuring specific requirements are satisfied. The drafting of a building project is a nonlinear, iterative decision-making process based on a succession of increasingly detailed analysis, synthesis and verification activities. Differently from other industry sectors, in construction the planning and design activities take place in a context of prevailing uncertainty and incompleteness of the data, where each choice must be preceded by the analysis of possible alternatives and must be followed by the verification of the selected solution. Due to the inherent characteristics of the building process, the quality of the project cannot be considered as punctual and definitive result, but as the outcome of a progressive qualification or of a process aimed at demonstrating the gradual and increasingly detailed compliance of the design decisions with the requirements assumed in the project brief. For this process to be effective, the various operators involved in the design activity, along with the client, shall contribute to it each for the part of their own competence. Indeed, the quality of the building is also the result of the dialog between the actors involved and the controls carried out during the different stages of design. Therefore, the dialog, coordination and control activities shall be programmed from the planning stage of the work and strongly integrated with the design activity. This would prevent errors or deficiencies in the project that can have important repercussions in terms of noncompliance with times and costs, low formal-spatial quality, contractability of the works, disputes with contractors, safety and health of workers, lack of well-being requirements, poor usability, high management costs, high energy consumption, maintenance difficulties. Dialog between the client, the contractor and the end-users must transmit to the project team the expressed and implicit building quality needs in full compliance with regulatory, technical, environmental and economic constraints. In turn, controls have the objective of the formal verification of the design documentation and the reliability of the data assumed and the design methods followed, and, above all, of the compliance of the design solutions (distributive, technological, operational) with the requirements contained in the project brief and with the needs of the client and users. It is therefore essential that the scheduling of client control stages allows to confirm the progress of the project in compliance with the phases of the program. The number of checks must then be consistent with the complexity of the work to be carried out and with the possible criticalities that the project involves.

With projects becoming more complex—physically, commercially, environmentally, and societally—the traditional process of design will increasingly fail to deliver acceptable outcomes.

Current objectives of sustainability in fact require a totally holistic approach to design, capable of simultaneously controlling the three “environmental, formal, and constructive” levels and of harmonizing compositional, structural and technological choices in the best possible way. In particular, the need for facade configurations capable of reducing

energy requirements is increasingly pushing toward the integration between architectural form, building technologies and plant solutions, leading to the adoption of a single, integrated building-plant system capable of adjusting its performance over time in relation to changes in the environmental context and the needs of users.

A new architecture is therefore taking shape, in which design itself becomes a tool for sociological investigation and scientific research of sustainable forms and innovative technological solutions, to be proposed to the community and to the materials and building industries. A different construction sector, more and more attentive to the needs and rules of a globalized society in continuous transformation.

Technology can take up this challenge and change how everything is designed, from physical assets, like buildings, to business artifacts, like commercial strategies, guaranteeing the feasibility of a work while respecting the balance of all the interests at stake, offering the technical and procedural tools to program the intervention, to plan the costs of the life cycle, to identify the most effective building process and to manage its different phases until the final decommissioning of the work, focusing on the effects of the design choices on all other phases (life cycle design).

In particular, a combination of different interconnected digital technologies on data acquisition, building modeling and digital fabrication, and data analytics along with new advanced materials and construction techniques, is poised to transform the conventional design activity by sidestepping the issue of constrained resources that defines the process today (see Table 3.4) (Autodesk, 2016; Boston Consulting Group, 2016; McKinsey, 2017b, 2018b; Qi et al., 2021; WEF, 2016; Yan et al., 2020).

Design shall be a “best possible” process, with significantly reduced costs, improved speed, and better outcomes. Although the most substantial benefits will accrue in the construction and operations phases, digitalization will continue to increase efficiency through new forms of design and engineering and increased frontloading.

In particular, new Construction 4.0 technologies for building design allow:

- data-driven design in a collaborative work environment, based on advanced survey systems for data acquisition and virtual migration of physical structures, parametric design and building performance simulations tools and advanced analytics empowered by AI and ML;
- enhanced design exploration and visualization through real-time 3D rendering and extended reality and rapid prototyping;
- design optimization through AI GD tools and design for digital fabrication.

BIM is certainly at the center of this transformation, as a collaborative platform of information that can interact and empower several digital technologies and that entails the creation of a digital representation system that allows rapid analysis and comparison of design alternatives, coordination, and collaboration between team members, communication and update of information, easy implementation and management of changes, clash avoidance (Boston Consulting Group, 2016).

BIM design allows the digital acquisition of geometric data through LiDAR scan and 3D photo reconstruction, also through the use of drones or autonomous robots, both for the preparation of the digital model and for its rapid and precise verification and possible update (advanced surveys), providing a digital environment that 100% matches the physical one. During the design phase, the BIM model can be used to carry out seamless, real-time simulations of energy and environmental performance, to optimize shape and performance through parametric and GD methods, to take advantage of a real-time 3D visualization and of VR and AR for a more immersive experience, to facilitate the future direct digital fabrication of highly complex elements. BIM streamlines design and engineering processes and facilitates their parallelization by helping architects, engineers, and consultants to merge their models, identify interdependencies and clashes, rapidly evaluate design alternatives and synch changes in real-time. A key benefit of the BIM based design development is that digital construction can start simultaneously and explore feasibility, construction and operational cost implications earlier for informed decision-making. This way, fewer decisions are pushed to the construction phase when the cost to change them is high. Long-term maintenance can be accounted as a real cost from the start, permitting early adjustments to mitigate these expenses. During the construction phase, the BIM model can allow data exchange with project management and construction monitoring tools, it can constitute a digital input to prefabrication and AM methods and for automated and autonomous construction equipment.

Working on a cloud-hosted, federated BIM model, all project stakeholders can operate within a Common Data Environment that automates data management and sharing. Federated BIM represents a single, trustworthy digital source of the latest, updated information, free of contradictory versions, and complete as of that moment, driving more confident decision-making resulting in better outcomes.

TABLE 3.4 Application of digital technologies and tools in design activities.

Design phase	Design activities	Design technologies and tools
Programming	Feasibility study • Context analysis • Site localization • Environmental impact analysis • Project requirements and objectives • Time and costs estimation • Project brief	Data-driven design • Advanced surveys • Big Data and analytics • GIS Design exploration and visualization • Extended reality
Conceptual design	Geometry design • Massing • Orientation • Space layout • Openings	Data-driven design • BIM 3D • Early-stage analysis • Big Data and analytics Design optimization • Parametric design • Generative design Design exploration and visualization • Real-time 3D • Extended reality • Rapid prototyping
Design development	Envelope design • Materials • Thermal mass and transmittance • Acoustic insulation • VLT and SHGC • Shading systems	Data-driven design • BIM 3D and 5D • Building performance simulation • LCA and LCC • Big Data and analytics Design optimization • Parametric design • Generative design Design exploration and visualization • Real-time 3D • Extended reality • Rapid prototyping
	Systems design • Systems typology and sizing • Renewable integration	
Final design	Preconstruction design • Detailed design • Project certification • Design for digital fabrication • Digital twin • Construction site planning	Data-driven design • BIM 3D, 4D, 5D, 6D and 7D • Building performance simulation • Big Data and analytics Design optimization • Parametric design Design exploration and visualization • VDC • Extended reality

3.2.1.1 Data-driven design

The quality of any building or infrastructure project is strongly dependent on the quality of the information designers must work with. Hence, all decisions shall be based on site and project-specific information using a data-driven design approach, rather than on arbitrary aesthetic or stylistic prejudice.

Advancement in data acquisition (LiDAR scanning, aerial imagery, IoT, GIS) and in data information and analytics technologies (BIM, building performance simulation tools, AI, and ML) enable today a knowledge-based building process capable of guaranteeing the formal and technical quality of the intervention, in compliance with the best ratio between the benefits and the overall costs of construction, operation and maintenance, starting right from its programming stage (ECSSO European Construction Sector Observatory, 2021).

In fact, programming any intervention involves the definition of the project choices and their priorities based on the correlation between needs, technical resources and financial resources. The output will be a project brief which contents may vary depending on a large number of factors, such as the context of the intervention, the nature of the client or the size and

complexity of the work. The programming phase is normally developed through successive levels of investigation. The first level is the strategic one, in which the client, through appropriate analyzes and studies, identifies and maps out all the significant components of the intervention. The second level of programming is the operational one, which defines the resources, constraints and quality objectives on which the intervention design will be based. This level corresponds to the preparation of the project brief document, which contains technical and administrative insights graduated in relation to the entity, type and category of the intervention to be carried out. Therefore, project programming plays a decisive role in contributing to the satisfaction of the expressed and implicit needs of all interested parties (client, user, community, etc.). A lack of programming culture can significantly affect the final quality of the building intervention, resulting in wrong cost forecasts and poorly formulated needs with repercussions to the entire design and construction process.

It is evident that a good project brief shall be the result of accurate insights and investigations in the programming phase, with quality and abundance of data becoming a main driver of reliable decision-making about investments and feasibility. Key performance indicators shall be considered to inform any investment decision, influencing the client's decision to build, retrofit, or renovate a building or infrastructure. Programming sets the bottom-line decisions on cost, defines the design objectives, and, ultimately, determines the "go or no-go" of any investment.

Traditionally, project programming has been largely drafted based on estimates and assumptions, rather than on actual information. In the last decade, however, the amount of reliable, structured, informative and visual data that is easily available has expanded exponentially, enabling a more holistic, data-driven and data-informed approach to programming. Clients and planning consultants can better manage financial risk, by laying out the total costs during the entire life cycle of the building, and allowing investors and building operators to make the most informed decision about their investments. Precise data allows to maximize the investment, by ensuring that the project brief, and therefore the intervention, is precisely tailored to its expected use, its market and its location. Project data can be cross analyzed with context data on different scales to perform advanced analytics, which leverage Big Data, AI and ML to highlight patterns, connections and opportunities to match with the intervention. Data can bring into the fold multiple aspects of the built and social environment, from energy efficiency statistics to usage data on various parts of buildings, to measurements of employee satisfaction, to demographic and census information, traffic and parking availability, base rents and turnover vacancy, socio-economic climate, transportation streams, zoning code requirements, and growth projections for the region. Ultimately, data-driven programming allows the design and construction of more efficient built environments, reduces financial risks and promotes sustainable and socially responsible investments.

Once the project brief is defined and the design team assembled, the design process will necessarily involve a thorough initial analysis of the needs to be met, the legislation to be respected, the services and performance to be provided, as well as the environmental context being transformed. In particular, the analysis of the environmental context constitutes a particularly important phase in terms of sustainability, and includes the investigation of both the territory and the climatic parameters, including the study of sunshine and daylighting, the investigation of the availability of renewable energy sources. Such activities have been traditionally based on gathering geographical data from different sources (maps, cadastral parcels, local government acts) as well as on-site measurements and investigation. The introduction in the last years of several digital tools for site survey and analysis, including both advanced sensing devices, comprehensive databases and innovative software instruments, has provided designers with unprecedented insight and clarity on all aspects, both geometrical and informative, of the built or natural environment in which the intervention may take place.

Right in the programming and urban planning stage, it is possible to obtain with great ease and low cost highly detailed aerial views of any place on earth, either by buying or requesting satellite imagery by a number of providers or by performing low altitude aerial mapping with unmanned aerial vehicles, also known as drones (see [Fig. 3.4](#)). Compared to traditional aerial surveys performed by manned aircrafts, these new services provide much greater accuracy at a fraction of the cost, allowing much greater freedom in using such tools: for instance, it is possible to request images taken at a specific season or hour of the day, to take into account vegetation or shadows, or request survey at regular intervals to document works progress or monitor other events from a vantage point. In particular, drones have greatly expanded the market and the possibility for aerial mapping due to their low cost, easy deployment and versatility: they can provide georeferenced orthographic photos as well as 3D point clouds, as well as thermographic imagery via IR sensors to enable energy diagnosis of buildings or inspection on energy infrastructure.

Geospatial analysis can be further refined by the use of GIS, which allow to superimpose orthophotos with all kinds of informative layers (topography, hydrology, transport infrastructure, cadastral parcels, permitted use of land, census information, civil services, amenities, etc.) to highlight patterns and obtain greater insights on the territory characteristics to better inform strategic decision-making (e.g., where to invest in retail or in housing, where to place services).



FIGURE 3.4 New LiDAR (left) and drone (right) data acquisition systems. *Courtesy of Trimble and DJI.*

On foot site surveys have also been greatly improved first by the introduction of robotic total stations (RTSs) and, more recently, by GNSS and by LiDAR scanning devices (see Fig. 3.4). These tools allow topography reconstruction and seamless import of geometrical data into the virtual design space, from hundreds of 3D points as allowed with RTS and GNSS, up to billions, as with LiDAR, all with millimeter accuracy, both indoor and outdoor. Existing structures can also be effectively digitalized by using 3D photo reconstruction from pictures taken from the ground or with drones, producing fully colorized 3D point clouds which can be easily integrated into the BIM workflow. In particular, LiDAR 3D scanners can also be used on the move, mounted on vehicles, backpacks or even handheld, allowing to map entire houses or extended infrastructure such as railways, tunnels or roads in minutes. Such effortless geometrical precision allows on the one hand to perform all design activities on a trustworthy and accurate base, on the other hand to identify and characterize all elements in the site or building subject to intervention, which opens new opportunities to manage removal, selective demolition, recycling or even reuse of available materials and products.

At the same time, climate analysis can be supported by several software tools, often integrated within main Building Performance Simulation (BPS) or BIM programs, to visualize, create graphics and perform computations on multiple datasets, mostly at large scale. Common tasks include difference maps, correlations, composites, climate monitoring and deriving climate indices.

Once this wealth of data is at the designer's disposal, AI-powered GD tools can support architects and developers in identifying potentials, constraints and strategies emerging from each unique context of intervention. Cloud-based AI, ML, Big Data and GD algorithms can be exploited to optimize design proposals for single developments, neighborhoods or districts. Factors such as accommodation density, access to daylight and views, access to local amenities, proximity to open space or transport links, traffic and parking, noise, as well as local microclimate, heat island and wind characteristics, are weighted up to analyze, suggest, generate, simulate and visualize alternative designs at much quicker pace compared to conventional early-stage and planning tools.

Once all relevant data and information is collected, the project team turns to tools that allow to create a digital replica of the physical building, evolving from concept to final design, for a truly accurate framework of a building's performance and costs. This digital twin, the 3D BIM model, is enriched during the design process with interoperable data that can represent every detail of the building's geometry, technical performance parameters, materials, and systems.

In the building design phase, architects and engineers try to optimize on a large number of criteria, such as energy demand, indoor environment, materials, life cycle cost, etc., which are often conflicting. Software tools integrated with BIM can automatically generate and evaluate design alternatives, supporting value engineering and enhancing design-to-cost, design-to-fabrication, and sustainability analyses. Designers operate within an iterative, trial and error feedback loop between design solutions and subsequent analysis, based on technical simulations of energy and materials intensity, daylight, sunshine, thermal exposure, airflow, turbulence, traffic and pedestrian flow. Such design methodology allows to literally shape the project by the forces that surround it. In particular, the integration of BPS into all phases of the design process, from programming to early-stage decisions, up to systems sizing and energy code compliance verification, can implement a performance-based design approach that enables optimization of all factors and requirements. Indeed, BPS programs have reached a level of accuracy, flexibility and ease of use that allows their full integration into the design workflow to compare the competing cost and performance attributes of any proposed design solution. These tools can focus on certain disciplines of BPS (e.g., climate analysis, life cycle assessment, thermal comfort, energy calculations, daylight) or simulate all domains interacting on the building. They can provide key performance indicators

such as overall heating and cooling loads, energy demand, ecological and economical impact, visual and thermal comfort at the single room or building level.

The simulation process can now be streamlined and enhanced by using parametric design methods, an interactive process that allows designers and engineers to automate drafting of solutions based on the input of parameters, such as materials, site constraints, and even environmental requirements. This way, changes to the boundary conditions automatically lead to the components of a BIM model being updated, thus removing the possibility of human calculation errors and significantly reducing the time required to update designs compared to making changes manually. As drawings are directly produced from the BIM model, layouts can be regenerated effortlessly after every change. This approach supports the exploration of a much larger design space, constituted by many options, before deciding on the final design. Parameters such as a building's geometry, massing, systems, materials and suppliers can be tweaked, and a simulation run against the new attributes conversely to see effect on cost and performance, allowing to catch and avoid untold issues later.

With BIM, parametric design and BPS tools it is possible to explore ways to minimize production waste, energy and water consumption, and to optimize suppliers and materials for a lower environmental impact. Movement paths can be simulated with different scenarios applicable for construction safety or end-user experiences, for instance to test fire escape routes for areas of congestion and where more exits might be needed. Thanks to the advancement in Big Data analytics and ML, various data-collection methods can be combined—including IoT, mobile surveys, security camera footage, and traffic flow reports—to inform and refine design decisions.

In the next future, the value added by accurate measurements and comprehensive databases will be increasingly essential for the sustainability and competitiveness of the sector. Thanks to digital twins, data collected from connected construction sites (costs, time, accidents, etc.), smart buildings (occupant behavior and preferences, energy consumption, movements and use of spaces, etc.) and smart cities (GNSS data from public transports, weather data, water levels of the rivers that flow through the city, air pollution on the different streets, or even the amount of people that are in the main shopping street at a certain moment in time), can be used both to simulate alternative scenarios, and as important feedback to subsequent design activities, even in other projects and disciplines. This will further contribute to the creation of an increasingly sustainable and comfortable built environment and to the increase of the productivity of the sector following a more data and performance driven design approach.

3.2.1.2 *Design exploration and visualization*

The new requirements and expectations posed by contemporary architecture have highlighted the limits of traditional visualization techniques, usually based on 2D drawings and on few computer graphics produced at the end of the design activity, and are requiring more immersive, interactive and photorealistic dynamic tools, perfectly integrated into the whole workflow, capable of allowing greater understanding of the project in all its phases.

This can be achieved thanks to the recent advancements in real-time 3D rendering (RT3D) software and extended reality technologies, which today allow to instantly transform 3D models into high-quality visualizations and immersive experiences, and thus to validate project solutions at any point during the design phase, greatly shortening the trial and feedback loop (see Section 6.2).

RT3D allows the project team to design and make changes to the model and experience them photo-realistically in real-time, allowing to reveal if a layout works as anticipated, or to detect clashes that may disrupt the construction process. All project stakeholders, even those not familiar with architecture visualization, can get a complete view of proposed designs, enabling them to understand what the project will accomplish and how the design and specifications are justified and to have a clear representation of the final outcome before construction commences.

The RT3D experience can now be made even more realistic with VR, allowing to completely immerse the viewer into a simulated and interactive digital reality (see Section 6.3.1). VR is finding more and more interesting applications in the building design phase, allowing the actors involved to test solutions, improve their understanding of the project and identify in advance potential conflicts.

Architecture firms can walk clients through a realistic VR environment, in which they can take an active role in refining the design, with changes instantly implemented in the virtual model. For a sports or conference venues, for example, VR allows designers to validate how fans view the game from various locations, helping to optimize the positioning of stands. Other uses include monitoring crowd movements to test security requirements before construction, and training facility staff before handover. Edge-case scenarios such as flooding, fires, or explosions, that are nearly impossible to simulate in the real world, can be re-created at scale in virtual environments to enable the collection of data necessary to train teams and autonomous systems.

New advanced design exploration and visualization tools include today augmented and MR as well, which can overlay computer-generated content on top of the real-world views (see Section 6.3.2). This ability places the maximum potential for AR and MR application within the AECO industry in the construction and maintenance phases of buildings, in which they act as real human augmentation devices (see Sections 9.3 and 11.3). Nonetheless, AR, and MR in particular, are finding numerous and interesting applications also in the design phase with particular reference to building renovation interventions, infrastructure design and urban planning, by bringing the 3D models into the user's physical environment. In addition to these possibilities, MR allows to create collaborative environments where several people can walk around and at the same time interact with a virtual 3D model as with a physical one actually present in the room, and show the design intent to stakeholders, even remotely. Interactive mockups that combine physical and digital elements can be prepared by inserting the digital model over the real one.

By integrating Extended reality in the process workflow, project teams can work more accurately and efficiently, make faster and better decisions, and collaborate and communicate more effectively. By enhancing physical realities with digital information and making that content readily shareable, XR allows to easily visualize, explore, and understand designs, models, and site conditions, improving workflows across the building and infrastructure life cycle. In particular, the main applications of XR in AECO concern stakeholder engagement, design support and review, construction planning, progress monitoring, construction safety, and operative support; operations and management, as well as personnel training.

Another opportunity enabled by new technology to visualize architecture models is rapid prototyping: the growing diffusion of 3D printers with improved performance and falling costs is allowing AM to become an integral part of the design activity in many firms. Physical models and mockups that where once produced only in the bidding phase, and took weeks of work by specialized artisans to obtain at a prohibitive cost, can now be realized in mere hours, at a little fraction of that cost, in a completely automated fashion. Different 3D printing techniques can be applied according to the result expected and the use of the model: finishing can be coarse or smooth, surfaces can be transparent or opaque, objects can be monochrome or multicolored. Work models can be used for real-world simulation in tandem with the virtual ones, for instance to measure wind loads of a scale model in a wind tunnel to confirm CFD analyses or evaluating performance of freeform structural elements.

3.2.1.3 *Design optimization and digital fabrication*

In the last 10 years, the increased computational capacity of workstations and the introduction of several computational design methods have enabled architects and engineers to enhance the design process, either by making it more efficient or by expanding its conceptual boundaries. Designers have been empowered to explore and evaluate more complex solutions, create and deploy advanced fabrication techniques, and control the design process at different stages.

Main computational design activities include automation of repetitive tasks, parametric design (or algorithmic design) to streamline design optioneering activities, and, more recently, GD powered by AI to optimize design solutions (see Section 6.4).

GD is an iterative technique that uses advanced algorithms to increase the user's ability to define, explore, and choose design alternatives: it automatically creates design solutions then ranks the outputs, based on a predefined set of criteria provided by the designer. GD solves the limit inherent to parametric approaches of having to investigate and evaluate the different design options manually. Instead, in GD the computer explores the parametric design space semi-autonomously and then reports back to the designer which options it considers promising for further analysis. As a computer can process information much quicker than a human operator, this allows a faster exploration of more complex design spaces which may amount to thousands of design alternatives.

GD allows the designer to identify rapidly the best design solutions which, among all procedurally generated of alternatives, succeed in simultaneously optimizing the target variables (environmental, functional, economic, performance, etc.) that are often antithetical to each other. GD applications in architecture are numerous, from the urban scale for identifying, for instance, the best shape ratio and orientation of a building within the construction lot, to that of building, structural and plant design, up to industrial design for the static optimization of the shape of a structural joint or the size of the cladding elements of a facade in order to minimize materials waste.

The application of BIM and GD in the design stage can foster the transition of the construction industry toward the digitalized, sustainable and productive manufacturing practices already established in more advanced industry sectors such as automotive, electronics and consumer goods manufacturing. As digital and automated construction methods have emerged, including AM, computer numerically controlled (CNC) routers and cutters, or multiaxis industrial robotic arms, it has become apparent the aspects related to the digital fabrication method and materials envisaged for

the construction of components can be effectively integrated within the BIM design workflow. Ideally, this would allow to close the process chain that links design to construction, greatly reducing the loss quality and performance usually involved in the transition between construction drawings and coded instruction for each digital fabrication process. Such Design for Digital Fabrication starts from the BIM model and employs parametric and generative modeling to create 3D models in fabrication quality, ready to be input as machine code directly to the digital fabricator, thus effectively zeroing the gap between design and construction (see [Fig. 3.5](#)). Moreover, the collaborative BIM environment enables the spatial coordination of designers and different trades and specialty fabricators already in the design stage (see [Section 6.5](#)). Along with reduction of time and costs, digital fabrication processes can allow to achieve high degrees of freedom in architectural solutions such as shapes with optimized performance/material ratio.

3.2.2 Connected construction

Within the building process, the actual construction phase has not seen significant improvements in productivity in recent years, which contrasts with the rapid advances that have occurred in other manufacturing sectors. The use of machines on construction sites already provides support, but a great deal of manual labor is still undoubtedly considered irreplaceable for most construction site activity. Moreover, the inherent fragmentation of construction firms and subcontractors entails a propensity for siloed teams and workflows, which has long been a problem in construction and a major cause of lack of productivity.

Indeed, the technological advances in general have not benefited the overall efficiency of the construction sector, as it has been slow to adopt new technologies and has never undergone a major transformation. For instance, whereas lean manufacturing process methodologies have already become the norm in several industrial sectors, take-up in construction has been limited, and many companies that have adopted them have failed to apply them wholeheartedly. Therefore, construction firms are now finding themselves struggling to cope with ever-larger and more complex projects, particularly in infrastructure. To stay competitive, they must find ways to improve job productivity, risk management, and workforce safety. They also need to explore how to complete projects more effectively, especially because major construction projects are, on average, delivered a year behind schedule and 30% over budget. Moreover, the construction phase is also critical as the best energy-efficient design does not work if implemented poorly. The quality of construction must be up to standards to ensure that energy-efficient design works as planned, therefore QA/QC practices

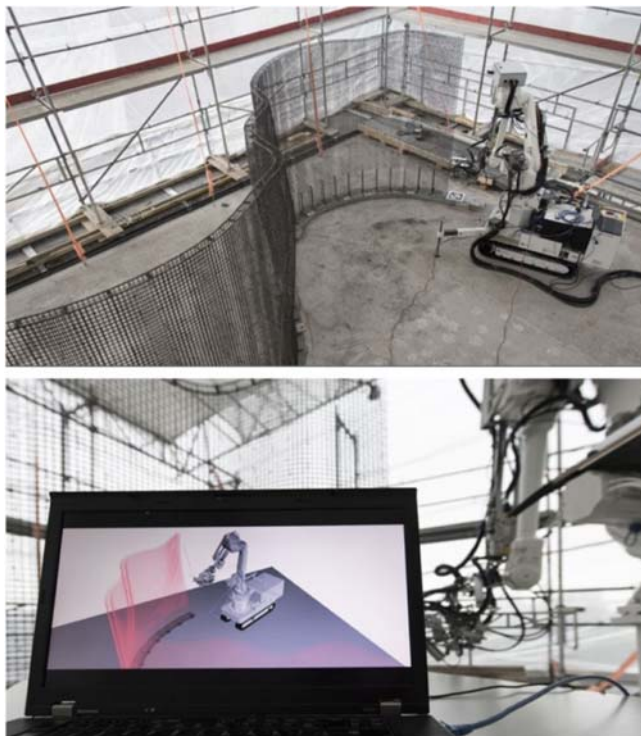


FIGURE 3.5 Digital fabrication technologies. Copyright © Gramazio Kohler, ETH Zurich.

must be thoroughly implemented as works progresses. Also, construction sites are energy and material-intensive, and generate huge amounts of waste which is often unnecessary.

Substantial change is on the way, however, driven by increased digitalization and through the development and deployment of digital technologies and processes, along with new advanced materials, new fabrication techniques and off-site construction methods. The industry will be more and more characterized by connected systems of sensors, intelligent machines, mobile devices, and new software applications, all integrated on a central platform of BIM empowered by AI. As their adoption increases, digital technologies are enabling companies to boost productivity, manage complexity, reduce project delays and cost overruns, and enhance safety and quality.

In particular, the wider adoption of tablets and mobiles as standard tools in the construction industry has ushered in a new generation of cloud-based project and task management apps that can be deployed even on remote construction sites with real-time updates, paving the way for a more connected working environment. By adopting these tools, front-line users such as project managers, tradespeople, and operators can effectively change the way the industry does everything from work- and change-order management, time and material tracking, dispatching, scheduling, productivity measurement, and incident reporting.

Many construction tasks are already being facilitated by the ability to exchange information rapidly, and the seamless integration of such tools in a BIM-integrated data pipeline will further smooth communications and real-time updates. All sorts of information can be visualized on portable devices (or with more sophisticated XR devices), georeferenced in a 3D graphical simulation model, to ensure plans and drawings as well as technical, financial, and legal information are always up to date, efficiently substituting paperwork. This way, change requests and fulfilment of additional details is greatly facilitated, leading to significant savings and improved quality and efficiency. An example from a real-world implementation in a medium-sized American construction company claims estimated savings of up to US \$1.8 million a year.

This connected construction model can ensure everyone is operating from the same playbook and on the same page, breaking down some of the barriers that create bottlenecks and miscommunication. It relies on hardware, software, and services to unify all actors, processes, and phases involved in each project, simultaneously connecting the digital world of modeling, imagery, and data with the physical world of contractors, materials, equipment, and the jobsite at each phase of construction, starting with preconstruction planning and continuing through maintenance and operation. Connected construction provides all stakeholders with access to reliable, updated, and central sources of truth about the project, enabling earlier problem detection and resolution, fewer human errors, streamlined operations, better communication, faster project delivery and smoother handover. The application of blockchain-based security protocols further improves trust between stakeholders and on shared data, allowing the automation of delicate tasks such as smart contracts, works compliance and project handover. Overall, digital technology fills the gaps that historically exist in construction, linking teams across disciplines and locations, from the office to the jobsite to the fabrication shop, in ways that simply aren't possible with traditional, analog tools and methods.

A connected jobsite greatly eases the management of more complex building and infrastructure projects and the sheer volume and scale of moving parts involved. Through cloud-based software, mobile devices on the jobsite, and Wi-Fi/5G enabled hardware and equipment, project managers can control the complexity of large-scale projects, confident that critical information and key teams or stakeholders are always in the loop. By connecting and updating every person on site at every phase, projects become much more manageable. Mobile user interfaces and AR allow real-time communication with remote construction workers and maintenance crews, and VR improves decisions, planning, and training.

On site, technologies like accessible BIM platforms, GNSS, LiDAR scanning, RTSs, and extended reality can drive significant productivity improvements at the task level over manual methods. They have accelerated the layout process while enhancing accuracy and improving documentation, as well as enabling more effective QA/QC. Using these technologies, teams can detect and resolve problems earlier, reducing costly rework and RFIs, and preventing errors from making it into the final build, both at the prefabrication and construction stages. The result is higher-quality projects delivered on time and on budget. In particular, MR and AR allow to visualize 3D models overlaid on real-world environments, providing a unique opportunity to streamline design collaboration, quickly resolve conflicts, and avoid rework. Connectivity also supports the automation that is driving productivity forward through advancements like digital fabrication, that is, the seamless transfer of virtual design information to the fabricating machine (3D printers, CNC routers, etc.), and off-site prefabrication. This way, building components can be fabricated on site with the same degree of accuracy obtainable in the factory, or be industrially prefabricated in controlled industrial environments according to stricter quality standards before they are assembled on the construction site. Prefabrication can be as extensive as the construction of fully finished and equipped building modules, sometimes already furnished, which reduce on-site works to the sole positioning and connection of those to complete the building (modular construction). With these innovative,

digitally driven construction methods, mistakes in construction which might require reworks or downgrade building performance can be avoided, materials waste is greatly reduced and construction speed substantially improved.

Moreover, thanks to the advancement in nanotechnology, smart materials sciences and biotechnology and to developments in engineered timber structural systems, today new materials allow to lower costs and speed up construction while improving quality and safety, leading to profound changes in the whole construction process, from design to maintenance.

The digital transition of the building sector toward a full connected construction model includes these main disciplines (see [Table 3.5](#)): Digital construction management, Connected construction site, Virtual design in construction and Digital twin, Automated construction processes, New on-site and off-site fabrication techniques.

3.2.2.1 Digital construction management

The management of the construction site, especially in larger and more complex projects, requires adequate IT support: dedicated software can allow remote management of all aspects related to the construction works, from setting up the yard to final handover to the client, as well as ensure easy control of project variations during execution and allow collaborative workspaces. One major challenge during the construction phase is in fact to provide all parties, from suppliers to subcontractors to on-site crews, with the right information at the right time in the right place. The best way to ensure a connected process is to maintain a common data environment that supports real-time collaboration and eliminates inconsistencies in progress reporting among subcontractors, contractors and building/project managers by increasing the transfer of accurate knowledge from stakeholder to stakeholder. This results in a better understanding of the project and increased productivity based on reduced delays, change orders and coordination problems or conflicts in the field. Cloud-based construction management software can automate traditionally manual tasks, including monitoring progress stages, creating a centralized communication and collaboration space for the members of the team, planning resources, keeping track of client requests, etc.

The application of AI tools in construction management can bring numerous advantages in planning the construction site layout, scheduling activities and tasks, managing workforce, subcontractors, and fleet, procuring materials, enforcing safety and security conditions, optimizing time and resources, identifying and prioritizing current or potential issues, preventing of workplace accidents, and identifying solutions and strategies to be implemented in management. In particular, AI-based construction management software is greatly expanding the functions of latest construction management tools, and some already integrate advanced data analytics powered by AI and ML to provide valuable business insights from data collected from multiple sources in real-time. These help project managers to understand issues in their process, look for better approaches, and improve tasks such as manpower logs, project billing, and job estimation. Management activities that require a greater degree of trust between the parts, such as contract enforcement, payments, supply order, quality checks and project handover, can be facilitated by entrusting relevant data flows with blockchain technology: this certifies that each piece of information is valid and has not been tampered with, allowing for instance to issue payments automatically right after a progress threshold is met (smart contracts).

TABLE 3.5 Main Construction 4.0 technologies for connected construction.

Construction 4.0 discipline	Technology application
Digital construction management	Common Data Environment, cloud-based construction management software, AI, blockchain
Connected construction site	IoT, wearable devices
Virtual design in construction	5D BIM, XR, digital twin
Automated construction processes	Construction robots, drones, autonomous vehicles, exoskeletons, robotic on-site factories
New on-site and off-site fabrication techniques	AM on-site and off-site, digital fabrication, off-site prefabrication

3.2.2.2 *Connected construction site*

Construction sites have been getting denser and denser in the last years in terms of number of workers, profusion of construction equipment, and amount of work going on at the same time. Vast amounts of data are generated daily, however a majority of that is not even captured, let alone measured and processed. With the development of IoT technology, more and more construction sites, especially larger and more complex ones, can leverage the network connection of construction machines, equipment, materials, structures, and employees, to monitor in a continuous and integrated way productivity and reliability of both personnel and resources (connected construction sites). The application of sensors and wireless communication technologies to objects, machines or people allows to generate real-time information on their position or physical state which can be collected for monitoring, control, statistical analysis and decision support, creating an actual intelligent space. Sensor-equipped machinery, vehicles and power tools can detect and communicate maintenance requirements, send automated alerts for preventive maintenance, and compile usage and maintenance data. Connected systems can forecast and alert site managers when stocks are running short and when orders need to be made. NFC tagging and tracking of materials can also pinpoint their location and movement and help reconcile physical and electronic inventory. Vibration sensors to test the strength and reliability of a structure can be embedded during construction to detect deficiencies and correct them early. Ambient conditions and fuel consumption for assets and equipment can be tracked to improve on-site energy efficiency. Wearable personal devices such as helmets, jackets or boots can identify and locate each worker, determine their action and vital state, and send alerts if drivers and operators are falling asleep, if potential clashes are predicted or if a vehicle or asset is stationary or nonoperational contrary to schedule.

The opportunities from the Internet of Things greatly support the digitalization in the construction-planning process and on the construction site itself by enabling firms to capture data that paper could not. The insights gained from on-site data through the adoption of advanced analytics can help to improve efficiency, timelines, and risk management, saving time and money. Field-sensor data, construction-progress data, and workforce and vehicle movements is fed to statistical and AI analysis to detect anomalies and identify potential risks, in particular for construction sites in dense and historically sensitive cities.

3.2.2.3 *Virtual design in construction*

The most useful innovation of latest construction management software is represented by their integration with the BIM model of the project to allow virtual inspection, design review, quantity take off, planning and management of the sequence of processes and times of execution (4D), as well as construction costs and proceeds (5D). Such integration allows to apply VDC, that is, the use of 3D BIM models and other information, to digitally plan out all aspects of a construction project—from estimating costs to scheduling and risk management—allowing to build a project virtually from site preparation to final handover, then track actual construction progress, optimize processes, minimize waste, and validate installations on that benchmark.

VDC enables all stakeholders to share data in real-time and to integrate and coordinate their activities, making collaboration less error-prone and more efficient. Each stakeholder can easily access schedules, cost data, and critical steps involved in their particular piece of the project. They can visualize for themselves where discrepancies, clashes, or mistakes are occurring so they can make better decisions and resolve issues quicker before they impact the project's schedule, budget, or quality. VDC also allows to audit, track project progress, and even reduce fraud or malicious behavior. Visualization technologies like MR and AR can allow to plan and optimize jobsite workflows around heavy equipment and other large obstacles, as well as to run safety scenarios to uncover potential hazards and practice responses to them (see Fig. 3.6). In turn, field workers can share progress or resolve problems with other project stakeholders, giving them the ability to visualize the project from their office.

With VDC, project teams take the geometrical representation of the asset, namely the BIM model, and couple it with spatial attributes like soil types, placement of utilities, or traffic patterns, often entailing the use of GIS data. This analysis allows to discover unforeseen overlaps or gaps, potential safety hazards, or design flaws that need to be addressed before construction begins. This representation and the associated information become the constructible model that will be available to all stakeholders throughout the construction life cycle. As works progresses, the constructible twin model or digital twin can be continually updated at every step by gathering real-world information about the building or structure using wireless technology like drones, sensors, cameras, and other IoT-related devices. Each time new information is gathered, the digital twin is updated to reflect it, while advanced analytics and AI-powered technologies continually analyze and measure its profitability and performance (see Fig. 3.7). Being a living model of the project, the digital twin can be used as a testbed for optioneering different construction alternatives, such as

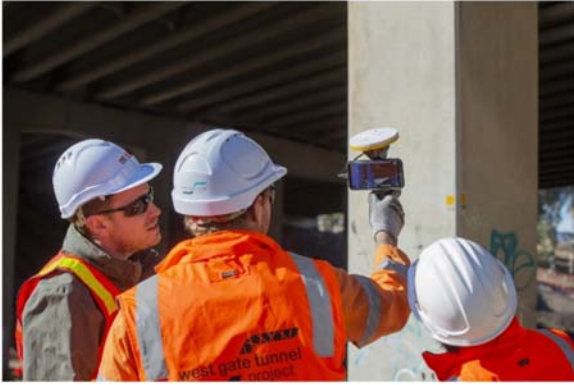


FIGURE 3.6 AR visualization of VDC information on site. *Courtesy of Trimble.*

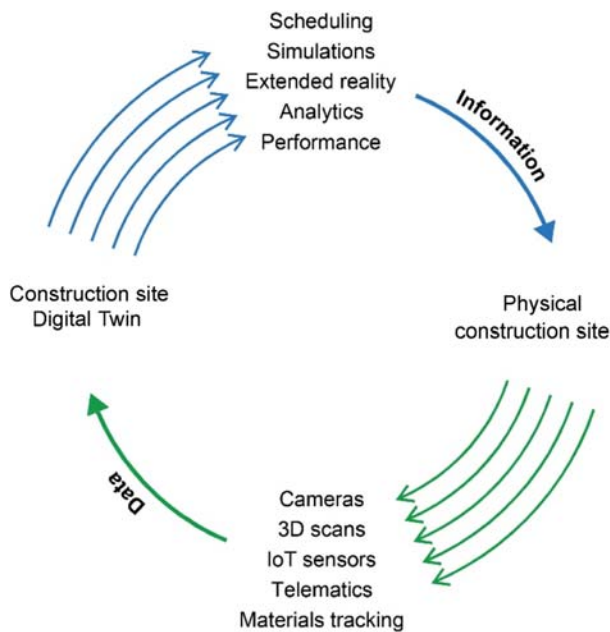


FIGURE 3.7 Construction digital twin feedback loop.

prefabrication and on-site assembly. The digital twin allows to experiment with options and analyze expected outcomes before they impact the actual work site. Lessons learned in the safety of the digital twin can then be applied to the real-world environment to reduce risk, save costs, and improve return on investment. The digital twin can also be used to inform future enhancements to a project by providing detailed knowledge about the existing structure.

3.2.2.4 Automated construction processes

Today, significant technological advancements are pushing the building sector toward new automated on-site and off-site construction methods and processes based on digitalization and robotics, which are finding application on a large scale.

Off-site automation systems have the main objective to improve the quality of prefabricated building components taking inspiration from the use of robots in other manufacturing sectors, such as automotive and shipbuilding industries. Off-site robotic systems are mainly employed in the prefabrication construction industry for the production of modular and prefabricated housing components such as ceilings, walls and roofs, where they deal with repetitive, quality demanding and labor-intensive tasks to improve productivity, cost efficiency, quality, and safety.

Robotics can find many applications in on-site activities as well. Main benefits include the improvement of productivity thanks to the possibility to perform tasks significantly faster and with higher endurance compared to human labor, of safety thanks to the ability to operate in harsh and unsafe environments where humans are unable to work, and of final quality due to the capacity to be more precise and accurate than humans.

Currently, robotic technologies can be applied to on-site construction at varying degrees of integration with the different operations that are carried out in the construction site, from building demolition and disassembly to site preparation and excavation, up to structure assembly, wall laying, or finishing. In particular, on-site robotic fabrication include: Single task construction robots, Biomorphic robots, Exoskeletons, Teleoperated machines and Autonomous vehicles, up to the implementation of highly-automated robotic on-site factories.

In particular, surveys, scans, and inspections on construction sites can be carried out by teleoperated vehicles such as drones (see Fig. 3.8). Imagery and 3D scans taken from drones allow for accurate 3D reconstruction of the site prior and during works to track progress (for instance by measuring excavations and earth movements) and monitor activities and safety conditions.

Indoor site inspections can be carried out by autonomous wheeled or legged robots equipped with LiDAR or cameras (see Fig. 3.9) to assess progress and compliance of construction, perform security patrol and detect hazardous situations such as fire or short circuits (via IR cameras) or gas leaks (via gas detectors). Autonomous vehicles also have a direct involvement on construction phase in earthmoving works, thanks to AI controlled dozers, dumpers and graders that operated based on project CAD files and often employ drones for coordination (see Fig. 3.10).

Specialty robots, mostly teleoperated, can perform site demolitions via jackhammers and waterjets (see Fig. 3.11), and some even separate concrete from rebar to facilitate recycling. Structural works can be aided by rebar assembling and tying robots, welding robotic arms, and by formworks fabricated by robotic arms. Automated on-site assembly of steel structures or precast concrete elements minimizes the risks during erection or installation works. Brick masonry can be assembled by bricklaying robots that allow great precision with fast execution times. Single task robots can perform tasks such as partition layout, rendering, drywall finishing, painting (also via drones to avoid costly scaffolding) or overhead drilling, all based on instruction inferred by the project BIM data.



FIGURE 3.8 Construction site monitoring with drones. *Courtesy of DJI.*

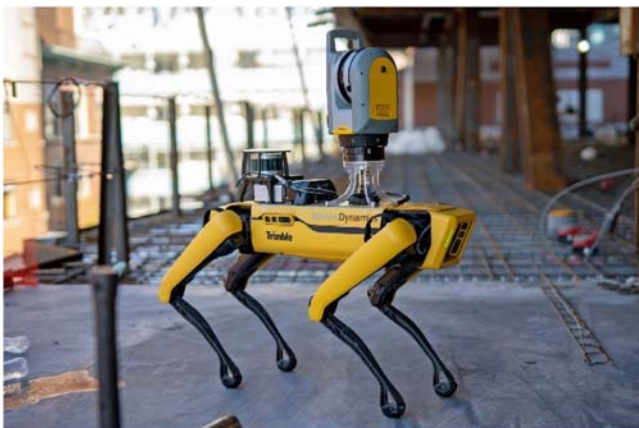


FIGURE 3.9 Biomorphic robot equipped with LiDAR for automated site scanning. *Courtesy of BostonDynamics.*



FIGURE 3.10 Autonomous dozer and excavator vehicles. *Courtesy of Built Robotics.*



FIGURE 3.11 Single task demolition robot. *Courtesy of Brokk.*

Robotics can furthermore aid human workers in performing most tiresome tasks thanks to the availability of various exoskeletons, able to greatly enhance the strength of the worker, correct their posture or mitigate strain (human augmentation). From power gloves and arm supports up to full body suits, exoskeletons allow great benefits in terms of both increased productivity and reduction of workplace accidents and long-term work-related diseases.

Finally, pervasive adoption of robotic works or support in all construction activities lead to the concept of on-site factory, that is, a construction site structured more similar to a factory, equipped with gantry cranes and extensive automated effectors, protected from external elements, able to move alongside the building or infrastructure under construction and usually heavily reliant on prefabricated elements. Examples include the so-called “sky factories” popular in Japan or specific infrastructure applications such as tunnel boring machines.

3.2.2.5 New on-site and off-site fabrication techniques

The increased adoption of digital tools in both design and construction activities has allowed the application in building and infrastructure construction of several innovative processes, collectively known as Digital Fabrication, that include 3D printers, CNC routers, multiaxis industrial robotic arms, laser-cutters, plasma cutters, water-jet cutters and hot-wire foam cutters, and other machinery. All these tools enable construction techniques that were once exclusive of the manufacturing or rapid prototyping industries, allowing huge benefits in terms of speed, freedom of shapes, customization, logistics, cost control and sustainability.

The main advantage of these techniques is that they are entirely digitally controlled with fabrication code that can be directly converted from design data, which allows 100% accurate reproduction of the virtual design into the finished object. This way, shapes to be constructed can be fully customized to the desired shape and performance, which can be the result of iterative optimization in design via parametric, generative and simulation tools, obtaining objects with reduced use of materials, structurally effective shapes and graded assemblies, and functional integration with sensors or technical systems. AM, or 3D printing, is particularly interesting for the vast array of printing techniques and materials available which can find application in fabrication of several building components, from scale models of the building



FIGURE 3.12 Buildings scale 3D printing. *Courtesy of Apis Cor (top) and ICON (bottom).*

for study and simulation purposes to plastic and ceramics façade and cladding elements, metal structural joints and members, up to larger cement building elements or even full-scale buildings.

Most of these innovative digital fabrication methods are employed in off-site construction facilities for prefabrication of complex building components as well as rapid prototyping, however several rugged and easy to set-up machines are being increasingly deployed on site. Much interesting in this case is large-scale 3D printing, which has already realized several functional buildings all over the world (see [Fig. 3.12](#)).

3.2.3 Smart operation

In the last years, the diffusion of digitalization and innovative technologies and systems have begun transforming the way that infrastructure, real estate and other built assets can be operated and maintained in order to provide a more comfortable, energy efficient, sustainable and cost-effective built environment. AI, Big Data, and the IoT, along with the technological advances which are driving down the cost of sensors, data storage and computer services, have created unprecedented possibilities in these disciplines. Buildings and cities are getting smarter and more connected, and the digital and physical worlds are becoming deeply interconnected and interrelated allowing to dramatically improve user experience.

The ongoing technological and digital revolution allows buildings to become intelligent, connected to the global network and able to receive, process and take advantage of data and information, to communicate with its users and, in turn, to share their infrastructure with that of the Smart city. The integration of the building's intelligent systems with the city's one provides a smarter urban system, enabling intelligent, real-time decisions at both levels, such as, for example, intelligent energy management considering the relationship between availability and demand of energy and times of higher and lower consumption at both levels.

Opportunities brought by digitalization in the operations phase mainly entail exploiting the performance analyses that had been conducted in the design phase, introducing an advanced BAS, and fully utilizing the building information handed over by the contractor after the construction phase through the BIM process.

In particular, BAS and energy management systems (EMSs) have been identified as a missing link for the successful implementation of zero-energy buildings and the deployment of an effective smart grid. Equally important is the role that such systems can play in bridging the information deficit of users and inducing virtuous behavior in the management of house equipment.

BAS acquire in real-time all relevant data and information from IoT sensors in the building, from smart meters and from the net, track users' needs and behavior, and dynamically control and optimize all building services—HVAC, lighting, power systems, dynamic façade elements, appliances, water supply, security, fire safety, egress and movement. Through AI and advanced algorithms such as model predictive control, BAS can be not only able to react effectively to any change in its usage parameters, but also to predict future necessities and prepare accordingly to minimize energy expenditure and comfort disruption. User experience is further improved by human interfaces (touchscreen, mobile apps, and vocal commands) which provide occupants with intuitive controls and clear information dashboards. In particular, BAS allows to reduce energy consumptions of the house, to optimize thermohygrometric and visual comfort of interiors as well as reduce operating costs thanks to:

- the autonomous integrated dynamic control of façade elements and of home appliances, allowing an efficient and continuous management of all energy and matter flows according to the climate conditions and users' behavior;
- a better use of building equipment by the inhabitants due both to the smart human interface and to the continuous information on house status and performances enriched with suggestions and alerts to manage energy consumptions and comfort levels in an efficient and conscious way;
- the full interaction with the Smart Grid by regulating home electrical loads, energy production from integrated renewable sources (PV, wind turbines, energy harvesting systems), energy storage (batteries or connected electric vehicles through V2B) according to dynamic weather and energy prices conditions.

Within the BAS, building equipment can perform manually using dedicated apps or vocal commands, partially autonomously (following fixed and predetermined responses to environmental parameters) or fully autonomously with programmed functions, based on responses to environmental parameters directed by dynamic programs that can be generated or improved by self-learning. Sensors allow the constant monitoring of environmental parameters and detect the presence of people in the buildings managed. AI-based tools then adjust the heating and electricity consumption not only on the basis of real-time data but by analyzing the building's usage statistics to adapt and anticipate needs.

Energy management is particularly important to promote the evolution of buildings from mere energy consumers to prosumers, able to buy, sell and negotiate the energy supply with the utility providers to benefit from reduced costs, secured energy supply and improved grid stability. This is today enabled by the increased diffusion of renewable energy, both centralized in the utility grid and distributed in single buildings often confederated in micro grids, of smart meters, which enable two-way interaction of the building with the energy provider, of building integrated energy storage systems or EVs, and of incentives and energy subscription programs such as Demand Response which vary energy prices dynamically according to grid loads, availability of connected renewable sources and scheduled interventions. This way, an evolved EMS is able to monitor energy usage, predict energy needs and renewable production, receiving pricing signals from the grid and therefore optimize energy flows within the building and with the grid, for instance shifting appliance use in off-peak hours, selling energy produced on site during the day and buying electricity at night to recharge on-site energy storage facilities.

Parallel to BAS, data for sensors can be tracked to support facility management by allowing both fault detection and predictive maintenance capabilities: aptly trained AI algorithms monitor continuously the status and parameters of all relevant building components, allowing to identify with sufficient anticipation failures and disservices and, therefore, enabling managers to schedule interventions timely to minimize downtime and disruption.

With the increasing diffusion of BIM and IoT devices, the future of both Building Operation and Maintenance is represented by the digital twin technology, which promises to revolutionize the way buildings are managed and maintained by transforming them into a rich ecosystem of data and insights. Digital twins provide an accurate and up-to-date virtual model for a physical entity, from a single building element, such as an HVAC unit, to the whole building, up to entire cities or districts. They allow to monitor the ongoing status of the physical twin, simulate entity behaviors, recognize internal and external complexities, detect abnormal patterns, reflect system performance, and predict future trends to optimize operation. Predictions and what-if scenarios can be conducted on the digital twin to see what might happen if adjustments are made that might be inconvenient to try out in the real-world, allowing a larger space for trial and

error and experimentation. Digital twins can be integrated with AI and ML functions to become more intelligent and autonomous in their decision-making. At the urban level, Smart City digital twins can gather together real-time data from multiple sources and make it available to citizens, policymakers and administrators, allowing more informed and participated decisions based on actual data for more intelligent and knowledge drive city management.

Extended reality is another technology that is greatly improving building management and maintenance. In particular, AR and MR have proven revolutionary in supporting both technicians and facility managers in their activities thanks to the ability to provide users with instructions, sensor data or superimposed technical schemes right in their field of view as well as allowing hands-free communication. Furthermore, integrated cooperation platforms allow remote connected colleagues and experts to see the live, first-person view taken by the MR headset and collaborate actively with the technician. Any scene of this video feed can be frozen and annotations and 3D holograms created, which are then integrated into the real-world view of the person wearing the device. This promises to revolutionize maintenance operations, which can be performed by nonspecialized, local technicians with the support of remote experts who can manage several facilities at once without leaving their workplace. Further advantages of XR in maintenance include improved training and the possibility of step-by-step indoor navigation, useful for visitors or emergency responders such as firefighters.

3.3 Conclusion and future trends

The recent contemporary and synergistic development of some key technologies, such as BIM, IoT, and AI, has finally created the conditions for the construction sector, traditionally reluctant to embrace ICT and technological innovation compared to other sectors such as industry manufacturing, to start its DT toward a “Construction 4.0” model. This is already bringing important benefits along the entire value chain in terms of productivity, competitiveness, efficiency in the use of resources and reduction of environmental impacts of the built environment over its entire life cycle. As the construction sector becomes more and more digitalized, cybersecurity and standardization are normally neglected topics poised to become more and more important in the next future.

The adoption of digital tools across the different phases of the digital construction process is promoting the fruitful collaboration of numerous and different actors in a digital environment, normally based on shared cloud platforms in which design, construction and maintenance data is stored and accessed by many project stakeholders, from contractors and subcontractors to architects, engineers and managers. However, the increasing volume of digital confidential data (e.g., budgets, bid numbers, technical drawings and product design, trade secrets, employees’ personal information) will inevitably create more security risks. In particular, the wider use of mobile devices on the field represents an increase in potential system vulnerability entry points, as cyber-attacks via USB keys containing malwares or public Wi-Fi networks will likely become more common. This risk is further aggravated by the heavy reliance of the sector on specialist consultants and subcontractors, which multiplies the number of professionals and devices that have access to the digital data and that therefore need to uphold high cybersecurity standards. For example, the BIM process is centered on a model that allows input from various parties, either working independently or working on the same federated model at the same time: this shared nature and the numerous connected parties greatly increase the risks of data security breaches.

Conversely, the importance of data privacy and confidentiality in the construction sector is growing exponentially. In fact, as contractual relations between service providers and clients today always include the gathering and use of increasingly large quantities of data coming from sensors, digital models and connected devices, the transparent treatment and protection of such data not only from security breaches, but also from unlawful commercial uses is paramount.

Standardization has become increasingly important as well, as it is pivotal for the effective interoperability of different digital tools. The construction sector, in particular, is governed by numerous standards, regulations, guidelines, and requirements, commonly meant to make construction projects safer and more efficient but challenging in terms of unlocking cooperation and interoperability of new technologies. A key issue faced by companies in this sector is the lack of a common standards when sharing information, including an agreed understanding of what is required at the various phases of the value chain. Furthermore, data standards should be accessible and applicable by all actors and disciplines across the wider construction sector, each using different software, data formats and terminologies and requesting different information. As the sector is highly fragmented, optimization initiatives are usually limited at the individual or organization level: since the same actors are rarely involved in the whole process in construction, there is little incentive to develop common standards outside the individual company or construction phase. For starters, standardized templates and formats for a precise data type would provide a consistent approach for product manufacturers

and thereby allow digital construction data processes, for example from BIM, to be automated and to have a higher degree of reliability. Data standardization will also support the delivery of more performing and sustainable construction projects by allowing to compare and benchmark results from different buildings and to more easily implement horizontal and vertical transfer of knowledge between projects and teams. An example is the adoption at European level of BIM standards - IFD (ISO 12006-3), IFC (ISO 16739) and IDM (ISO 29481-2) - by the European Committee for Standardization (CEN/TC 442), which has progressed the creation of a common language when sharing information and of an agreed understanding of the information required at the various stages of a project.

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Part II

Building modeling and advanced digital design tools

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Building information modeling

4.1 The road to building information modeling

To increase its productivity and keep up with global industry innovation, the architecture, engineering, construction, and operation (AECO) sector must fully embrace digitalization, and building information modeling (BIM) is an important first step in this transformation (ECSO, 2021; WEF, 2016).

At its core, BIM is an intelligent, 3D model-based process that provides AECO professionals with the insight and tools to more efficiently plan, design, construct, and manage buildings and infrastructure. In an accomplished BIM process, all parties involved use 3D design applications which can include information about the building's scheduling, cost, sustainability, operations and maintenance to ensure information is shared accurately and consistently throughout total assets' lifecycles. BIM can optimize and automate design activities, support optioneering and decision-making, enable clash analysis and verify constructability, improve project and investment planning, ensure project control over all its phases and, finally, store information for project handover to enable preventive and predictive maintenance and final recover of its components, among other functions (see Fig. 4.1). Therefore, BIM can constitute the centerpiece of the digital transition of AECO industry and is widely recognized as the go-to platform and process that facilitates collaboration, raises efficiency and cuts costs (Boston Consulting Group, 2016; Roland Berger, 2017; WEF, 2016).

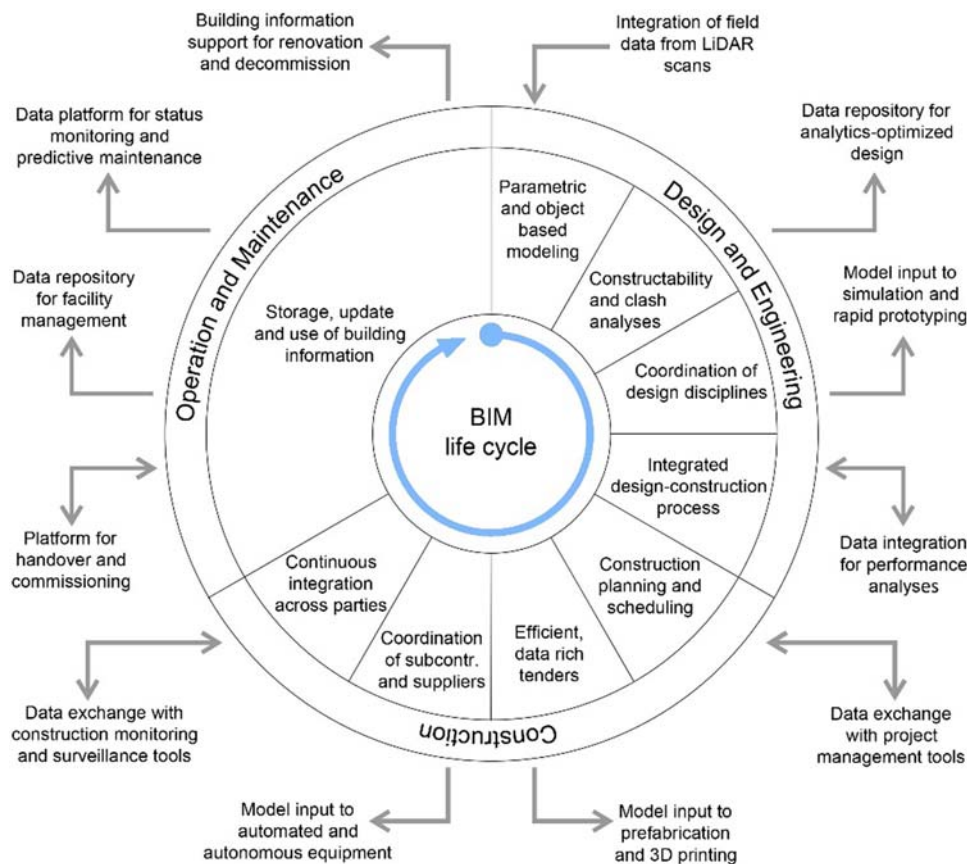


FIGURE 4.1 Application of BIM along the AECO value chain. Redrawn from Boston Consulting Group. (2016). Digital in engineering and construction, the transformative power of building information modeling. BCG.

BIM favors new technologies such as prefabrication, automated equipment and mobile applications and enables users to benefit from a wide range of integrated digital technologies such as reality capture, virtual and mixed reality, generative design and digital twins (Alizadehsalehi, Hadavi, Huang, & From, 2020; He, Li, Gan, & Ma, 2021; Khan, Sepasgozar, Liu, & Yu, 2021; Sacks, Girolami, & Brilakis, 2020).

The design and engineering phase is currently the most receptive to BIM, which acts as a technological and process successor to computer-aided design (CAD) and 2D and 3D drawings. The parametric modeling approach of BIM attaches a variety of information to each object in a digital 3D model and guarantees the consistency of all drawings, reports, and data interfaces. Design and engineering elements can easily be imported from digital object libraries, often prepared directly by manufacturers, and checked for compliance with specifications and code requirements. Geometric and rule-based analyses can be automated to preemptively identify potential design clashes and constructability issues, averting costly and time-consuming corrections and reworks on-site. Integrated workflows among different design disciplines can further prevent design errors and streamline the design and engineering stage, allowing everyone to work with the same model and data to quickly identify and resolve problems. BIM facilitates the exchange of information between all participants, increasing the quality of both design and construction as well as enabling greater insights for owners and project stakeholders. BIM helps design teams to generate multiple relevant design options, which can be quickly and effectively analyzed by several BIM insight capabilities to identify best-possible solutions that drive value throughout the design process and to the performance of the completed building. Finally, BIM enables early construction-level planning (including quantity takeoffs) and supports new, more collaborative forms of project delivery such as design-build or integrated project delivery.

In the construction phase, BIM enables contractors to simulate and schedule works and activities in both time and space (BIM 4D), and costs (BIM 5D), creating and comparing various scenarios of procurement, resources, and spatial or other constraints, therefore providing the foundation for lean construction approaches. BIM methodology can in fact help the construction industry in achieving lean construction principles by eliminating waste, cutting costs, improving team productivity and creating positive project outcomes (see Section 9.1.3). With BIM, tendering processes become more accurate and transparent, thanks to the wealth of precise information derived from the building model and available to potential bidders. BIM data sharing allows to inform subcontractors and suppliers about scope and design changes in real time, thereby reducing the number of requests for information (RFI). Finally, BIM ensures that all parties' systems are compliant with designs. Blockchain-based technologies, moreover, can be applied to the BIM process to make it more secure and trustworthy. A blockchain-certified BIM model, for instance, is absolutely tinker-proof and therefore can be used to implement smart construction contracts, in which payments are automatically issued upon task completion and validation, or to secure delicate aspects of construction such as supply chains and final BIM handover (see Section 9.1.5).

In the building operation and management phase, BIM has numerous potential applications, both as a central part of an integrated facility management system or as a relevant data repository for the latter, though these are not yet in wide use. BIM allows facility managers to store, maintain, and access building information, including spatial, technical, warranty, maintenance and spare parts data, and thereby to conduct their commissioning and operations and maintenance (O&M) activities more efficiently. The planning of major repairs, retrofits, and expansions greatly benefits from up-to-date BIM model.

In addition to these core benefits over the building's life cycle, BIM interfaces easily with numerous digital technologies, facilitating their adoption or enhanced application and benefiting from them in return. For example, in renovation projects BIM acquires and processes data from 3D laser scans; input data from the BIM model is required for advanced prefabrication practices; automated field equipment, measurement sensors and mobile devices link to BIM information during both construction and operations. The use of Big Data methods to process and extract knowledge from historical BIM data is also growing fast, and combined with the use of sensors, can significantly improve actual building performance (Boston Consulting Group, 2016; ECSO, 2021; Panteli, Kylili, & Fokaides, 2020; WEF, 2016).

An abundance of external data can be integrated in BIM and applied to several software applications and data systems central to digitalization in AECO, including analytics, simulation, and value-engineering software during the design and engineering phase, project management tools in the construction phase, and facility- and asset-management systems in the operations phase (Eleftheriadis, Mumovic, & Greening, 2017; Gao, Koch, & Wu, 2019; Kamela & Memari, 2019).

BIM is already changing how sustainable construction and assessment is conducted by improving the access to information and the quality of the sustainability analyses. Novel topics in this sense are the use of life-cycle assessment (LCA) and life-cycle cost (LCC) methods integrated with BIM and the automatic assessment of green building certification scheme credits [Leadership in Energy and Environmental Design (LEED), Building Research Establishment

Environmental Assessment Methodology (BREEAM), etc.] (Antón & Díaz, 2014; Carvalho, Braganc, & Mateusa, 2021; Dalla Mora, Bolzonello, Cavalliere, & Peron, 2020; Jina, Zhong, Mac, Hashemia, & Ding, 2019; Naneva, Bonanomi, Hollberg, Habert, & Hall, 2020; Obrecht, Röck, Hoxha, & Passer, 2020; Rad, Jalaei, Golpour, Hosseini Varzande, & Guest, 2021).

Geographic information systems (GISs), which are used to map and analyze structures in their geospatial context, are an important large-scale technology that can potentially complement BIM once the integrating interfaces are fully defined. GIS already plays a key role in the planning of infrastructure, large projects, and even entire urban developments (Ma & Ren, 2017; Wang, Pan, & Luo, 2019).

The growing adoption of BIM methodology has already reported clear advantages regarding collaboration, scheduling, 3D drawings, management, quantity, and material sorting. Moreover, BIM enables the project team to access analytical insight early on in the design phase, thus supporting “best possible” instead of “best practical” project outcomes. Users can also learn from operational data gathered across the building life cycle to support the continuous improvement of decision-making (Dodge Data & Analytics, 2017). BIM advantages concern not only AECO companies and consultants, but also the public sector. Indeed, BIM entails a better value for public money during the delivery phase as well as improved quality of public goods and services during the use of the built asset (European Commission, 2019; WEF, 2018).

Environmental benefits are also possible, such as more accurate material ordering leading to less waste to landfill, and optimized simulation of energy analysis leading to lower energy demands in operation. The collaborative nature of BIM can also be used effectively in public planning to promote people engagement to support public infrastructure that is well designed and aligned with the needs of the local community resulting in improved social outcomes such as better resource planning, greater use of public facilities or mapping and protection of architectural historic heritage. In addition to these advantages, the use of BIM in professional or university training has demonstrated that it provides a less expensive and more comprehensive learning tool compared with traditional approaches. BIM models can also improve the understanding of the layout of new workspaces, improving operational activities.

Nonetheless, large-scale BIM benefits can only be achieved once all participants along the value chain get involved, as advantages for the first movers are limited (CECE, 2019; ECSO, 2019; JRC, 2019).

Various obstacles must be overcome before large-scale implementation and all the potential benefits of BIM can be obtained. Indeed, the transition to BIM, both within a company and industrywide, requires a considerable step-up of expertise and employee training as well as substantial IT upgrading (European Commission, 2019; WEF, 2018).

This may be particularly challenging for consultants and small companies which might struggle to afford the upfront investments. A coordinated effort by the industry is needed to attract new talent with digital and BIM skills, upskill existing workers, and changing corporate cultures to support new processes. Collaboration among stakeholders can be improved by increased use of integrated contracts and open standards for data sharing. In addition, technological standards have to be enforced and interoperability must be ensured to allow all stakeholders to share information and cooperate on planning. The first international standards for BIM, ISO 19650 parts 1 and 2, were published in 2019 based on British standards, and aim to provide the necessary framework for designers and contractors from different countries to collaborate more efficiently, while encouraging further uptake of BIM. Being major owners of built assets, it is responsibility of public authorities to commit to BIM technology by enforcing it in public tenders and promoting its acceptance through codes and regulations, including backing innovative forms of financing. Overall, the technical challenges are likely to be overcome in the near future, but it might prove more difficult to change existing processes and to increase collaboration, including data sharing.

Since its origins in 1990s, BIM adoption in the AECO sector has progressively grown worldwide, with a substantial increase in rate in recent years in part due to the rise in construction activities globally. The global BIM market size increased from \$2,760 million in 2014 to \$5,205 million in 2019, and is projected to reach \$15,892 million by 2027, registering a CAGR of 15.2% from 2020 to 2027 (Gaikwad & Rake, 2020). In Europe BIM market was valued at EUR1.8 billion in 2016, and is predicted to grow by 13% to reach EUR2.1 billion in 2023 (JRC, 2019).

Nonetheless, the uptake and maturity of BIM vary considerably from country to country, as well as between companies according to their size and position in the value chain. BIM is already part of the business for several large engineering and architecture firm, but most small companies across the value chain still have little BIM experience.

Some of the best BIM adoption rates can be found in Europe, where several countries have been praised for their approaches to BIM standardization. In the EU, BIM adoption is promoted by Directive 2014/24/UE on public procurement [European Union Public Procurement Directive (EUPPD)], which expressly invites member states to request, starting from 2016, for public works contracts “the use of specific electronic tools such as, in particular, BIM software” (Article 22, paragraph 4). Today, BIM is already mandatory in several European countries such as the Netherlands,

Denmark, Finland, Norway, Germany and Italy, soon to be followed by Spain, Czech Republic (2022), and Latvia (2025). In addition, several EU countries such as Poland, Ireland, Slovakia, Slovenia, France, the Netherlands, Belgium have put in place partial BIM requirements, often through specific public authorities (e.g., rail and road state agencies) (ECSO, 2021).

Moreover, Italy, the Netherlands, and Austria have openBIM standards to support a transparent workflow among project members, who are not obliged to adopt specific software. Around the world, BIM is compulsory in various countries, including the UK, Australia, and Singapore. HM Government Report of the United Kingdom notes that “by 2016 all [UK] Government construction projects will be using BIM at level 2, irrespective of project size,” and that “between 2016 and 2025 it is expected that the UK Government and industry will move to Level 3 BIM.”

Although the United States is where BIM first emerged, with the earliest virtual models developed there in the 1970s, it doesn’t have a nationwide mandate yet. Instead, several federal agencies and departments have come up with their own BIM mandates, which, on the one hand, have helped to increase adoption, but, on the other hand, have required contractors, architects, and engineers to learn multiple standards. A National BIM Standard-United States, which seeks to improve the consistency of BIM use across the country, is progressing, meanwhile the high level of BIM maturity across the country, as well as the size and diversity of its construction sector, might mean a nationwide mandate may not be necessary after all.

Regarding China, it is seeing growing interest in the benefits of BIM and other digital technologies as well. However, while large projects like the Shanghai Tower saw extensive BIM use, adoption among the country’s construction sector remains fragmented. The Ministry of Housing and Urban Rural Development proposed in 2016 a plan which set out how BIM adoption would be driven by government, with new policies aimed at developing guidelines and standards, with the objective of pushing BIM in the construction sector.

Parallel to industry adoption, BIM interest has also steadily grown in academic and research sectors as well. In the last decade, the number of publications related with BIM has increased by 78.59 times, with a further acceleration between 2015 and 2019 with a 291% increase which is expected to continue as BIM becomes an established part of the AECO practices (Liu, Lu, & Peh, 2019; Santosa, Costab, Silvestreb, & Pyl, 2019; Wen, Ren, Lu, & Wu, 2021).

Key players of the BIM software market include Autodesk, Inc., Trimble Navigation Ltd, Nemetschek AG, Synchro Software Ltd., Bentley Systems Inc., Dassault Systemes, Asite Solutions Ltd., Pentagon Solutions Ltd., AECOM, Beck Technology Ltd., which provide both on-premise and cloud-based tools. Cloud-based services are currently the fastest-growing segment and one of the main drivers of BIM adoption, mainly due to their convenience as the high cost of on-premise software deployment can be prohibitive by AECO small and medium enterprises.

Major end-users of BIM include architects, engineers, contractors, and developers, with the first two categories dominating the first phase of adoption. However, contractors are expected to be the major users of BIM, with their presence expanding at a CAGR of 22.7% from 2015 to 2022. Several industries are adopting BIM solutions in their infrastructural development, including water and wastewater, bridges, roads, and highways, rail transit and aviation, energy generation facilities, houses and apartments, education institutes and commercial spaces, government buildings, as well as factories and warehouses, with rail transit and aviation sector holding the majority share of the BIM market revenue (NBS, 2020).

4.2 Building information modeling and multidimensional design

The technology under design and engineering tools has developed greatly in recent years, from traditional 2D hand-drafting to CAD, BIM, parametric design, generative design, including enhanced project visualization through augmented and virtual reality. Advanced software tools can automate repetitive calculation and drawing tasks, help find new design solutions and provide precise insights, making the design process faster, clearer and more effective compared to traditional manual drafting.

CAD originated in the aircraft industry in the 1960s and expanded to architectural design in the 1980s, starting from the gradual improvement of the 2D drawing process. In the 1990s, first 3D drawing tools become available and, subsequently, object-oriented design systems were developed. However, such 3D software is still mostly used to prepare presentational images or production information for the manufacture of building components. More accurately, computer-aided drafting refers to the use of software to solely drafting without the design element, whereas its inclusion leads to computer-aided drafting and design (CADD), commonly referred simply as CAD.

Generally, CAD can be used to create 2D or 3D representations, generate animations and other presentational material, and may also allow the addition of supplementary information such as dimensions, descriptions of components and references to specifications. Basic software for 2D drafting, drawing and design is also widely available as free and

open-source programs, which provide a simple approach to 2D drafting and allow various adjustments to be made in the final draft, such as scale and placing on the project sheet. Many progresses have also been made in semiautomating the freehand drawing arena: drawing and painting software provides the possibilities of sketching and creating illustrations and can suit most platforms and devices.

More complete 3D modeling CAD software allow designers to create and inspect the designed object as if it were the real thing (a virtual model) and generate views from various directions. It can generate wireframe models or create 3D solids that can modeled in two ways: parametric modeling using equations and functions, and direct or explicit modeling through direct geometric operations (extrusions, subtraction of addition of volumes, etc.). Professional programs such as AutoCAD also include tools for collaboration and documentation that allow enhanced mobility, as work can be accessed anywhere through web browsers and mobile apps.

CAD software aims to support the design or technical drawing activity through the creation of 2D or 3D models that describe the product to create. However, these representations in plan, in orthogonal projection, in section, in axonometry, in exploded view, up to 3D, all constitute a descriptive model of the object, not a model of the object itself. No information is associated with the lines or surfaces of the object and the changes made do not indicate the impact on the objectives of the project.

Instead, model-based design such as BIM entails the creation of a digital representation system that allows rapid analysis and comparison of design alternatives, coordination and collaboration between team members, communication and visualization of information, easy alteration and management of changes, clash avoidance. By creating one model, as opposed to multiple independent drawings, a single data set can be developed from which all documents relating to the project are generated (Czmoch & Adam Pekala, 2014).

This digital model is actually made up of a number of different component models that may be produced by different consultants, contractors or suppliers. At the start of a project, it may simply include information such as 3D context models, site and condition surveys, existing utilities, etc. It becomes more detailed and enriched as design progresses, up to the construction phase, in which contractors take over development of the model from designers and transform it into a virtual construction model (VCM), containing information allowing all the objects in the model to be manufactured, installed, or constructed.

BIM models are created from the combination of a series of BIM objects, which in turn are digital descriptions of single products or materials. Each BIM object usually has 3D geometry that describes its physical appearance, as well as integral data that describe and classify it by reporting its performance values, material types, expected lifetime, its relationships to other elements in the model, positional data, dimensions, manufacturer's data, algorithms describing form, etc. Therefore, all objects within the BIM model possess a meaning, that is, they are instances of object types such as a wall, column, window, or door. This also implies that each object needs only to be defined once and can then be placed in the model in multiple instances, and when the object is changed, each instance will be automatically updated throughout the model, improving consistency and reducing errors. In addition to manual manipulation, models can be generated based on a series of preprogrammed rules or algorithms known as parameters. For instance, a rule might be created to ensure that walls must start at floor level and reach the underside of the ceiling, therefore if the floor to ceiling height is changed, the walls will automatically adjust to suit. Working with objects is a prerequisite for using the model for any kind of analysis, including quantity take-off, structural analysis or building performance simulations. In addition, object-based modeling allows to derive technical drawings which often employ abstract or symbolized representations which cannot be produced from the 3D geometry alone.

BIM objects can be categorized in two types: component and layered. Component objects represent building elements that have a distinct geometrical shape, such as furniture, windows, doors, or equipment. Layered objects are instead products that do not have a fixed shape or size, such as flooring, insulation materials, ceiling materials, etc. Objects can also be classified as generic and specific. Generic, or library, objects are those used as placeholders during the initial stage of design, to be replaced later with specific one as design progresses in detail and decisions are taken. Specific (or manufacturer) objects are in fact those that identify products specific to a manufacturer.

Objects may be available in formats suitable for a specific authoring BIM software (such as Revit, Archicad, etc.) or they can be provided in open exchange formats. The most used databases for BIM objects are nationalbimlibrary.com, bimobject.com, polantis.com, bimstore.co.uk and datbim.com. To improve creation and sharing of BIM objects, the National BIM Library (NBS), an online BIM object repository, published in 2014 the NBS BIM object standard which defines what constitutes a high-quality BIM object with the right levels of information, appropriate geometry, and a consistent, structured, easy to use format. The standard is intended for use by professionals, manufacturers and other BIM content developers for the creation of BIM objects that operate in a common data environment (CDE).

It "...defines the information, geometry, behavior and presentation of BIM Objects to enable consistency, efficiency and interoperability across the construction industry."

An important aspect that must be addressed in the near future is the identification of additional information that could be incorporated in BIM objects to improve simulations performed within a BIM-based environment, for instance about environmental impact categories and circularity index of materials. In particular, current guides and standards on the integration of data into BIM have little focus on sustainability information and how it should be structured according to the project's level of development (LOD). Until now, BIM use in sustainability analyses has largely been limited to quantity take-off, mainly because BIM objects lack useful semantic information. By integrating the information required for environmental analyses into objects, BIM models may effectively incorporate the whole useful life-cycle information of buildings and of relevant equipment inside them.

The goal is to leverage BIM models as real data repositories, which could be used by facility managers to monitor assets or to plan refurbishments by simply replacing necessary objects, expediting the transition from BIM to building information management.

4.2.1 Project and asset information models

The building information model is developed progressively first as a project information model (PIM) during the design and construction phase, then as an asset information model (AIM) after the project's handover and commissioning (Patacas, Dawood, & Kassem, 2020).

The PIM consist of a federated building information model, that is, an assembly of distinct discipline models to create the complete model of the building, of nongraphical data and of associated documentation. The requirements for the PIM are set out in the exchange information requirements (EIRs). It is developed first as a design intent model, then as a virtual construction model (VCM).

In the early stages of the project, the design intent model shows the architectural and engineering intentions of the designer, often including massing diagrams or 2D symbols to represent generic elements of the design, with some critical elements developed in more detail. The objective of the design intent model is to demonstrate early how the different aspects of the design are integrated by including, depending on the employer's information requirements:

- esthetic intent, architectural form and spatial arrangements;
- schematic structural and services systems;
- outline of site and landscape design;
- outline of specifications;
- schedules, simulation results and reports to demonstrate compliance with the requirements;
- preliminary construction and sequencing studies;
- an elemental cost plan.

As the design progresses, the model will develop and the level of detail will increase, including first generic, then specific BIM objects complete with specifications and method statements attached along with information about space allocation for operation, access, maintenance, installation, replacement and so on. Upon entering the construction phase, the design intent model is developed into a VCM containing all the objects to be manufactured, installed or fabricated. The VCM provides information describing the detailed design, and may also include the following:

- a detailed construction sequence that might be linked to a project management scheduling tool;
- information about temporary works and activities linked to construction, such as fences, scaffolding, facade retention structures, falsework, formwork, etc.;
- method statements;
- health and safety information, security status information and visualization of potentially hazardous activities;
- access to site details, traffic routes, and diversions;
- crane zones and other lifting operations;
- information about site logistics;

The VCM may be used for activities such as:

- visualizing and planning the construction sequencing and site logistics;
- clash avoidance and clash detection;
- manufacturing processes;
- providing access to information on site, increasingly using mobile devices and tablets;

- health and safety risk management, site inductions and safety briefing;
- security monitoring;
- improving familiarity with construction activities;
- assessing material requirements, ordering and delivery scheduling;
- progress and costs tracking;
- capturing feedback and as-installed information, again, increasingly using mobile devices and tablets.

Where changes are decided or new information is acquired, the VCM shall be updated as quick as possible in order to gauge timely the impact on subsequent works and scheduled activities.

Once construction is complete, the building information model shall be verified against what has actually been constructed, for instance carrying out point cloud or LiDAR survey to confirm the completeness of the as-constructed model. Then, it is handed over to the client as an as-constructed AIM. The AIM is the model that compiles all data and information necessary to support asset management and is required for the operation and maintenance of the commissioned building.

An AIM can provide both graphical and nongraphical data and information as well as documents and metadata, pertaining to a single asset or to a portfolio of assets. It can be created from information in the PIM that was created for the construction of a new asset, or from existing asset information systems, as well as from entirely new information. It generally includes information describing the original design intent, 3D models, as well as information about ownership, rights and restrictions, surveys, work that has been carried out, operational performance information, condition status, etc. For existing assets some of this information may be incomplete.

To update and maintain the integrity of the AIM, an information management process is generally established and a data manager (sometimes referred to as a data administrator or data technician) is appointed. Updates to the AIM may be required by events such as maintenance work, repairs, refurbishments or upgrades, replacement, decommissioning, risk assessments, performance evaluations, changes in regulations, changes in the party responsible for maintaining or operating the asset, or changes in ownership.

4.2.2 Levels of development of a building information model

Building design is a process of continuous development, elaboration and refinement, and as the project proceeds, accordingly the level of detail of a BIM increases. The different aspects of the model may be developed at different rates by different members of the project team, and their development may pass from the client to consultants, to the contractor and suppliers and ultimately back to the client themselves. Whereas in conventional planning processes the drawing scale is considered a well-established indicator for the geometric resolution required for a certain project stage, thus of the degree of elaboration, maturity and reliability of the design information to be delivered, an analogy had to be found for reflecting the concept of geometric resolution and degree of elaboration because there is no scale in the world of digital models.

Therefore, it is important that clients define the level of detail they require at each stage of development of the project. This ensures that the design is developed in sufficient detail and that the information to make decisions about the project development and then to operate the completed project efficiently is actually provided. It also gives an indication of the reliance that can be placed on information.

Initially, the term “level of detail” was used, later replaced by the term “level of development” (LOD) to avoid putting too much emphasis on the geometric appearance. In fact, a BIM objects that appears visually very detailed may be generic and, despite appearances, be at a low level of design development.

LOD defines both the required geometric detail [also called level of geometry (LOG)] as well as the required alphanumeric information [level of information (LOI)], defines the extent of information provided and also gives an indication of its maturity and reliability. In most cases, each design phase can be associated with a specific LOD. LOG and LOI requirements are generally defined for key stages of the project at which critical deliverables take place, allowing the employer to verify that project information is consistent with their requirements and enabling them to decide whether to proceed to the next stage, in a way analogous to a stage report on a conventional non-BIM project.

To improve communication among BIM professionals and to systematically convey the accuracy to expect from model elements, the American Institute of Architects (AIA) published a LOD framework for its E202-2009 BIM and Digital Data Exhibit, updated for the AIA’s G202-2013 Project BIM Protocol Form, defining five different LODs (100, 200, 300, 400, and 500). The AIA LOD framework recognizes that different elements of the project will develop at different rates and allows to efficiently communicate the extent to which a model element is developed and may be relied on.

In 2013, the United States-American BIMForum published the “Level of Development (LOD) Specification,” that expanded the AIA LOD framework to six standardized levels (100, 200, 300, 350, 400, 500) and presented an extensive catalog depicting the LOG for typical building components as well as defining and illustrating the characteristics of model elements of different building systems expected at each LOD (see [Table 4.1](#)). Such standards, on the one hand, allow model authors to define what their models can be relied on, and on the other hand allows downstream users to clearly understand the usability and the limitations of models they are receiving.

The EIR defined by the client at the beginning of the project typically prescribes its LOD requirements. LOD specifications help teams and clients to schedule BIM deliverables and to get a clear picture of what will be included in each of them, help design managers to understand the information and detail expected at various points in the design process, and provide a standard that can be referenced by contracts and BIM execution plans (BEPs).

4.2.3 Building information modeling dimensions

The main way BIM presents information about a construction project is in the form of 3D graphical representations of elements (e.g., doors, beams, etc.), which can be further associated with a wealth of nongraphical data about other

TABLE 4.1 Building information modeling levels of development (LODs) (BIMForum, 2020).

LOD	Description
LOD 100 Concept design	<i>The Model Element may be graphically represented in the Model with a symbol or other generic representation, but does not satisfy the requirements for LOD 200. Information related to the Model Element (i.e., cost per square foot, tonnage of HVAC, etc.) can be derived from other Model Elements.</i> BIMForum Interpretation: LOD 100 elements are not geometric representations. Examples are information attached to other model elements or symbols showing the existence of a component but not its shape, size, or precise location. Any information derived from LOD 100 elements must be considered approximate.
LOD 200 Design development	<i>The Model Element is graphically represented within the Model as a generic system, object, or assembly with approximate quantities, size, shape, location, and orientation. Non-graphic information may also be attached to the Model Element.</i> BIMForum interpretation: At this LOD elements are generic placeholders. They may be recognizable as the components they represent, or they may be volumes for space reservation. Any information derived from LOD 200 elements must be considered approximate.
LOD 300 Final design	<i>The Model Element is graphically represented within the Model as a specific system, object or assembly in terms of quantity, size, shape, location, and orientation. Non-graphic information may also be attached to the Model Element.</i> BIMForum interpretation: The quantity, size, shape, location, and orientation of the element as designed can be measured directly from the model without referring to non-modeled information such as notes or dimension call-outs. The project origin is defined and the element is located accurately with respect to the project origin.
LOD 350 Final design	<i>The Model Element is graphically represented within the Model as a specific system, object, or assembly in terms of quantity, size, shape, location, orientation, and interfaces with other building systems. Non-graphic information may also be attached to the Model Element.</i> BIMForum interpretation: Parts necessary for coordination of the element with nearby or attached elements are modeled. These parts will include such items as supports and connections. The quantity, size, shape, location, and orientation of the element as designed can be measured directly from the model without referring to non-modeled information such as notes or dimension call-outs.
LOD 400 Construction	<i>The Model Element is graphically represented within the Model as a specific system, object or assembly in terms of size, shape, location, quantity, and orientation with detailing, fabrication, assembly, and installation information. Non-graphic information may also be attached to the Model Element.</i> BIMForum interpretation: An LOD 400 element is modeled at sufficient detail and accuracy for fabrication of the represented component. The quantity, size, shape, location, and orientation of the element as designed can be measured directly from the model without referring to non-modeled information such as notes or dimension call-outs.
LOD 500 [NOT USED] Building operation	<i>The Model Element is a field verified representation in terms of size, shape, location, quantity, and orientation. Non-graphic information may also be attached to the Model Elements.</i> BIMForum interpretation: Since LOD 500 relates to field verification and is not an indication of progression to a higher level of model element geometry or non-graphic information, this Specification does not define or illustrate it.

characteristics such as performances, costs, assembly and maintenance instructions, and many more. In fact, BIM can be a virtually limitless source of structured data about a digital virtual building in its current state, which in turn can be leveraged in numerous ways to manage the design, construction and operation of built assets and to inform decisions, direct processes, support new digital solutions, and explore new interactions between buildings and people (Charef, Alaka, & Emmitt, 2018). All these types of additional building information linked with 3D BIM model are broadly described in the literature as “BIM dimensions.” A nD BIM model is an extension of the 3D BIM model that integrates “multiaspects of design information required at each stage of the life cycle of a building facility.” According to its dimensions, the nD model provides an additional data set, directly retrievable from the 3D BIM model, relevant to various stakeholders to allow them to improve their work during the project. The most common used dimensions in BIM are as follows:

- 2D: Two-dimensional graphical information.
- 3D: Three-dimensional graphical information.
- 4D: Time and program information.
- 5D: Cost information.
- 6D: Sustainability information.
- 7D: Facilities management information.
- 8D: End-of-life information.

4.2.3.1 Two- and three-dimensional BIM: virtual three-dimensional parametric model

The 3D BIM models describe a building’s complete geometry and parametric attributes. Parametric data allow to connect every object and element in the 3D model, thereby a change to one attribute can automatically update related attributes and components. Today, 3D BIM is an established design standard that enables stakeholders to coordinate multidiscipline aspects, digitally fit options of a building, create renderings, and experience tangible visualizations such as virtual walkthroughs in Extended Reality. 2D BIM in turn represents the project in line drawings, usually produced with drafting software tools. Differently from CAD drawings, 2D BIM drawings can be “intelligent 1-lines” and have BIM attribute data attached to them. 2D BIM drawings communicate the plan in a familiar way while ensuring that the data-centric approach is maintained in the process.

4.2.3.2 Four-dimensional building information modeling—scheduling

The 4D BIM concerns the enrichment of a 3D digital model with an extra layer related to time or schedule information. Traditionally, Gantt charts are the most widely used method for project scheduling and to develop the timeframe of construction activities. However, Gantt charts are lacking in the ability for visualization of a construction timeline. Adding this 4th dimension to BIM allows architects and engineers to plan the sequence of construction activities by integrating a time-related attribute data to model elements, which also enables the creation and visualization of 3D visuals of a project’s development. Moreover, 4D BIM allows digital scheduling of specific elements or working areas and can include installation period, sequencing or interdependencies with other activities (Li, Xu, & Zhang, 2017). This way, 4D BIM greatly contributes to risk mitigation and smoother scheduling processes by improving team coordination and communication. Indeed, the explication and visualization of project parameters in a step by step construction timeline allows a better understanding of project’s status, especially in more complex construction projects, and is also helpful for clients and other non-technical stakeholders. Recognized benefits of 4D BIM include reduction of the direct and indirect cost due to inefficient schedules and updates issues, improved management of changes occurring during the construction phase, control of errors associated with the construction phase and better assessment and measurement of project progress. Current 4D BIM scheduling tools have become very user friendly and capable, and are widely used for simulating, testing schedules and installation sequences, and planning task overlap without interfering with the quality, cost, or schedule of individual jobs (see Section 9.1.2.3).

4.2.3.3 Five-dimensional building information modeling—cost estimation

5D BIM expands 4D BIM with another variable: the cost of labor and delivery for each item. Pricing information from suppliers and manufacturers is parametrically linked to the models, enabling fast, even real-time estimation of costs for conceptual and detailed designs. 5D BIM allows to compare easily and quickly the total costs of various alternatives in terms of materials and technology, enabling a better optimization of the investment (Smith, 2016).

5D BIM is increasingly diffused among contractors and construction managers to make cost and schedule overruns easier to control or avoid. Teams can share real-time data over the cloud to discuss how to optimize resources dynamically to stay within the project's budget as its parameters and attributes change. 5D BIM also enables suppliers and manufacturers to participate in balancing product choices with available budgets by providing on time the total performance of their manufactured products. The benefits of 5D BIM can be reaped from the early design stages of a project as well as later during the construction, in which changes often occur and cost control becomes more challenging (see Section 9.1.2.4). It can also support contractors in the bidding phase, by helping in the accurate prediction of the budgetary requirements along with the changes in scope and material, providing accurate cash flow forecasts and detailed project risk analysis. The BIM's ability to detect clashes and quickly readjust changes to all dimensions can greatly reduce unbudgeted changes on projects. Finally, 5D BIM allows designers and clients to investigate the costs correlated with specific activities as well as those associated with different design scenarios.

4.2.3.4 Six-dimensional building information modeling—sustainability

The 3D BIM model and the information and data associated with it can be used for simulations and analyzes aimed at verifying and optimizing the environmental and social sustainability of design choices, expanding the BIM process to a six dimension (Jin, Zhong, Ma, Hashemi, & Ding, 2019). Design tasks and decisions related to the overall sustainability of a building which can benefit from 6D BIM include the following:

- the assessment of the energy performance of the building;
- the quantification of the carbon footprint resulting from the construction and operation of the building;
- the simulation of the solar exposure, the natural and the artificial lighting of the building;
- the management of the construction waste and the efficient use of resources;
- the human-centric design of the indoor air quality, including thermal and human comfort aspects;
- the simulation of movement paths with different scenarios applicable for construction safety or end-user experiences;
- the simulation and analysis of security and safety aspects to test fire escape routes for congestion areas, identify where more exits might be needed or to optimize placement of security monitoring equipment by testing camera viewpoints.

The 6D BIM models are often used as a primary tool to meet requirements defined by Green Building Rating Systems such as LEED and BREEAM. Moreover, parametric data in 6D BIM from product suppliers can be exported to LCA and LCC software tools to run analyses on real product choices and obtain reports about materials and design options in terms of their embodied carbon, operational carbon, and health, safety, and environmental attributes such as indoor air emissions (see Section 5.4.3).

4.2.3.5 Seven-dimensional building information modeling—facility management

The 3D BIM model can be extended to a seventh dimension by enriching it with all those data and information required for the Operation & Maintenance (O&M) stage of a built asset (Chen & Tang, 2019; Nicała & Wodyński, 2016; Pishdad-Bozorgi, Gao, Eastman, & Self, 2018).

In particular, the 7D BIM database should present detailed information for each element embedded in the building: structure, finish, and all equipment and systems. Relevant data concern the type and description of the item, its specification, the time of the next maintenance or replacement, the warranty period, the expected performance over time, indicators for wear and consumption, etc. This information greatly facilitates building management and maintenance activities: when failure occurs, the affected item can be quickly located, its maintenance history and spare parts retrieved, and the disruption repaired in short time (Aziz, Nawawi, & Ariff, 2016; Gao & Pishdad-Bozorgi, 2019). 7D BIM can also embed O&M manuals, maintenance plans and technical support contacts. 7D BIM provides owners and facility managers with data-rich building models for data-driven proactive maintenance, warranty planning, and predictive daily operations. It is a living, as-built and as-maintenance model that needs to be updated during the asset life cycle. If accurate and up-to-date, 7D BIM allows digital building operations management by linking the physical building and the digital virtual building, providing an on-time digital platform that can identify if a part needs replacement, show the physical location of the repair, support technicians' task planning, help update maintenance records after the ticket is resolved, and identify similar parts elsewhere that may need timely attention. Such digitally driven maintenance and predictive analysis allow for leaner, more holistic maintenance operations. A further evolution of 7D BIM is the Digital Building Twin, which consists of an exact, living virtual replica of the built asset that is continuously updated

with real-time information from a network of sensors and equipment, and in turn can be used to monitor and control its operations as well as simulating changes and scenarios (see [Section 11.4](#)). In this application, 7D BIM model provides the backbone on which to construct the digital twin, by linking data feed from sensors and systems to the correspondent building element and defining the relationships between them.

4.2.3.6 *Eight-dimensional building information modeling—end of life*

The growing importance assumed by the need to recover and recycle building materials at the end of a building's operating life is leading designers to include all the information useful for its adaptability and deconstruction within the BIM model of the asset to be created. In addition to specific design decisions aimed at favoring the future separation of materials and elements, the effective possibility of recovering most, if not all, building materials and components at the end of their life is based on the availability of information on the characteristics of materials and products valuable for recovery and reuse, on their deconstruction techniques and on the presence of a deconstruction plan developed during design phase. In this picture, 8D BIM information, to be kept updated throughout the life of the building, will allow to maximize the recovery of components at the end-of-life stage, up to the adaptive reuse of the entire building (see [Section 2.3.6.1](#)).

4.2.4 Building information modeling software tools

BIM software provides all tools needed to implement a model-based process for the planning, organization, design, and management of buildings and infrastructures. The software collects and stores all data and displays a real-world representation of buildings and infrastructure before they are constructed, during construction, and after they are completed.

According to BuildingSmart International (BSI), BIM software can be divided into two main groups:

- programs that are able to create and export a BIM model (so-called BIM authoring software—BIM AS);
- programs that are only capable of importing and interrogating a BIM model, including BIM Viewer and Model checkers tools (BIM reviewing), BIM tools for creating construction sequence simulations (BIM 4D/5D) and to support the construction phase (BIM processing), and BIM Data Server tools that enable network, cooperative collaboration in openBIM projects (BIM project spaces).

The BIM model is often pictured as a single file containing, ideally, all the information. In current practice, however, for reasons essentially related to the limitations of the available technology, each project consists of a certain number of models focused on specific disciplines. These models, generated by BIM authoring software, are then combined, managed and interrogated using BIM processing and BIM reviewing software, in a so-called “federated” model, which will constitute a centralized repository of information for the entire project. In a typical building project, the federated model can be formed from the architectural model, the structural model and other specialized models. The choice of BIM applications on the market depends on the specific needs of the design team and is linked to many factors, including: the diffusion in the reference market, the compatibility with other software already practiced, the ease of finding collaborators trained on the specific software tool. When choosing, it is also important to verify that the software application identified is among those certified by BSI as conforming to the most recent version of the Industry Foundation Class (IFC) format.

Therefore, BIM-compatible conventional CAD software notwithstanding, practices that want to take part in BIM-based projects shall familiarize with completely new tools: BIM Viewers for visualizing models and adding comments, BIM Model Checkers for analyzing and inspecting models, 4D and 5D BIM simulation, and BIM Project Spaces for cooperative collaboration.

BIM AS allow to create, modify, view and export the BIM model in the main disciplines of architectural, structural and systems engineering. There are numerous products on the market, some that run on Windows operating system, others also compatible with macOS, some that allow to develop all disciplines, others instead expressly dedicated only to the architectural part, to structures or to systems, some finally dedicated to building modeling, others expressly designed for infrastructure modeling (see [Table 4.2](#)).

These programs allow the user to create a “virtual building” using “real” elements such as walls, floors, roofs, doors, windows, and furniture as BIM objects to which the user applies parametric data relating to the geometry and information on the technical characteristics, thus allowing documentation and drawings to be kept together in a single integrated model. Such programs come with a large variety of prepackaged customizable objects that the user can also create

TABLE 4.2 Main building information modeling authoring software.

Vendor/developer	Software	Category
Autodesk Inc	Revit Civil 3D Infraworks Advance Steel	Architectural, Structural, Building Services (MEP) Infrastructure Infrastructure Structural steel
Graphisoft (Nemetschek Group)	ArchiCAD	Architectural, Structural, Building Services (MEP)
Bentley Systems, Inc	OpenBuilding Designer	Architectural, Structural, Building Services (MEP)
Vectorworks, Inc (Nemetschek Group)	Vectorworks Architect	Architectural
ALLPLAN Deutschland GmbH (Nemetschek Group)	Allplan Architecture Allplan Engineering	Architectural Structural
Tekla (Trimble, Inc)	Tekla structures Tekla civil	Structural Infrastructure
Cadwork	Cadwork 3D	Structural

independently. Plans, sections, elevations, lists of materials and other documents can be generated directly by the program based on the 3D model of the building, and are updated in real time.

BIM AS allow to import and export 2D sheets and to work using both 2D and 3D representations. Perspective or axonometric views, which would require considerable effort in manual drawing, can be easily generated (an example is the creation of shaded perspective sections), as well as 3D rendering of the building (sketches, white models, photorealistic models) thanks to integrated render engines (such as CineRender by Maxon for ArchiCAD, or Autodesk Raytracer for Revit) or with the use of plug-ins such as V-Ray or Enscape.

Regarding plant engineering, MEP BIM software offers a suite of tools to help users designing and evaluating mechanical, electrical and hydraulic systems quickly and accurately, allowing to estimate quantities correctly and to reduce any risks in the installation and laying phase, avoiding collisions between elements or work phases in advance (see Fig. 4.2).

Most used BIM AS products on the market are certainly Autodesk Revit (see Fig. 4.3), created in 2000 by Revit Technologies Inc. and bought in 2002 by Autodesk, and ArchiCAD (see Fig. 4.4), developed starting from 1982 by the Hungarian company Graphisoft owned by the Nemetschek group and marketed until 1995 with the name of Radar/Ch. Both products have greatly evolved over time with the release of continuous new versions aimed at improving interoperability with other software, speed of execution, cloud capability and the implementation of new functions for design and project management.

The use of BIM AS can be integrated and supported by parametric modeling tools such as Dynamo, Grasshopper, GenerativeComponents and Marionette, for automating repetitive tasks and managing information in the model more efficiently or to support the creation of complex geometry, and by generative software design such as Refinery or Galapagos for the optimization of design choices and the automated creation and evaluation of alternatives (see Section 6.4). 3D BIM models can then be imported into software for building performance simulation (DesignBuilder, Openstudio, Ladybug Tools, IES-VE), also available as plug-ins within the BIM AS environment (Sefaira, Insight360), or for LCA or carbon calculation (Tally, openLCA, EC3) (see Section 5.4).

For a more immersive visualization and to improve collaboration and decision-making, the 3D BIM models can then be imported into software for real-time 3D visualization such as Enscape, Lumion, Unity Reflect, Twinmotion, Fuzor or BimX (see Section 6.2) or for Extended reality such as Enscape, IrisVR, InsiteVR, The Wild or Fuzor (see Section 6.3.1).

Once the building is finished, the as-built BIM model becomes a valuable resource for its O&M activities, as it can be transferred as an AIM to several compatible Computer-Aided Facility Management (CAFM) software tools to enable planning modifications and maintain the facility-management model throughout the building life cycle (see Section 11.1.2).

A BIM project is not planned, designed, exchanged, checked, commented, and modified in a conventional, drawing-oriented way, but instead in a model-oriented way, making specific viewer programs a necessary tool in the workflow.



FIGURE 4.2 MEP design with BIM. *Courtesy of BIMon.*

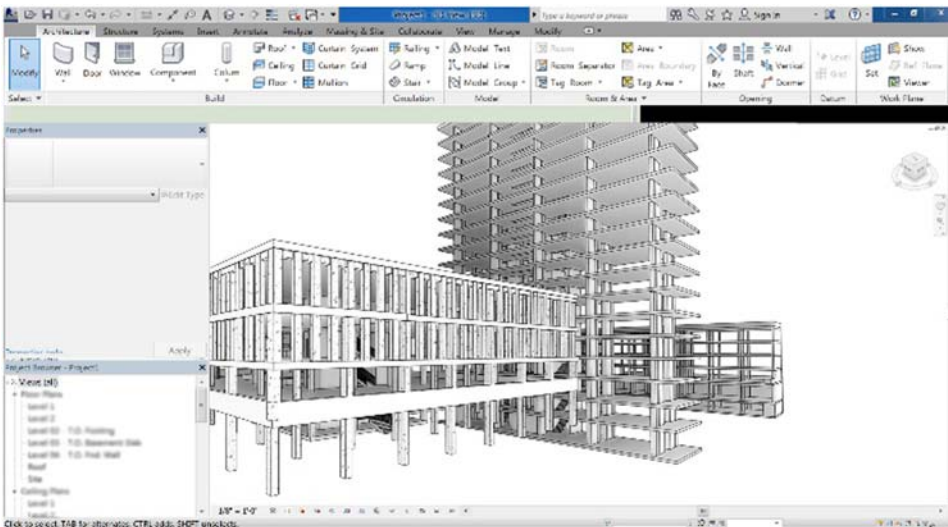


FIGURE 4.3 Autodesk Revit building information modeling authoring tool. *Courtesy of BIMon.*

BIM Viewers such as Bentley Navigator, Solibri Model Viewer, Tekla BIMsight and others (see [Table 4.3](#)) allow to view and analyze 3D BIM models, imported as IFC files or in any other file formats. In this process, all technical models—produced by architects, structural engineers, or other engineering professionals—can be merged to view them as a combination within a single complete model—irrespective of the particular CAD program they have been created with. BIM model viewers function without any original software, and most are easy to use and free of charge, allowing to involve stakeholders outside the project team in the BIM planning process, along with the clients, such as craftsmen, construction companies and manufacturers of prefabricated elements. On their PC or even on mobile devices they can therefore view and manipulate the 3D BIM model from different perspectives or have a virtual tour, create any (sectional) views, check measurements and report any discrepancies to planners.

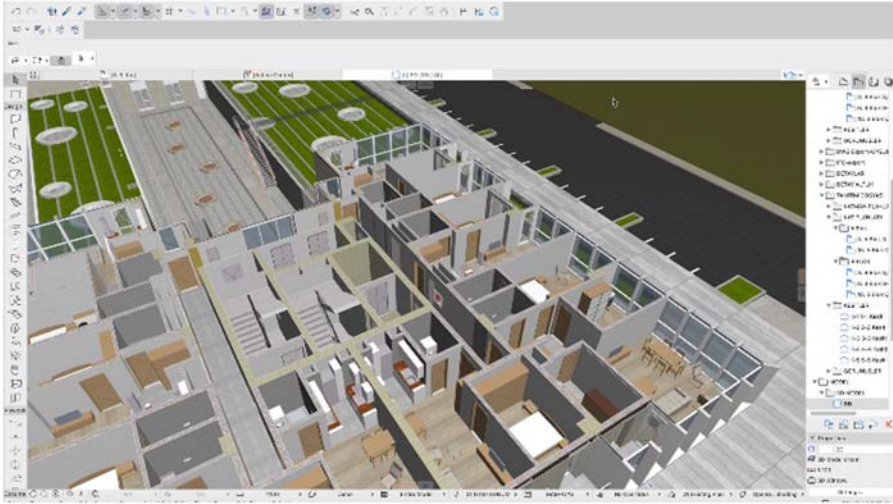


FIGURE 4.4 Graphisoft Archicad building information modeling authoring tool. *Courtesy of Graphisoft.*

TABLE 4.3 BIM Viewer/Checker and BIM project spaces software.

BIM Viewer/Checker		BIM project spaces	
Vendor/developer	Product	Vendor/developer	Product
Datacomp Sp. Z.o.o.	BIM Vision	Autodesk	BIM 360
Autodesk	Naviswork	Oracle	Aconex
Bentley Systems, Inc.	Bentley Navigator	ALLPLAN	Allplan Bimplus
ALLPLAN	Allplan Bimplus	Invicara	BIM Assure
Tekla (Trimble, Inc)	Tekla BIMSight	Asite Solutions Ltd.	Adoddle
Vizerra SA	Revizto	Catenda AS	Bimsync
BIM Track	BIM Track	Trimble, Inc	Trimble Connect
Solibri, Inc.	Solibri Model Checker	Dalux	Dalux box
Bexel Consulting	Bexel manager	Bentley	ProjectWise
Trimble, Inc	Quadri	Graphisoft	BIMCloud
Datacubist Oy	simplebim		
Graphisoft	BIMx		
BIM construction sequence (BIM 4D/5D)		BIM processing tools	
Vendor/developer	Product	Vendor/developer	Product
Bentley	Syncro	Rendra AS	StreamBIM
Autodesk	Naviswork	Dalux	Dalux Field
RIB Software AG	RIB iTWO	Trimble, Inc	SiteVision
Bexel Consulting	Bexel manager		

Moreover, BIM Viewers can have various additional functions, that is, for indicating the characteristics of building components (component number, material, dimensions, delivery date, etc.), for filtering BIM data according to different criteria, or for checking on possible component clashes and commenting on them accordingly. BIM Viewers can be integrated in industry-specific CAD/CAM or enterprise resource planning solutions allowing a much better coordination

of production and manufacturing processes between designers, clients, and elements fabricators. Control and communication functions of BIM Viewers also allow for managing modifications or assigning of tasks and thereby support the coordination and cooperation among the parties involved in openBIM projects. These are BIM projects where several project parties are involved, using different software tools. Since BIM Viewers often consist merely in BIM Model Reviewers with limited functions, the range of functions partially overlaps.

BIM Reviewing or Model Checker tools include software applications designed for BIM model review activities such as project review, verification of interferences (Clash detection), and the verification of compliance of the model to current building codes and regulations (Code checking), which are now an integral part and key element in information modeling and management. In standard design processes, only 5%–10% of the project information content is systematically checked, whereas BIM model checking allows an automatic validation of 40%–60% of the project (Common, 2012).

Code checking is the verification of the compliance of the digital model with relevant regulatory or technical requirements. Logical analysis rules and classifications integrated in the Model checking tool are individually extendable and enable automated checking of projects concerning building regulations, guidelines for workplaces, fire protection regulations. For instance, they can verify compliance with fundamental rules concerning stairs such as step size and headroom, fire protection regulations such as the length of escape routes, provisions for freedom from barriers such as the wheelchair accessibility of bathrooms and restrooms, or space requirements for minimum floor areas or heights. Automating these checks allows to speed up times and limit errors, improving the efficiency of the whole AEC process.

BIM Model Checker tools allow for active participation in BIM projects. This includes tools such as Autodesk Navisworks, Bentley Navigator, Solibri Model Checker and others (see Table 4.3). They can be used to inspect BIM models and objects for conformity with regulations, to analyze spaces, mass, and quantities, or to create clash and deficiency reports according to previously defined specifications. Virtually everything in the model can be manually or automatically checked during planning, before mass assessment and quantity evaluation, or before the transfer to project partners. It is possible to control, for example, whether the number of wall openings corresponds to the number of doors and windows, or if the number of caps matches that of pipe ends. If errors are detected, resulting work orders can be transferred via BIM Collaboration Format to the respective planning partners, who can import them into their BIM AS and accomplish the task.

In addition to model analysis and quality control services, Model Checkers can provide communication and coordination functions. For example, individual BIM technical models originating from different design professionals can be checked for errors or nonconformities when merging into an overall or coordination model. As individual technical models have to be united on a regular basis, BIM Model Checkers help to save time because they eliminate the need for manual comparisons.

Clash detection consists in the verification of geometric interferences, which can be a common coordination problem in 3D BIM (see Fig. 4.5). Two objects can collide because they occupy the same physical space, such as a pipe that

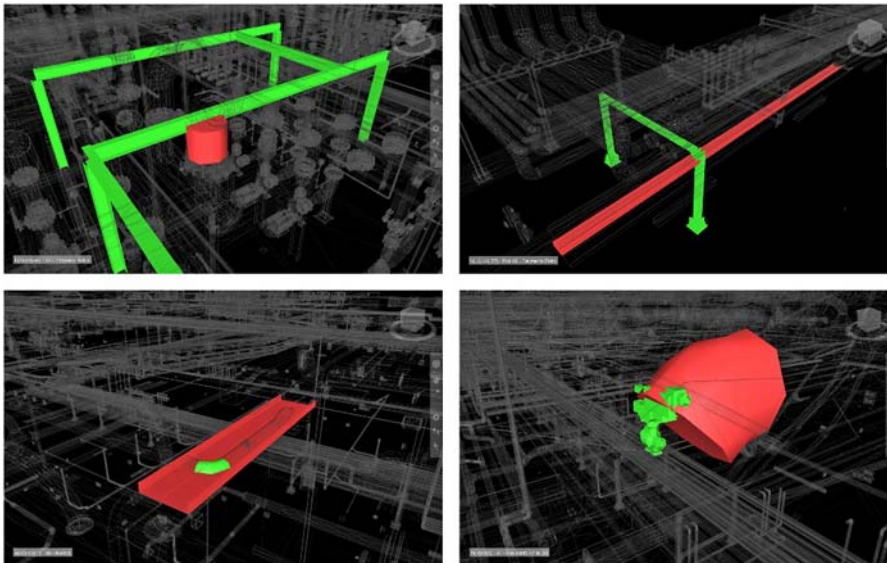


FIGURE 4.5 3D clash detection in building information modeling. *Courtesy of BIMon.*

passes through a beam (hard clash), or can generate interference because they are too close to each other and there is not enough space for maintenance (clearance clash or soft clash). Moreover, conflicts can develop between two objects designed to overlap during assembly (4D or workflow clash).

In addition to manual and visual controls on geometric collisions of structural members, component assemblies or parts, automated collision checks are also possible on the basis of corresponding rule specifications. The overlaps detected by the program can be prioritized according to a previously defined relevance to simplify error processing, in particular in larger and complex projects. During defect checking, projects can also be examined on possible errors, such as collisions with the reinforcement, missing embedded parts, wrong quantities or mass, using logical analysis rules. Corrective changes in planning on the BIM model are tracked to make project management more transparent, provide for more discipline among the persons involved in planning and reduce sources of error. By linking 3D BIM models with deadlines (4D BIM) or costs (5D BIM), some Model Checkers can be used to create model-based cost and time schedules from data available in the BIM model. Building components linked to working processes and time schedules as well as the interdependencies are automatically evaluated in this process. Such applications include: Syncro, Naviswork, RIB iTwo.

Appropriate BIM applications are specific for giving access to documents, plans, and models on the go, allowing figures such as BIM coordinators to deal with project documentation on site through their tablet or smartphone. Such applications include Dalux Field, StreamBIM and SiteVision. For Archicad users, the BIMx app developed by Graphisoft is particularly useful as it allows to present and explore the model on any mobile device, allowing contextual measurements and markup of the project. The “BIM Hyper-model” mode allows a navigation experience within the 3D model similar to that of a video game and which, with the use of VR Google Cardboard viewers, allows the user to fully experience virtual immersion.

Finally, BIM Project Spaces programs are used for project cooperation and information within a closed user group. They are also called BIM Server, Project Communication and Management Systems, or Internet-Based Project Management systems (IBPM). Examples include Allplan Bimplus, Autodesk BIM 360, Bentley ProjectWise, Graphisoft BIMCloud and Trimble Connect (see Table 4.3). Only the use of BIM Project Spaces allows all project parties to get access to all information and communication structures, at any time, which is an absolute necessity for openBIM projects. Indeed, BIM Project Spaces provide all authorized project parties with access through the cloud to 3D models but also to construction plans, documents, calculations, construction schedules, requests for proposals, protocols, etc. independently from time and place and platform. In addition, they manage information on document contents, document versions, users and their access rights, and on process flows, for instance on adjustment and release. This way, BIM Project Spaces support cooperative planning, implementation and documentation of construction projects by enabling the exchange of information and data in a continuous, structured and documented manner over the entire course of the project. Ideally, the shared BIM Project Space would provide each user with the BIM model showing exactly the depth and selection of information relevant for their current task, for example, including all precast concrete elements, concrete blocks and staircases, or HVAC and plumbing systems. This also ensures greater security in terms of planning, scheduling and costs. Therefore BIM Project Spaces are already an established practice in almost every larger building and civil engineering project, and have become common in case of small- and medium-sized projects as well.

4.3 Application of building information modeling along the construction value chain

BIM-based processes can be adopted at any stage of a building or an infrastructure project, namely the design stage, the construction stage or the operation stage (Borrmann, König, Koch, & Beetz, 2018; Liu et al., 2019; Panteli et al., 2020).

In the design stage, aspects of architectural design, structural analysis, MEP engineering, as well as other analysis including environmental and energy assessment are generally implemented. During the construction stage, the implementation of BIM includes the monitoring of the construction progress, as well as health and safety issues and vigilance. Post-construction application of BIM is related to the as-built assessment of the building operational performance, including actual energy behavior, as well as to the monitoring of the operation of a building, typically in terms of digital twins, integration with the building automation system, and application of IoT and machine learning practices. Lastly, BIM can greatly support activities pertaining the final decommission, recycling or reuse of the building and its components in a circular economy scope.

4.3.1 Design development

In the project planning and development phase, BIM can greatly benefit the design and engineering process with several advantages over traditional 2D CAD processes. A significant convenience of using BIM is that most technical drawings,

such as horizontal and vertical sections, are derived directly from the 3D model and are thus automatically consistent with each other. Moreover, the 3D representation permits an enhanced understanding, visualization and resolution of any problem throughout the whole process. The coordination of different parties within a single model is also considerably better with respect to 2D documentations.

3D geometry of the facility under design provides the basis for performing clash detection between the different partial models (architecture, structure, MEP, etc.) allowing to identify and resolve conflicts between the design disciplines at an early stage, saving significant costs both during design process and during works at site.

BIM also facilitates the integration of computations and simulations into the design process in a seamless way, as a lot of input information about the building's geometry and material parameters can be taken directly from the model. A wide range of simulations, including structural analysis, building performance simulation, evacuation simulation, or lightning analysis, are then usable at any stage of design to set performance targets and identify and address any deviations in a timely manner. The BIM model can be checked for compliance with codes and regulations, currently mostly in a semiautomated manner but in the future with a higher degree of automation. In BIM reviewing procedures integrated with AI (clash detection and code checking BIM review), it is possible to perform massive automatic checking of the conformity of all kinds of computable rules and interferences without direct human control. Such an automated approach could be of great interest and impact for the public administrations in the process of construction authorization, and in automatic control of compliance not only to the project's building codes but also of the built structures through 3D scanning and AI.

Model data can be used to compute a very precise quantity take-off, providing the basis for reliable cost estimations and improving accuracy in the tendering and bidding process. Moreover, BIM can support the LCA of the building through the direct extraction of information from the model (types of materials and quantities) and their allocation to the available LCI databases for the purpose of calculating the LCA, or by the automatic calculation of LCA when environmental properties are included in BIM objects (see [Section 5.4.3](#)).

BIM is also the base for parametric design, which consists in linking determined design activities to user-defined scripts, allowing to automate these tasks according to the specific parameters (e.g., placing lighting fixtures or doors in corridors at specific intervals). Parametric design enables to correlate design actions to results from equations or performance simulations, as well as the iterative comparison of different solutions procedurally generated by a specific algorithm, allowing the user to evaluate numerous potential designs at once (see [Section 6.4.1](#)). In some cases, the integration of AI and advanced statistical tools in the parametric BIM workflow also allows to identify autonomously the best solutions based on specified evaluation parameters (generative design), for instance by optimizing the tessellation of a curved surface to reduce the number of different sizes for cladding panels (see [Section 6.4.2](#)).

The 3D model-based design also allows much better visualization of the building and its components, enabling unprecedented possibilities for immersive and interactive fruition and understanding of the designed spaces. The high degree of geometric detail and the wealth of information associated with 3D BIM can in fact be seamlessly transferred into specific software for Real-Time 3D Visualization to preview the actual, physics-based appearance and behavior of any building component, for example, how light will shimmer into a room at dusk or which outside views can be enjoyed from a window (see [Section 6.2](#)). Augmented Reality and Virtual Reality programs further improve immersion allowing the user to visit every room and space of the virtual building and gauge esthetic and functional aspects with unprecedented fidelity (Czmoch & Adam Pekala, 2014; NBS, 2020). These functions are particularly useful for involving non-professional clients and occupants that are finally able to see what the final product will be like instead of just imagining it from a few renders and schematic materials (see [Section 6.3](#)).

Lastly, the application of BIM in the design stage is a keystone in the transition of the construction industry toward the digitalized, sustainable and productive manufacturing practices already established in more advanced industry sectors such as automotive, electronics and consumer goods manufacturing. Automated construction methods have emerged, such as 3D printers, computer numerically controlled (CNC) routers and cutters, multiaxis industrial robotic arms, laser-cutters, or robotic end-effectors, which are digitally controlled based on informatic fabrication code directly extracted from design and engineered data (digital fabrication). It is apparent that the integration within the BIM process of the questions related to the digital fabrication method and materials envisaged for the construction of components allows to greatly reduce or even close the process chain that links design to construction, greatly reducing the loss of time, money and performance usually involved in the transition between construction drawings and coded instruction for each digital fabrication process. This approach, called design for digital fabrication, is based on BIM and parametric, algorithmic and generative modeling and aims to close the gap with construction with the creation of 3D models in fabrication quality and in the use of the collaborative BIM environment to enable the spatial coordination of different trades and specialty fabricators already in the design stage (see [Section 6.5](#)).

In any case, applying BIM in the planning process results in shifting the design effort to earlier phases, as illustrated in Fig. 4.6 (Borrmann et al., 2018).

In conventional planning processes, in fact, the main design and engineering effort usually takes place in the later phases of detailed design, and sometimes even stretches during the actual construction phase. As a consequence, key aspects of design such as coordination of different disciplines, performance simulation, sustainability assessment can only occur at a relatively late point in the overall process. At such point, however, discovered issues and deviations from projects requirements are difficult to address as the possibilities for design changes are more limited and also more costly to implement. By contrast, in a BIM-based planning process much of this effort can be brought forward by building up a comprehensive digital building model, planning the coordination requirements in detail and employing computational analyses already in the early design phases. This allows to evaluate the impact of design decisions more comprehensively and to identify and resolve possible conflicts early on, significantly decreasing the effort required at later phases and improving the overall design quality.

Finally, in the longer term, BIM's greatest potential may be in optimizing building operations and management, and capturing operations data, so that lessons learned can be quickly and easily incorporated into the next round of designs. If a structural or functional problem arises after a building was built, BIM can assist with tracing the problem back to the root cause and help engineers eliminate the problem in future designs.

4.3.2 Building information modeling in the construction phase

The advantages of BIM are not limited to the design activity but extend to the preparation and execution of its actual construction. During the tendering process, the provision of the BIM model allows contractors to determine the services required and costs with much greater accuracy when preparing the bid and also facilitates precise billing at a later stage. Furthermore, 4D BIM associates individual building components with the scheduled construction times, allowing to validate the construction sequence, detect spatial and sequencing collisions and organize the site logistics (Jupp, 2017).

Additionally, 5D BIM integrates cost information and can be used to simulate the cost development and cash flows over time as well as to closely monitor budget deviations (Jiang, 2017).

Finally, the invoicing of construction work, as well as issue management and RFI, can also be supported using BIM methods.

The data contained in the BIM model can also support off-site construction of components. The project team can leverage the collection of data available on cloud that already includes product and specification libraries, directly

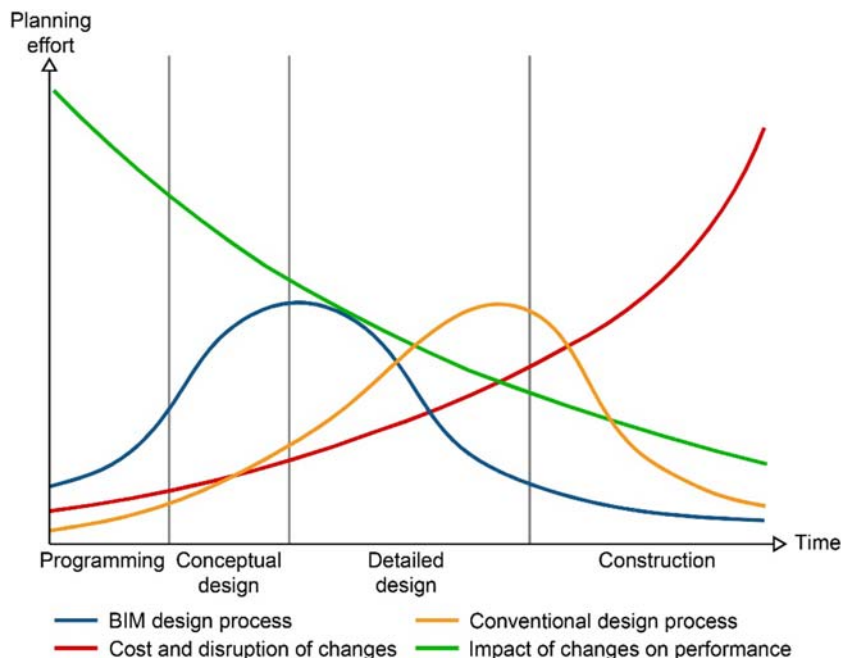


FIGURE 4.6 Front loading shifting through BIM.

prepared by off-site manufacturers and suppliers, which contain 3D component models, digital shop-drawings, and digitized design-to-fabrication documentations that will guide the manufacturers' work.

Moreover, the BIM model provides the precise, high-quality standardized data that manufacturers need to accurately manage workflows and run their production line machines as they create the requested components per the required parameters. The same data can also be read by construction robots, 3D printers, CNC machines, and other digital fabrication equipment. BIM data acts as a "digital source of truth" for production processes in a factory setting where these data-driven machines automate many tasks traditionally performed manually on-site, such as cutting, drilling, sawing, connecting, and assembling. BIM data can also enable extended-reality technologies to guide production crews who work alongside robots, or who carry out tasks such as inventorying, loading, and preparation for shipment. Furthermore, BIM effectively bridges off-site and on-site construction data and greatly helps coordinating off-site/on-site construction sequences for just-in-time delivery of the volumetric and modular components. 4D and 5D BIM can be used to link digital off-site construction with leaner digital supply chain management. Production data collected during off-site construction can be further integrated into the as-built AIM to serve the building's future needs during upgrades, repairs, maintenance, and improvements.

4.3.3 Building information modeling in the operation phase

Further benefits are achieved by applying the BIM method also across the operation phase of the built facility (Aziz et al., 2016; Nicała & Wodyński, 2016) (see Section 11.1.3).

The wealth and structuring of data associated with the BIM model, including all relevant information from the construction phase, can greatly improve project handover of information from the design team to the owner. The availability of a high-value AIM model instead of "dead" drawings allows direct transfer into CAFM systems. All data about room sizes, HVAC, electricity and telecommunication, including valuable information such as maintenance cycles and warranty conditions, is directly transferred and does not need to be entered manually, with risks of errors and loss of time (Pishdad-Bozorgi et al., 2018).

However, an important aspect is the constant upkeep of the AIM model which must be updated with all changes that occur in the real facility. Data from sensors and equipment can also be fed automatically to the AIM, which thus becomes a living digital twin that replicates in real time the operations and conditions of its real-world counterpart. When larger renovations or modifications may be required at a later stage, the AIM provides an excellent basis for the necessary design activities. When the built facility reaches the end of its life cycle and is going to be demolished, the AIM provides detailed information about the materials used in its construction, in order to plan their environmentally sound recycling or disposal.

The AIM can be used by facility managers to better visualize the building and so manage it more effectively, reducing their operating costs and increasing competitive strengths. As BIM provides tools for optimizing building efficiency throughout its life cycle, lessons learned can be reinvested in new BIM projects and applied in the early design phases, sharing the knowledge about buildings optimization. As the use of BIM evolves and expands, new jobs may emerge in the facility manager profession, including "BIM data manager" and "BIM data modeler," and who will be in charge of geometric updates of the model. Another possible job, "BIM project manager," may involve integrating BIM into existing property management processes (Aziz et al., 2016; Gao & Pishdad-Bozorgi, 2019).

Finally, BIM is a valuable tool to manage the end-of-life phase of the buildings, which pertains its ultimate decommission and the optimal recycling and reuse of its parts and materials in a circular economy framework (Charef et al., 2018; Ganiyu et al., 2020). In this stage, BIM provides the backbone for development of the building's material passport and project database, and its information can support data checking, circularity assessment, and ultimately materials' recovery and building as materials' bank (BAMB) processes (Honic, Kovacic, Sibenik, & Rechberger, 2019).

4.4 Building information modeling information requirements

For the successful realization of BIM projects, an important prerequisite is represented by the legally binding agreements that should address model contents, model qualities and workflows, in particular concerning the final handover of building models to the owner. General contractual specifications are typically provided by a contract appendix that defines the applied terminology as well as global responsibilities (Cavka, Staub-French, & Poirier, 2017).

In this context, a very important role is played by the EIRs and the BEP. These documents shall be developed specifically for the construction project and form part of the contractual agreements. In particular, the EIR forms part of the tendering documents, indicates the objectives set by the client for applying BIM in the project and how the digital

processes shall be executed. It contains detailed specifications on responsibilities, handover dates and procedures, as well as data exchange formats. The content of the models to be delivered is specified through well-defined LODs for each element type, including detailed lists of attributes. The EIR is normally framed in a wider asset information requirements document prepared by the organization in line with its wider asset management plan, as defined in the organizational information requirements. Bidders (potential contractors) describe how they plan to meet the EIR requirements in a preaward BEP, which is refined into a more detailed document after the contract is awarded.

To properly validate and control BIM projects as they develop, data from the evolving model is submitted to the employer at key milestones, an event called “data drop” or “information exchange.” These data drops are generally aligned to stages of the design process and the information required reflects the LOD that the project should have reached by that stage, in a way analogous a stage report on a conventional project. Exchanged information includes IFC models and native PIMs, data structures such as construction operations building information exchange (COBie) files and schedules, and PDF reports.

General specifications for BIM project execution are contained in the ISO standards of the series 19650, which have the goal to ensure that appropriate information is created in a suitable format at the right time so that better decisions can be made throughout the design, construction and operation of built assets.

4.4.1 Exchange information requirements

The EIR defines all information that will be required by the client from both their own internal team and from professionals (project team, contractor, facility managers) for the development of the project and for the operation of the completed built asset. Relevant extracts from the EIR are commonly included in procurement documents for the appointment of each supplier, which may include advisors, consultants, etc. Prospective suppliers respond to the EIR with a preaward BEP from which their proposed approach, capability, and capacity can be evaluated.

Development of the EIR is likely to be an iterative process: it might take the form of a simple information requirements process map which identifies the key decisions that will need to be made during the project to ensure the solution developed satisfies the business need and defines in very broad terms the information that will be needed to make those decisions. Afterwards, it may identify the material, functional and performance information required about facilities, floors and spaces. As the design develops, the EIR identifies more specific requirements about the proposed systems and building components to support procurement. By the end of the project, it defines the need for information to support the maintenance and operation of systems and components that are actually installed. The EIR should clearly describe the expected information deliverables in terms of documents, model files and structured information and define how and when information should be exchanged in the project life cycle.

However, the exact nature of the EIR will depend on the complexity of the project and the requirements of the employer. Demanding employers may develop very detailed EIR, whereas others may only set out high-level requirements and some basic rules, leaving the supplier to propose how those requirements will be met. Common elements of the EIR include the following:

- standard methods and procedures to define the way information is created, named and exchanged;
- clear definitions of the information-related roles and their responsibility;
- an information delivery plan that defines which information deliverables should be delivered, by whom and when;
- a COBie demand matrix that identifies which structured data about the facility, floors, spaces, zones and building components should be delivered and when.

The contractual status of the EIR can be established by referencing it in or appending it to a BIM protocol. The BIM protocol sets out the contractual definition of BIM responsibilities, liabilities, and limitations. The contract used for appointments can be appended with a BIM protocol by the addition a model enabling amendment clause.

4.4.2 Building information modeling execution plan

The BIM BEP, sometimes abbreviated as BxP or referred to as a BIM delivery plan or digital execution plan, explains how the information management aspects of the appointment will be carried out by the delivery team. The BEP has two focal points: to demonstrate that the design team has the relevant experience, skills, software and hardware to satisfy the EIR, and to set out how they will use these tools to undertake the project, including details on collaborative workflow and file naming.

Usually, a preaward BEP is prepared by prospective suppliers, setting out their proposed approach, capability, capacity, and competence to meet the EIR part of the tendering process. The preaward BEP may include the following:

- a project implementation plan (PIP) that sets out the capability, competence and experience of the suppliers, along with quality documentation;
- the goals for collaboration and information modeling;
- the proposed project milestones in line with the project program;
- the deliverable strategy.

Once the contract has been awarded, the supplier submits a more detailed BEP which confirms the supply chain's capabilities and provides a master information delivery plan (MIDP). In turn, the MIDP sets out when project information is to be prepared, by whom, and using what protocols and procedures, based on a series of individual task information delivery plans (TIDP) which set out responsibility for specific information tasks.

The BEP considers issues beyond the modeling strategies, looking at the connectivity of all the software used on the project. The post-contract-award BEP sets out how the information required in the EIR will be provided with reference to management, planning and documentation, standard methods and procedures, and IT solutions (see [Table 4.4](#)).

If more suppliers have been appointed, there may be an overarching BEP, with responsibility for its preparation set out in appointment documents, with which subsequent BEPs prepared by later appointments should be compatible. A number of templates have been published for both the EIR and BEP by different institutions, for instance precontract and postcontract BEP templates can be found on the Construction Project Information Committee (CPIC) website.

4.4.3 Building information modeling roles and professions

The proper management of the flow of information that is generated, used and shared in the BIM process requires the clear definition of the roles and responsibilities of all stakeholders associated with the project. At the same time, the introduction of the BIM methodology entails the acquisition of new skills, the development of new workflows and the emergence of new professional figures ([Borrmann et al., 2018](#)).

TABLE 4.4 Building information modeling execution plan.

Area	Information required
Management	• Roles, responsibilities and authorities • Project milestones in line with the project program • Deliverable strategy • Survey strategy • Existing legacy data use • Approval of information • Authorization process
Planning and documentation	• Revised PIP confirming the capability of the supply chain • Agreed processes for collaboration and modeling • Agreed matrix of responsibilities • TIDP setting out responsibility for delivery of each supplier's information • MIDP setting out when project information is to be prepared, by whom and using what protocols and procedures
Standard method and procedure	• Volume strategy • Origin and orientation • File naming convention • Layer naming convention • Construction tolerances • Drawing sheet templates • Annotation, dimensions, abbreviations, and symbols • Attribute data
IT solutions	• Software versions • Exchange formats • Process and data management systems

Several academic and professional sources have described the profiles and areas of competence of the professionals that operate in BIM. For instance, the norm PAS 1192-2:2013 by the British Standard Institution (BSI) identifies up to seven types of roles that can be considered for the managing process of BIM, specifying that these roles should not be mistaken with the professional roles of individuals belonging to an organization, but are only characterized by the level of authority in the management of the flow of information within the BIM process.

Overall, it is possible to identify three main types of professional figure: (1) BIM specialists, (2) BIM coordinators, and (3) BIM managers. Although they have different responsibilities, abilities and knowledge, some overlap is present and thus the definitions are not necessarily clear cut (see [Table 4.5](#)).

BIM specialists are able to use the software to create a BIM project in accordance with their areas of expertise (architectural, structural, plant engineering, environmental, and infrastructural). They shall have a deep understanding of the technical and operative documentation (standards and procedures) and use them for the production of the composition and models. BIM specialists work under the supervision and coordination of the BIM coordinator or of the BIM manager of the planning team and have the role of “designer of information” for graphic and nongraphic design. Within their activities, BIM Specialists elaborate, edit and extract data from the graphic models and the correlated objects that have been defined consequently from the result of the coordination procedures.

The role of BIM coordinator entails the management and coordination of the multidisciplinary BIM projects according to the resources, the standards and the company procedures; the coordination of the activities of reviewing, controlling and managing of the project by the specific software tools; as well as the comprehension, use and update of the technical and operative documentation for the production of BIM elaborates and models. Their abilities range from the coordination of the content held within the model to the collaboration with the BIM manager, also contributing to the elaboration of the BEP. Their responsibility is also related to sharing, coordination and aggregation of content, identifying potential interferences and/or inconsistencies, and proposing solutions to the BIM Manager and relevant persons on the project. Two specializations that can follow both the role of the BIM specialist and the BIM coordinator are the BIM specialist/coordinator for building and the BIM specialist/coordinator for infrastructure. The BIM specialist/coordinator for building is responsible for the planning, construction, and management of buildings in residential, culture, administrative, sports, and entertainment fields. On the other hand, the BIM specialist/coordinator for infrastructure is responsible for the planning and construction of roads, railways, harbors and others.

As multidimension BIM modeling can become rather complex and still requires people to provide and control information, it is necessary to coordinate the BIM project team. This task is usually entrusted to a BIM manager trained for this purpose, who defines the workflow and monitors both the development stages and any existing guidelines. This role also involves the maintenance, structuring, and management of the building data model as well as the submodels. BIM managers coordinate project teams and maintain an overview of any steps ahead, providing support when hurdles and questions converge, according to the overall resources and the standards, in conjunction with the business procedures. They use the software tools that are requested for the coordination of the activities, control and management of the BIM project. External BIM managers can be brought in as part of a company’s BIM strategy to act as consultants or to provide support to inexperienced teams in the implementation and integration of the BIM method.

BIM managers are also responsible for the management and coordination of information for suppliers that are involved in the design and management service of the building. They must write down the documentation for the technical and operative parts of the building commission, and make key decisions on the strategy to be implemented within the company. Most of the time these figures are transversal to the building and infrastructure disciplines, since they may manage and coordinate different teams in several fields from engineering to architecture. Concerning the management of information, the BIM manager is tasked with choosing the programs to use and with determining the resources needed. They set up and take part in regular team meetings to keep up to date on progress and coordination. In case of interferences or inconsistencies, they are entrusted with the decisions that need to be taken in such a case.

4.5 Building information modeling maturity levels

The transition from conventional, 2D CAD workflows to BIM-based ones requires significant changes in both internal company workflows as well as cross-company processes, therefore a stepwise shift is recommended to prevent unnecessary unsettling of the basic functioning of established workflows. Indeed, successful adoption of BIM entails a structured approach that accounts for the many integrated components of a company’s business, from leadership to the professionals who will apply BIM in the daily workflow. Pilot projects can be a viable component for an effective BIM implementation plan.

TABLE 4.5 Responsibilities of building information modeling specialist, BIM coordinator, and BIM manager.

Roles	Responsibilities											
	Production		Management				Strategic					
	Modeling	Drawing production	Content creation	Model coordination	Modeling audit	Execution plan	Training	Implementation	Standards	Process + workflow	Research	Corporate objectives
BIM specialist	■	■	■									
BIM coordinator	■		■	■	■	■	■					
BIM manager						■	■	■	■	■	■	■

Nevertheless, implementing BIM will inevitably impact on the company's business and processes, as well as on its technology toolset, therefore it must be supported by the business as a whole instead of being limited to an IT or an R&D initiative or done solely at a project or disciplinary level.

In a typical BIM transition roadmap, first BIM software is used to create a building model and derive drawings which are fed into the conventional downstream process, with the building model not used across different software packages nor handed over to other stakeholders. Such insular BIM implementation is limited within the single design discipline, with all external communications taking place using drawings. Some efficiency can be gained, however the ultimate potential of BIM remains untapped. By contrast, a more mature BIM approach entails the consistent model-based communication between all stakeholders and across the entire life cycle of the building. Digital technologies such as model servers, databases or project platforms must be employed for the data exchange and the coordination of the model-based workflows.

The BIM maturity scale is commonly represented as a wedge with 4 progressive levels, from level 0 (Unmanaged CAD) to level 3 (Single, online, project model with construction sequencing, cost, and life-cycle management information), as shown in Fig. 4.7 (Borrmann et al., 2018; JRC, 2017). Recently a level 4 has been added introducing the concepts of improved social outcomes and wellbeing. To evaluate which level is reached, indicators have been introduced to measure four aspects: the content, the digitalization, the interoperability and the collaboration.

BIM level 0 corresponds to traditional workflows based on 2D CAD and the exchange of paper-based or electronic text and drawings, without common standards and processes.

BIM level 1 comprises the 3D modeling of parts of the building (mostly for complex geometries) and the 2D drawing for most of the design. Data exchange still entails sending and receiving individual files without employing a central project platform, and models are not shared between project team members.

BIM level 2 is in turn defined by the use of BIM AS for model design, with each of the various disciplines involved developing its own model. Mutual consistency of the specialized submodels is ensured by periodic coordination sessions in which they are brought together and checked for clashes or other discrepancies (federated model approach). 2D drawings are mostly derived from BIM models. Information exchange takes place on a central platform called a CDE, but is still realized on the basis of individual files (in native formats). BIM data may include time sequencing (4D BIM) and cost information (5D BIM). BIM level 2 is recognized as a convenient method to ensure appropriate information is created and shared in a suitable format at the right time so that better decisions can be made throughout the planning, delivery and operation of any built asset. The British Government has made BIM level 2 mandatory for all public construction projects since 2016, requiring fully collaborative 3D BIM with all project and asset information delivered in electronic format.

Finally, BIM level 3 involves the concept of a fully integrated openBIM, that is, a single collaborative cloud-based project model integrated with construction sequencing (4D BIM), cost (5D BIM) as well as asset life-cycle information (6D BIM). Specific ISO standards are employed for data exchange and process descriptions, and deeply integrated digital models are used throughout the entire project life cycle. All project data is managed through cloud services so it is

	Level 0	Level 1	Level 2	Level 3	
		2D 3D	Federated BIMs	Integrated BIMs IDM, IFC, IFD	
	CAD	Proprietary Formats	Proprietary Formats+COBie	ISO standards	Exchange Formats
Drawings		Geometric models	Coordinated Discipline specific BIM models	Integrated, interoperable Building Information Models for the entire life cycle	Depth of information
Papers		File-based collaboration	Central management of files (CDE), Shared libraries	Cloud-based model management (BIM Hub)	Coordination and Collaboration

FIGURE 4.7 BIM maturity levels.

continuously and consistently maintained over the building's life cycle. BIM level 3 aims at linking the digital design of various elements in the built environment and at extending BIM method into the whole life cycle of the involved assets. This way, it can fully support the delivery of smart cities, services and grids. With level 3 BIM, building owners and operators are able to best manage assets and services as they track their real-time efficiency, maximizing utilization and minimizing energy use.

4.6 Collaborative practices and standardization

4.6.1 Building information modeling standardization

As with all industry and manufacturing sectors, the construction industry is regulated by a wealth of standards, guidelines, codes of practice and regulations at different levels of enforcements and application. Their objective is to make construction projects safer, reduce failures and increase productivity, while promoting a collective understanding of the relevant principles applicable to all projects, aligning client's expectations of project results and leveling them across cultures, time, and geography. Standards regulate materials strength and suitability, calculation methods, quality levels, practice methodologies and outputs, and are critical when communicating between stakeholders in a fragmented industry in temporary project organizations.

For BIM development, standardization is particularly important, with common concepts and their definition and classification, as well as neutral formats for data models, required to ensure convenient communication (JRC, 2017). Uniform processes for information delivery and common workflows and methodologies are also necessary. Currently, BIM standardization at the international level is involving many organizations with different tasks, including:

- ISO/TC 59/SC 13 "Organization and digitization of information about buildings and civil engineering works, including BIM," an ISO committee tasked with international standardization of information through the whole life cycle of buildings and infrastructure across the built environment;
- CEN/TC 442 "BIM," a technical body of the European Committee for Standardization (CEN) charged with developing a structured set of standards and specifications to define, describe, exchange, monitor, record and securely handle asset data, semantics and processes;
- BuildingSMART, an international organization which aims to improve the exchange of information between software applications used in the construction industry.

In particular, BuildingSMART is the leading organization in the standardization of information exchange between software applications used in the construction industry, which is responsible for developing and maintaining the IFCs as a neutral and open specification for BIM data model. Other standardization work include data dictionaries (International Framework for Dictionaries Libraries) and processes (data delivery manuals).

4.6.2 Common data environment

Collaborative workflows are becoming increasingly important for building planning and construction projects, as these often bring together a large number of heterogeneous disciplines, some of which may not have collaborated before (Bello et al., 2021).

Such works also require the coordination and management of a great deal of complex information, procedures and systems. Indeed, the absence of clear and efficient project-wide collaborative practices can lead to suboptimal project processes and delivery, errors in design and construction, increased time and costs as well as lower overall quality of the built environment. This has become especially relevant in the last years as project delivery has evolved from established client—consultant—contractor relationships to more integrated structures with complex financing arrangements, early engagement of the supply chain and the introduction of suppliers for different design disciplines.

The broad principles of collaborative practice shall be defined as early as possible in the project, even leaving some details unresolved until later stages. The decision to adopt a collaborative approach should be taken by the client from the very start, so that it can be included in appointment documents such as the EIR and contribute to the selection of procurement route, form of contract and preparation of tender documentation. How to implement these collaborative practices can then be discussed in detail in start-up meetings with the project team and specialist contractors.

Conversely, a typical construction project today involves the generation and exchange of a remarkable amount of data during its life cycle, regardless of its dimension. In a typical construction project, several tools and technologies are being used to capture, collect, and process data. However, much of this data remains siloed. All this information

must be managed and dispersed effectively, otherwise the lack of communication may lead to errors, rework, missed deadlines, cost overruns, and litigation. It is estimated that more than 95% of all data captured goes unused in engineering and construction, 30% of initial data created during the design and construction phases is lost by project closeout, 29% of construction professionals report that none of their software solutions integrate, 51.8% of construction professionals report they transfer data manually when solutions don't integrate and 13% of construction teams' working hours were spent looking for project data and information (JBKnowledge, 2020).

Although lot of that necessary information can be obtained while the project is underway, owners often lack visibility into the construction of their buildings and struggle to collect and manage the data required to own and operate their facility's profitability. This issue is even more pronounced when owners are managing a portfolio of buildings.

Conversely, construction companies shall start understanding data as more than mere numbers. Simplified, numerical indicators, facts and figures are still essential for decision-making, however today's construction data also comes in the form of visual information, 3D models and scans as well as photo and video imagery throughout the project's progression. Immense amounts of qualitative data are available further beyond. Therefore chains of communications become crucial for every project process and change to get an accurate picture of the construction process.

In fact, one of the most significant enabling factors of data-driven design and construction is to allow any stakeholder to easily see, obtain and understand the data they need, from anywhere. Systems and technologies to enable this should be easy to use, centrally organized with high-level dashboards, include customization and standardization options to fit with niche business workflows, and should provide snapshots of insights for easily digested decision-making information. They need to be free from error and mistakes, without double entry, updated in real-time in the cloud and trustworthy enough to be used as a decision-making tool.

The best way to address all these requirements is to adopt a CDE, that is, a standardized way of structuring data and collaboration used to capture, manage, and distribute information and documents throughout the project. The CDE acts as the central hub where team members can find all the information they need about a project, including BIM data, plans, and contracts, facilitating communication between stakeholders and ensuring everyone is working using the same platform. Since everything is channeled through a single source, the information extracted can be trusted to be up-to-date and reliable, resulting in lower risks and improved predictability.

Furthermore, the CDE enhances project visibility for the owner and supports their involvement during the construction phase. They can tap into valuable data and information and view projects at a dashboard level using data visualization tools throughout the construction process to spot trends and gain insights that can inform portfolio-wide decisions.

As the single source of information for the project, the CDE is used to collect, manage and disseminate documentation, graphical models and nongraphical data by all project stakeholders at the specified access level. Such central data repository is required to perform the BIM level 2 information sharing function, facilitates collaboration between project team members and helps avoid duplication and mistakes. It features an automated information flow and uses predefined ways of sharing, accepting and commenting documents. The CDE platform is generally hosted on an external server, accessible to all parties with the appropriate permissions, and may use a project server, an extranet, a file-based retrieval system or other suitable toolset. Examples of more common CDE cloud-based software include Autodesk BIM 360, Graphisoft BimCloud, Viewpoint for Projects, Asite, Trimble Connect, Bentley ProjectWise, Allplan Bimplus, Bimsync, Dalux Box, as well as Microsoft SharePoint.

The CDE may include a number of different information environments, such as a supply-side CDE used by the project delivery team, and an employer's side CDE with a proprietary document and data management system for the receipt, validation and approval of project information delivered by suppliers. CDE procedures for sharing information can entail spatial coordination as well, so that delivered production information is right first time. The CDE can provide the ability to produce traditional drawings or documents as views of multiauthored data, and gives greater control over the revisions and versions of that data.

Within the CDE, ownership of information remains with its author, and individual models produced by different project team members do not interact, have clear authorship and remain separate. Therefore the liabilities of each author are maintained in the incorporation of their model into the federated model. Some complications may arise in case of ownership changes as the project progresses, for example, when replacing design team BIM objects with specialist subcontractor BIM objects. Generally, a license is granted to the client to use the information contained in the separate models for their permitted purpose, that is, for the purpose for which that level of detail of information was intended, as defined in the EIR and BEP. A sublicense from the client may enable different project team members to use models prepared by each other.

The Construction Industry Council (CIC) BIM protocol proposes that the CDE should be set up and managed by an information manager, appointed by the client. Responsibilities for supplying and managing the supply-side CDE should

be clearly identified in the EIR. Such information managers act essentially a procedural gate-keeper, overseeing the CDE to ensure that agreed protocols are followed and data is secure. They should not be confused with BIM coordinators as they do not have any responsibility for clash detection or model coordination.

The benefits of the CDE also extend after the handover process to building management and maintenance. Connected data as well as comprehensive as-builts that incorporate any changes made during the project can be accessed through the same CDE. By gaining access to accurate data from construction, facility managers can operate the building more efficiently and profitably, even more so when they were involved already in construction, or had access to data throughout the project. This equips them to manage the facility immediately, on day one—reducing the learning curve and ensuring speed to efficient operations. The CDE can further provide data on mobile devices, allowing facility managers to quickly identify and resolve issues, instead of running back to their office for a binder of papers or contacting their contractor via email for documentation of plans, warranties, and other asset specifications. They can be proactive about maintaining their buildings and assets instead of only responding when something goes wrong. The construction data in the CDE that is handed over after the project can finally be used to gain knowledge that can be used in ongoing capital programs and future construction projects across the owner's portfolio.

4.6.3 Interoperability

BIM standardization becomes paramount in the exchange of information between the different software applications inevitably used by teams coming together from different organizations (JRC, 2017; Shirowzhan, Sepasgozara, Edwards, HLid, & Wange, 2020).

As reported, data exchange among different tools is crucial for the effective collaboration and digital workflows through various organizations, disciplines and phases in the AECO industry. Interoperability of files and software is the key to enable digital workflows and connection between all relevant stakeholders. It can be defined as the uninterrupted ability of different systems or products interfaces to communicate freely without restrictions (Shehzad et al., 2021).

Therefore the concept of interoperability is deeply intertwined with the management of project data in a CDE, with the goal to ease data exchanges and models accessibility between various construction domains. Interoperability entails the ability for different stakeholders to effectively communicate and streamline the flow of information between each another, which is essential in the digital age of construction and is considered a key to building business resiliency. A common data exchange (CDX) framework further allows project teams to define the interoperability requirements that will unlock machine learning and AI capabilities.

4.6.3.1 Industry Foundation Classes and openBIM

Software tools and systems communicate through common data formats and protocols, which requires the development of versatile standards. To improve data exchange between software products in the AECO industry, in 1994 several software vendors, users and public authorities founded the International Alliance for Interoperability, later renamed in 2003 as buildingSMART.

BuildingSMART aims to develop the standards necessary to allow an efficient exchange of data in the built environment sector, through a strategy defined as “openBIM.” The openBIM concept is essentially based on four elements: IFCs, BuildingSMART Data Dictionary (bSDD), Information Delivery Manual, and Model View Definition (MVD).

The standardization work carried out by buildingSMART primarily concerned the definition of a vendor-independent data format for exchanging comprehensive BIM models. This resulted in the definition of the object-oriented data model named IFCs, which very rich data structures cover almost all aspects of built facilities. In 2013, IFC was adopted as an ISO standard (ISO 16739) and today it forms the basis for many national guidelines that stipulate the implementation of openBIM. IFC is an openBIM data standard that can be exchanged and shared among the software applications used in a construction or asset management project. It is meant to save and exchange model and object data like walls, floors, doors, windows, etc. with all their real-live properties. This opposite to CAD file formats in which only the graphical entities (lines, arcs, fills, etc.) are identified.

In the IFC standard, each building object is linked to a Globally Unique Identifier (GUID) or Universal Unique Identifier (UUID). This, however, is not suitable for documenting issues or workflows. In recent years, indeed, it has become apparent that communicating about clashes and deviations in a model is extremely cumbersome and time-consuming: a specific object had to be communicated and shared with partners via IFC and each specific clash had to be described by telephone or with screenshots. In addition, each issue arisen during design reviews needed to be addressed by one of those team members.

For these reasons, in 2009 Solibri and Tekla Corporation conceptualized an open standard dedicated to enabling workflow communications between BIM software tools. Thus a XML schema, called Building Collaboration Format (BCF), was developed. BCF is a file format specific for communicating issues of a BIM model, which functions completely independently of the model itself. BCF allows to add textual comments, screenshots and tags on top of the IFC model layer for better communication between coordinating parties. The format is implemented as an XML file format (bcfXML), and a RESTful API network service (bcfAPI). BCF is designed to link BIM model checkers like Solibri with BIM AS tools like ARCHICAD, Tekla, and Revit. It primarily defines model views, then the related information on clashes and issues associated with specific objects in the view. BCF links with specific components of the model through their GUID. It allows to exchange comments and indicate the place to which they apply, their author and the time when they were posted. BCF consists of three parts: a screenshot, a camera angle and the list of objects from the BIM model that the issue is about. Like IFC, BCF is a BSI openBIM standard, where it is tasked with the important aspect of coordinating changes.

Equally important are MVDs, which define the IFC data model subset necessary to support the need for data exchange specific to the built environment sector throughout the life cycle of a project. In fact, the IFC schema was designed to cover many different configurations and levels of detail to support BIM interoperability across hundreds of applications, industry domains and regions around the world. The intent of MVD is to limit the amount of information extracted from an IFC file according to the actual requirements of the recipient and the specific workflow and stages of the process. MVDs give indications for the implementation of all IFC concepts (classes, attributes, relationships, property sets, quantitative definitions, etc.) used within a specific subset. This way, they represent the specification of the software requirements for the implementation of an IFC interface to meet the specific needs for data and information exchange.

As for bSDD, it is a protocol that allows the creation of multilingual dictionaries. It is a reference library intended to improve interoperability in the built environment sector (ISO 12006-3). Data Dictionaries can link together all existing and new databases and registries in the world, connecting all domains' terminology with internationally standardized and machine-readable concepts. Therefore they provide the ability to search information from around the world with a standardized interface, and can be used both to define unambiguous information flows with IFC files, and in direct communication with databases without the use of the IFC model.

Finally, IDMs provide detailed specifications of information needed for all processes in the project life cycle. They contain and progressively integrate the business processes of the built environment sector, and specify the nature and timing of the information that the various project team members shall provide during the project. In essence, the IDM ensures that data are communicated in an orderly manner and are interpreted by the hardware or software system that receives them in the intended way. A classic example is that of the calendar date format, where day/month/year order varies in different countries of the world.

4.6.3.2 *Construction operations building information exchange*

Another standard that contributes to the advancement of interoperability in the construction sector is COBie, although not formally part of ISO (Patacas et al., 2020).

COBie is a standardized approach that allows the integration of essential information into the BIM process to support operational activities, maintenance and property management of by the owner or asset manager. Specifically, COBie is an open data format for the publication of a subset of BIM data, focused on delivering asset data rather than geometric information. It is formally defined as a subset of IFC, but can also be conveyed using worksheets or relational databases (JRC, 2017).

COBie was first devised in 2007 by the United States Army Corps of Engineers (USACE) as a pilot standard to improve the process of information handover to building owners, occupiers and operators enabling them to manage their asset more efficiently. In 2008, it was revised to comply with international standards for data and classification and became the current COBie standard.

COBie helps to capture and record essential project data at the point of origin, including equipment lists, product data sheets, warranties, spare parts lists, preventive maintenance schedules, etc. It does not increase the need for information, but simply structures it in a more accessible format to make it easier to use and re-purpose by any organization, irrespective of size and IT capability. The simplicity of COBie enables all tiers of the supply chain to contribute to the data set, even if just by entering it directly into the spreadsheet. Such format also removes the client from unnecessary complexity, technology changes, interoperability problems and proprietary software issues.

Basically, COBie consists of multiple spreadsheets that document the attributes of the facility, its systems and assets, the details of each product type, warranties, maintenance requirements, technical and operational parameters, origin, price, date of installation, spare parts lists, inspection dates, etc. As the project progresses, specific items can be associated to additional attributes, issues and documents. Main COBie characteristics include the following:

- interoperability at the user level, as COBie data are accessible and understandable to any participants of the investment process and can be easily imported into facility management and CAFM systems;
- interoperability at the authoring level, as most BIM AS tools include the function of automatic generation of COBie files;
- openness, as COBie is compatible with the open IFC format;
- multidisciplinary, as data from COBie cover all disciplines within the object;
- possibility of applying various classification standards (e.g., Omniclass in the United States, Uniclass in the United Kingdom, or NS-3451 in Norway).

4.7 Conclusion and future trends

BIM represents an authentic revolution in the AECO sector, that is determining important effects along the entire value chain both in the approach to work and in the tools that can be used, paving the way for the use of artificial intelligence and automation (robots, digital fabrication, 3D printing, LiDAR, drones, etc.).

BIM constitutes the main pillar of the new Construction 4.0 framework, allowing the evolution from digital representation to virtual creation, thereby enhancing collaboration, creativity and knowledge sharing on every project. First of all, BIM changes the way assets are designed. Design with BIM is driven by data and verifications, becomes a real choral activity, and allows to explore and test more alternatives and anticipate errors. During the construction phase, BIM allows to plan, to better evaluate times and costs and to monitor the progress of the project. BIM also allows to work remotely and streamline corrections, and to use XR to match progress between the physical and digital worlds. In the operation and management phase, the BIM digital model powered by the data of its real twin enables optimization and predictive maintenance.

Several studies suggest that BIM contributes to important efficiency gains, lower costs, lower possibility of mistakes, faster delivery with less miscommunication, inaccuracies and delays, growing business opportunities and lower lifecycle emissions and waste. BIM implementation in construction projects can reduce overall costs by around 7%. Benefits are particularly concentrated in the construction stage, but can also be achieved in the other phases, such as a 15% saving in planning, risk assessment, safety and assurance costs, waste production reduced by up to 15%, and construction waste management costs by up to 57% (ECSO, 2021).

As with all revolutions, switch to BIM won't happen in one day. The conversion to BIM is neither simple nor immediate. In fact, it first implies a cultural transition that involves a different approach to the construction process, new IT software and hardware equipment, full proficiency with the tools, and the knowledge of the whole BIM ecosystem, that is, the technologies that support and are in turn supported by BIM. The maximum benefits are in fact obtained when BIM is used throughout the supply chain, from programming to maintenance, and when digital technologies are used from the start and are present in all phases.

This transition has already begun and is now firmly underway. To accelerate it, it is necessary to inform and train the actors involved, starting with university students, the future architects and engineers. In fact, BIM education cannot be delegated to self-learning as occurred until now with CAD tools, nor take place only in postgraduate training courses. Contrary to CAD, BIM is not simply a digital pen, but represents a virtual creation process in which disciplines of computer science, materials technology, building physics, design, and composition converge. Therefore a great learning effort is needed, which must necessarily be supported, guided and coordinated with all the other professional teachings. BIM learning must go hand in hand with learning all the other disciplines, supporting and being supported by them. More than merely acquiring computer knowledge, it involves the acquisition of a different way of thinking and working, a BIM oriented approach, which must be obtained from the very beginning in order for it to take root. This learning path, although certainly longer and more complex than that of CAD, allows to achieve important advantages both regarding the quality of the project and its representation.

On the one hand, in fact, the use of BIM, further enhanced by parametric design, allows to speed up project changes and the production of drawings (plans, sections, elevations). On the other hand, the virtual creation of the building through BIM allows a greater possibility of exploration and optimization of design alternatives (further amplified by the use of AI and virtual reality) and, ultimately, a greater understanding of the project and of the architecture in general.

BIM allows to fully develop all the logical and physical steps that range from concept to construction (geometric modeling, clash detection, materials selection, quantity take-off, scheduling, costs, life-cycle assessment), allowing at the same time a more close and profitable connection between design, production of materials and components (digital fabrication), and construction works (design for construction), ensuring the project is spot-on and fully responsive to requirements and needs.

Main emerging trends on the use of BIM regard in particular its combination with other digital solutions. For instance, the BIM model can be used to 3D print construction parts using various materials (design to digital fabrication), or can be integrated with information gathered through sensors to visualize architectural elements before building them (Virtual and augmented reality). Furthermore, GIS and parametric/generative design can be linked to BIM models for specialized usages. For instance, GIS allows for the integration of geospatial data into BIM models, and the use of parametric and generative design allows for real-time automated update and optimization of BIM design.

Future BIM developments will include the integration of real-time sensor data from smart buildings to create a fully functioning virtual living model of the construction, including information on the status of possible damage and malfunctioning (digital twin), bringing important developments also to BIM-based facility management (BIM 7D).

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Building performance simulation tools

5.1 Basic principles of building performance simulation

The digital simulation of the performance of the building or its parts (building performance simulation, BPS) has now become an essential activity within the entire building process—from design to operation—to achieve the highest quality of the construction work from a technical, environmental, economic, and social point of view throughout its whole life cycle (Chang, Yang, Yamagata, & Tobey, 2020; Clarke & Hensen, 2015; Hensen & Lamberts, 2011).

In the last two decades, with the increased demand of the global market for more efficient, comfortable, sustainable, and complex buildings, the number and degree of sophistication of the variables to take into account in building design, construction, and operation have grown significantly, to the point of requiring the full integration into the workflow of disruptive computational and simulation tools. BPS replicates building performances using a computer-based, mathematical model created on the basis of fundamental physical principles and sound engineering practice and, more recently, also on statistical and algorithm-based approaches. Initially dedicated only to the final phases of the design to support systems sizing, code compliance, benchmarking, or quality control, BPS has now expanded both to the early stages of design and postconstruction activities and today finds full application in the complete building life-cycle. Indeed, BPS allows to reduce environmental impacts, improves indoor quality and productivity, and facilitates future innovation and technological progress in construction. An optimal design and management of buildings have in fact to consider multiple, and usually competitive, objectives such as energy efficiency, internal comfort, users' preferences, safety, and reduction of financial costs and environmental impacts. This implies to operate following a “data-driven approach” within a continuous feedback loop between design and analysis, trial and error, based on technical simulations of aspects such as daylight, sunshine, thermal exposure, airflow, turbulence, wind, space syntax, traffic flow, etc. BPS is also an important stimulus to the identification of innovative solutions, allowing not only to obtain higher performance but also helping to create new and more innovative architectural languages in continuous evolution.

The rise of BPS stems directly from the wider diffusion of building information modeling (BIM) and the wider availability of accurate BPS software tools, which have seen continuous development over the last decades and have now reached the level of maturity, flexibility, and ease of use that allows their full integration into the architecture, engineering, construction, and operation (AECO) sector. Indeed, model-based design such as BIM entails the creation of a digital representation system that allows rapid analysis and comparison of design alternatives, communication and visualization of information, easy alteration, and management of changes. The 3D BIM model and the information and data associated with it can be easily used for simulations and analyses, aimed at verifying and optimizing the effect on performances of design and operation choices (6D and 7D BIM) (see Section 4.2.3).

Some software tools only cover certain parts of BPS (e.g., climate analysis, thermal comfort, energy calculations, plant sizing, and daylight assessment), whereas others can simulate the different domains acting on the building and their mutual interaction (whole-building simulation) and provide key performance indicators (KPI) such as overall heating and cooling loads, energy demand, ecological and economic impact, visual and thermal comfort at the single room or building level. Required inputs for simulation and possible outputs are largely variable between the different BPS tools and their application at the design stage (e.g., early-stage simulation, system sizing, and code compliance assessment), as the ease of input and the accessibility of output data.

BPS takes as inputs the characteristics of the building, which may include geometry, orientation, construction materials, electro-mechanical systems, water heating configurations, and renewable energy generation systems, as well as occupancy schedules and operation patterns of plug loads, lighting, and heat, ventilation and air conditioning (HVAC) systems. The physics equations of the building systems are then combined with outdoor weather conditions to output numerical values for the requested indicators, which may relate to building's energy flows and energy consumption, peak loads, carbon emissions, energy generation, daylighting availability, or occupants' comfort conditions (Azar et al., 2020).

Particular attention must be given to the choice of input parameters relating to the occupancy, behavior and preferences of users, which values may greatly influence the actual performance of buildings. Main input and output data are reported in [Tables 5.1 and 5.2](#).

In the last decade, in addition to more consolidated physics-based BPS, statistical and algorithm-based tools have been researched to propose an alternative method to predict the future behavior of buildings in the design and operation phase. These methods take advantage of the availability of a wealth of data concerning building design and operation (Big Data) as well as advanced artificial intelligence (AI) and machine learning (ML) techniques to draw correlations between inputs from the projects and expected performance in operation and to extract interrelationships and patterns of interest from a large database. Data mining-based energy modeling could help project teams discover useful patterns to improve the efficiency of building (Architectural Intelligence). Big Data used for ML includes local and global weather

TABLE 5.1 Main input parameters for building performance simulation.

Domain	Input parameter
Climatic context	Ambient air temperature, humidity, direct and diffuse solar radiation, wind speed and direction, yearly rain and snow indexes
Building site	Building location and orientation, shading by topography, surrounding buildings and vegetation, ground properties
Geometry	Building shape and zone layout, modeled in-software or imported from 2D CAD or 3D BIM models
Materials	Construction characteristics for each surface and layer, windows properties, thermal bridges
Activity and occupancy	Intended use of the building, people occupancy, clothes and activity, light density, plug loads, gas loads (cooking, etc.), steam loads, water using equipment, ventilation requirements, infiltration
HVAC	Specification of hot, chilled, and condenser water systems, air systems, zone-level heating and cooling, boilers and chilled water storage
Lighting	Electrical lighting fixtures, windows parameters, shading devices
BAS	Control systems and logics for HVAC, temperature set points, window opening, shading devices with sensors and actuators

TABLE 5.2 Main output parameters from building performance simulation.

Domain	Output parameter
Thermal balance	Temperature trends in zones, on surfaces, in construction layers or in double glass facades, hot or cold water supply, heat balances for the whole building, single rooms or zones, or single plant components, internal gains
IEQ	Temperature distribution curves, PMV/PPD, radiant temperature asymmetry, CO ₂ , humidity, underheating and overheating hours distribution curves.
Energy load and consumption profiles	Load profiles for heating and cooling energy demand, electricity profiles for HVAC, equipment, lighting, auxiliary systems, demand/response simulation, on-site energy generation
Daylighting	Daylight availability at different time points with variable outside conditions, illuminance and glare calculations, artificial lighting calculation
CFD analysis	Natural/artificial ventilation, wind loads, pressure and flow lines visualization, contaminants distribution
Building systems design	HVAC, PV, thermal systems autosizing and design support
Traffic and pedestrian patterns	Outdoor and indoor traffic and pedestrian simulation, emergency egress routes, rooms, and corridors sizing
Life cycle cost	Full life cycle costing including fuel escalation rates and inflation, capital, recurring O&M, salvage, and replacement costs
Code compliance	Performance-based verification of compliance to building codes or sustainability programs, tax returns/incentives eligibility check

data, building codes and historical data, databases developed by societies, research groups, and commercial companies (e.g., ASHRAE, LEED, DoE, etc.) related to energy research and sustainable architecture, as well as data mined from building-integrated sensors and Internet of Things (IoT) devices already on the field (Mehmood, Chun, Hyunjoon Han, Jeon, & Chen, 2019). Today statistical methods find their greatest use in the early stage of building design when, by definition, the descriptive data of the building and its systems are not yet available, or in the building management phase as tools for controlling the performance of building automation systems (see Section 10.4). During design development, although statistical methods offer good accuracy, their usefulness is still debated as they lack analytical correlation between single inputs and outputs and are therefore less scalable compared to conventional physics-based BPS tools, for instance, to perform sensitivity analyses of how a specific design choice affects determined building metrics.

5.1.1 Building performance metrics

Using significant performance metrics able to evaluate and control the design solutions since the early stage represents today an essential element in ensuring the final quality of any building project (O'Brien et al., 2017).

The performance indicators can relate to a single space or to the entire building and can refer both to the operating modes (energy consumption, polluting emissions, costs, etc.) and to the indoor environmental quality (IEQ) for the occupants, i.e. occupant-centric metrics (thermal and visual comfort, noise, etc.). For benchmarking purposes operational building performances are commonly normalized using building-centric quantities such as the building's gross volume, the net, gross or treated floor areas, or the façade surface.

Following is a summary of the main building performance metrics which can be commonly provided by BPS software and can be used as KPI in the design phase (see Table 5.3).

5.1.1.1 Building energy performance and emissions metrics

Energy use intensity (EUI) indicates a building's annual energy use per unit area and is typically measured in kWh/m²yr. It is a baseline and widely used benchmark that allows to compare at a glance performance of buildings across sizes, types, and locations and is used by most building codes and sustainability programs, which have specific EUI goals for different building types. As a performance metric, EUI can be used to set objectives for the design and to understand via simulations whether the building's performance is good or bad relative to one's target or to other similar buildings. EUI can be calculated either limited to the building's boundary, without taking into account the inefficiencies associated with the creation, transportation, and distribution of electricity and fossil fuels (EUI_{site}), or including these additional energy processes (Primary Energy Intensity or EUI_{source}). The latter metric is that commonly referenced for code ZEB definitions.

Annual carbon emissions measure the carbon emissions associated with a building's energy consumption, calculated as CO₂/m²yr. Carbon calculation, however, depends on the carbon intensity of each fuel, which in case of electricity

TABLE 5.3 Main metrics of building performance.

Building performance	Metric	Units
Energy demand	Energy use intensity (EUI)	kWh/m ² yr
	Peak heating/cooling load	kW
	Annual operating costs (AOC)	\$/yr or \$/m ² yr
CO ₂ emissions	Annual carbon emissions (ACE)	CO ₂ /m ² yr
Thermal comfort	Predicted mean vote (PMV)	PMV index between (-)3 and 3
	Predicted percentage of dissatisfied (PPD)	%
Visual comfort	Uniformity ratio (UR)	%
	Useful daylight illuminance (UDI)	%
	Spatial daylight autonomy (sDA)	%
	Annual sun exposure (ASE)	%
	Daylight glare probability (DGP)	%

refers on the mix of power sources in a region. Other noncarbon greenhouse gasses (e.g., methane) are assigned a standard carbon equivalency, so the end result is in terms of carbon. Some codes and standards use a zero carbon metric, rather than a zero energy metric. Annual carbon emissions can be used in design to get a quick idea of how design options compare to one another similar to EUI.

Annual operating costs refers to the annual utility costs incurred for operating a building, in terms of electricity, fuel, and water, measured in bulk or divided per floor area. This metric is important for evaluating payback period of energy efficiency measures, as well as calculating ROI and life cycle cost (LCC), and is significant to building owners who are looking to reduce operating cost. Operating costs can be simulated or calculated to demonstrate the benefits of different design options and optimizations, and several BPS tool use response curves to identify strategies that minimize operating cost.

Among these metrics, EUI is the most familiar with design teams and is often the benchmark for specific building targets. However, to understand EUI, it is necessary to dive deeper into the energy use data to determine what is driving it, and it is important to always consider EUI against other indicators to get the whole picture, as lower EUI values do not always translate to lower costs, emissions or better comfort conditions. In particular, operating costs and emissions are closely related to the price and carbon intensities of the fuel used on site (e.g., gas or electricity); hence, a solution with slightly higher EUI may at the same time yield lower cost and emissions in terms of €/m²yr or CO₂/m²yr. Furthermore, EUI is normalized per floor area, thus it inherently tends to favor solutions which spread the same energy use on a greater area, for instance with unoptimized layouts of circulation or support spaces (bathroom, corridors, etc.). An architectural solution with better Building Efficiency Ratio—net lettable area to gross floor area—can result in savings in upfront capital costs and ongoing energy costs, even if the associated EUI is slightly higher.

Another important energy performance metric is peak heating/cooling load, which indicates the amount of heat that needs to be added to or removed from a space to maintain the desired temperature in the most severe condition over the span of a year and is measured in kW. Peak heating/cooling load typically dictates the size of HVAC systems, thus reducing this metric allows smaller, less expensive HVAC system, more leasable square footage, and more options when it comes to system selection. Peak loads can be used as an early proxy for predicting systems size and cost, and as an indication of the effectiveness of passive design strategies (e.g., shading devices).

5.1.1.2 *Occupant-centric performance metrics*

As stated earlier, occupant-centric building performance metrics effectively complement conventional building performance metrics and provide insight and guidance on the future satisfaction and well-being of occupants which in turn dictate the quality and success of the building process (see [Table 5.3](#)).

Thermal comfort of occupants is traditionally tricky to quantify empirically, as it is primarily assessed by subjective evaluation (e.g., occupant surveys). In practice, empirical models are used to predict the human perception of thermal comfort based on physically observable qualities. Most used method is Fanger's model of thermal comfort, introduced in the 1970s, which expresses human thermal sensation based on environmental (air temperature, radiant temperature, airspeed, humidity) and personal (metabolic rate, clothing insulation) factors according to the steady-state heat balance principle ([Azar et al., 2020](#)). Thermal comfort is expressed through the Predicted Mean Vote (PMV) and the Predicted Percentage of Dissatisfied (PPD) indexes which can provide a global estimation of thermal sensation and acceptability of indoor environmental conditions by a large group of people. Being quantified deterministically via equations, PMV/PPD indexes can be provided by most modern BPS tools, on the hypothesis that operating conditions of subject environment are relatively constant because they are highly correlated to activity level (METs) and operative temperature. Nevertheless, the accuracy of PMV-PPD model in predicting thermal comfort has been questioned through field studies in real buildings as well as in laboratory studies, concluding that acceptable indoor temperatures are often underestimated ([Cheung, Schiavon, Parkinson, Li, & Brager, 2019](#)), leading to narrow temperature prescriptions that are energy-intensive to maintain.

An alternative approach is presented by adaptive comfort models, which instead express acceptable indoor temperatures based on prevailing outdoor temperatures taking into account the human's ability to adapt to variable environmental conditions in naturally conditioned buildings. Adaptive comfort models are suited to support passive design strategies or mixed-mode operation, which often allow a wider range of temperatures than those accepted by the PMV/PPD model.

Visual comfort refers to the personal well-being of occupants as induced by their visual environment and depends on several connected aspects, from the physiology of the human eye, to the amount of light and its distribution in space, and the spectral emission of artificial light sources. The renewed interest of harnessing daylight in building stems from

its inherent pleasantness for occupants and the positive effect of natural light on users' well-being and circadian rhythm, in addition to the achievable saving in energy spent for artificial lighting. To keep track of the visual quality and comfort of the building during the design phase, several performance metrics have been developed, which can be used to assess both the potential of exploiting natural lighting and how to complement it at best with artificial fixtures. The range of daylight and artificial lighting-related metrics will likely evolve as new building regulations become more energy-conscious and more considerate to the well-being of building occupants.

Illuminance is the baseline photometric term that measures light incident on a surface, which is benchmarked against code targets to ensure adequate illumination and safety for different occupants and operations. Illuminance is expressed in lux (lumens per square meter) and can include contributions from both electric light and daylight. For instance, worldwide occupational Health and Safety administrations prescribe minimum illuminance levels for workplaces, ranging from 300 to 500 lux on desks, and LEED requires to demonstrate daylight illuminance levels between 300 and 3000 lux for each regularly occupied space.

Uniformity ratio (UR) is the ratio of minimum illuminance to average illuminance within a given room, and may refer to both artificial lighting and daylighting (Lee, Boubekri, & Liang, 2019). For side-lit rooms, uniformity should be in the range of 0.3–0.4, whereas in top-lit spaces, such as atriums, a uniformity of 0.7 could be expected. For instance, a working environment with a 0.6 ratio is one in which people do not notice different lighting levels with the naked eye and perceive an environment in which light is well-distributed.

Useful daylight illuminance (UDI) refers to the annual occurrence of daylight that is within a “useful” range for occupants. UDI is a dynamic (climate-based) metric which is derived from yearly illuminance levels under real sky conditions. Results in literature agree that a point is considered to receive good daylighting if the illuminance level is between 100 and 2000 lux for at least 50% of the time occupied time. Illuminance levels above 2000 lux represents excessive amounts of daylight and a source of glare, forcing the use of blinds, whereas insufficient UDI (e.g., below 100 lux) represents lighting levels that are considered insufficient without electric lighting (Berardi & Anaraki, 2015).

Spatial Daylight Autonomy (sDA) describes how much of a space receives sufficient daylight throughout the year. More specifically, sDA measures the percentage of floor area that receives a minimum illumination level for a minimum percentage of annual occupied hours—a common standard refers to the area that receives at least 300 lux for at least 50% of occupied hours and is notated as $sDA_{300/50\%}$. The sDA index is used in some sustainability programs as a daylight harvesting metric: for instance, LEED v4 awards credits for $sDA_{300/50\%}$ of 55% and 75% for regularly occupied floor area. This index is a climate-based daylighting metric and its simulation requires a location-specific weather file, returning a good predictor of actual as-built daylight performance which can be used to assess the right amount and location of glazing in the building, the optimal floor-to-floor heights, and best floorplate depths.

Annual sun exposure (ASE) measures how much of space receives too much direct sunlight, which can cause visual or thermal discomfort, as the percentage of an area that exceeds a specified illuminance level more than a specified number of hours. Commonly, ASE measures the percentage of floor area that receives at least 1000 lux for at least 250 occupied hours per year ($ASE_{1000,250}$). As sDA, ASE metric is increasingly featured in sustainability programs—LEED awards points for daylight only when $ASE_{1000,250}$ is 10% or less for regularly occupied floor area. From simulations, ASE can be an early indicator of whether there is too much direct sunlight in a current design, which can be reduced by correcting window to wall ratio (WWR), adding shading devices, or reducing visible light transmission (VLT) of glazing.

Daylight glare probability (DGP) is a visual comfort metric introduced to effectively predict the discomfort caused by glare in daylit spaces. The metric was developed in 2006 on the basis of both photometric measurements and occupant survey and has displayed good accuracy, particularly when compared against older glare metrics such as unified glare rating (UGR), daylight glare index (DGI), CIE glare index (CGI), and visual comfort probability (VCP) (Chaloeytoy, Ichinose, & Chien, 2020). DGP is equation based and can be calculated by several BPS programs. Commonly used DGP ranges are imperceptible (below 35%), perceptible (35%–40%), disturbing (40%–45%), and intolerable glare (over 45%) (Wienold, 2009).

5.1.2 BPS applications

BPS can find application in the complete building life cycle, from conception to demolition, although currently its main scope is to provide better support for the design of buildings, and for building operation and maintenance in the use phase (Hensen & Lamberts, 2011).

In particular, both the rise of innovative technologies and materials and the increased awareness of the multifaceted effects that context and use cases have on buildings' performance have transformed the building design process into a

much more complex and multidisciplinary effort, in which traditional approaches based on designer's experience and "Rule of Thumb" are proving unsuited to achieve the current objectives of building quality and efficiency. The design team must try to optimize a large number of criteria, such as energy demand, indoor environment, materials, LCC, etc., which are often conflicting. Only the integration of BPS into all phases of the design process, from planning and programming, to early-stage decisions, up to systems sizing and energy code compliance verification, can allow to implement the informed and performance-based design approach that enables optimization of all factors and requirements. Once the building is operational, BPS finds application as a tool to enable predictive control of the building's systems.

5.1.2.1 Early-stage simulation

Concerning the first stages of design, these are currently underrepresented in BPS use workflows and still rely on intuitive decisioning. However, supporting decision-making and guiding the design toward high performance is of utmost importance in the early design phase where decisions have the highest impact on final performance and costs. In fact, narrowing the consequences of early decisions is crucial, as uninformed decisions may reduce the remaining design space and make it more strenuous and expensive to meet high performance goals (Østergård, Jensen, & Maagaard, 2016).

For starters, specific software such as ClimateTool and Climate Consultant can provide detailed climate analysis for most locations worldwide. These tools allow the evaluation of different building concepts for any climate and location, and are specifically intended to be implemented at the concept development stage.

Using BPS, the right analysis at the right time can provide key insights and timely feedback on performance implications. Simulation results at this stage shall be proactive rather than only evaluative, that is, shall allow to compare and rank multiple design variations to understand and suggest how to steer the design decisions. Although consolidated BPS software is sophisticated, accurate, and capable of assessing a wide range of different performance indicators, it is often most suitable for code compliance, benchmarking, and quality control. Specific BPS tools have therefore been developed with a focus on early-stage design support (Trimble Sefaira, Autodesk Insight, Cove.tool, etc.), often integrated or available as plug-ins for main 3D sketching, massing, and conceptual modeling tools or BIM authoring software such as Revit, SketchUp, Archicad, or Rhinoceros.

Before starting the actual building design, available information about the project, such as its site, program, areas, likely number of stories, can already provide valuable insights into how the building is likely to perform. The simplest way to inform early design thinking is to start from a basic box model with the correct square footage, space uses, and location, on which to run preliminary energy analysis. First results can help to contextualize the likely load profile of the building, whether it is dominated by internal loads such as lighting and equipment, or by external loads such as solar gain or conduction losses, or if heating or cooling is more important. This information begins to suggest which design strategies are likely to be the most impactful and can help to shape early design concepts.

Following is the evaluation of the different massing options, design concepts, or facade variations, conducted through schematic design and performance reports: comparisons of energy, daylight, comfort, or cost predictions can help the design team understand the advantages and liabilities of each concept, steering the design in the right direction (see Fig. 5.1). In this phase, parametric design can be integrated effectively with building performance analysis procedures, allowing to test rapidly multiple design variables without excessive remodeling, creating a more cohesive and effective design process (Aksamija, 2018). Building performance indexes to be extracted and compared should be identified carefully, as many factors can drive design decisions and understanding why some options perform worse than others, and how those problems can be addressed in following design activities, is a key part of informed decision-making and helps to avoid more costly issues down the road. In particular, this stage of design is where passive design solutions can be most effectively integrated. Opportunities for natural ventilation, ratio of operable glazing, impact of shading and WWR ratio on year-long comfort conditions, and several other questions can be investigated even with simple 3D study models to obtain early recommendations on passive design decisions. Parametric design and optimization are investigated more thoroughly in Chapter 6.

Equally important in this stage is the opportunity to start reducing the peak heating and/or cooling loads of the building, with the objective of both reducing the size and cost of a project's mechanical systems, and to expand the system options available for a project. Peak load analysis can help identify location, date, and causes of worst peak loads, allowing to address them granularly. Moreover, in many types of buildings, certain envelope improvements that have a small impact on overall energy use may have a big impact on peak loads. Schematic HVAC options can be integrated in the study models to see how different systems interact with load reduction strategies, leading to the optimal HVAC and envelope combination.

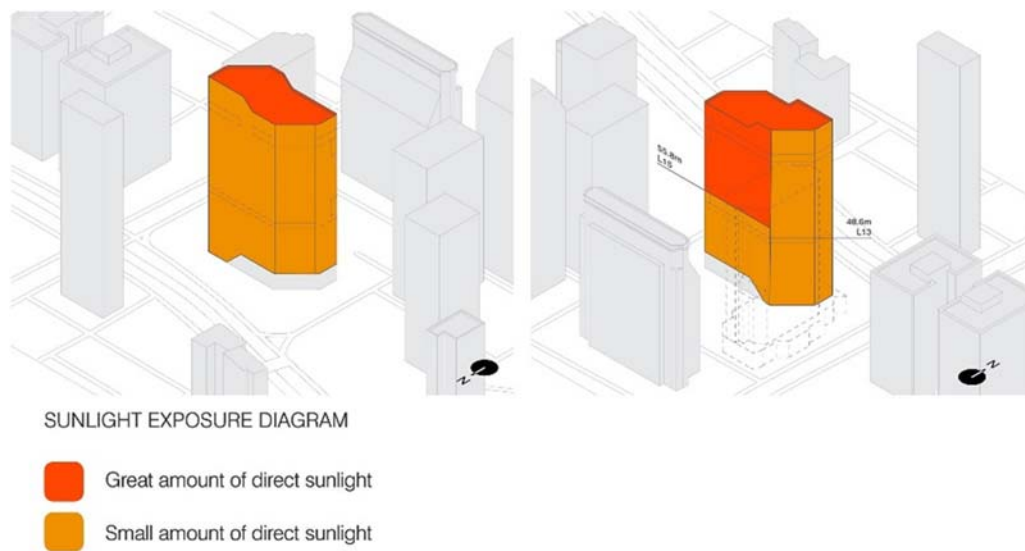


FIGURE 5.1 Sunlight exposure study. Courtesy of UNStudio.

Comparative analysis software such as Edge App or RETScreen can be used to calculate the cost-effectiveness of energy-efficient measures against a base case. These tools are suitable for early-stage modeling to test different building design concepts and can assess the ecological and economic savings of default energy efficiency measures regarding energy and water use as well as embodied carbon. A dashboard shows the extra costs to build green and the time it takes to earn back the money through operational savings, for multiple worldwide locations.

A specific application of early-stage simulation concerns the investigation of urban microclimate effects as dictated by interventions at the district and city-wide scale. The significant advances in computational resources of the last decades have considerably enhanced the application of numerical simulation approaches involving both computational fluid dynamics (CFD) and thermal energy balance models to assess the complex interactions between the urban fabric (i.e., buildings and ground surfaces) and local weather parameters. Such models would ideally consider direct, diffuse, and reflected solar radiation, airflow patterns, heat transfer from the urban surfaces to the air, heat island effects, vegetation, as well as anthropogenic heat emitted from the traffic and air-conditioning waste heat.

CFD in particular can be effective in analyzing the current wind movements in the intervention site and in predicting how these will affect and be affected by the various solutions under consideration during early-stage design, instead of resorting to expensive and time-consuming experimental approaches (field measurements and tunnel tests). In fact, predicting the actual wind loads and the performance of constructions in advance will ensure structural and shape choices will ensure the comfort and safety of people at minimum cost. CFD tools, such as cloud-based SimScale, allow to evaluate not only wind flows over the constructions but also the bending and the twisting phenomenon on the structures (see Fig. 5.2). Moreover, these allow pedestrian wind environment simulations which become a critical factor in urban design, helping to ensure the overall well-being, safety, and comfort in pedestrian zones in today's complex urban fabrics.

One of the most widely employed dynamic simulation tools for microclimate analysis is the ENVI-met model (Tsoka, Tsikaloudaki, & Theodosiou, 2018), a program which can simulate climates in urban environments and assess the effects of atmosphere, vegetation, soil, architecture, and materials (see Fig. 5.3).

Main results obtainable from ENVI-met simulations include solar analysis (sun and shade hours, glazing analysis, shadow casting, solar energy gain), air pollutant dispersion (emission and transport of particles and gases, chemical reactions between NO_x , ozone and VOC, deposition on plants and surfaces, traffic emission profiles), building physical metrics (façade temperatures, exchange processes with vegetated walls, interaction between the outdoor microclimate and the indoor climate, water and energy balance of living wall systems), green and blue technologies (effects of façade and rooftop greening, impact of green spaces and bodies of water, simulation of living walls, air cooling through water spray), wind flow (wind patterns in complex environments, wind speed around buildings and trees, wind comfort), outdoor thermal comfort metric (air temperature, radiant temperature of surrounding surfaces, air movement in the vicinity of the body, relative humidity), vegetation (analysis of plant growing conditions, simulation of wind stress and tree damage, simulation of water usage).

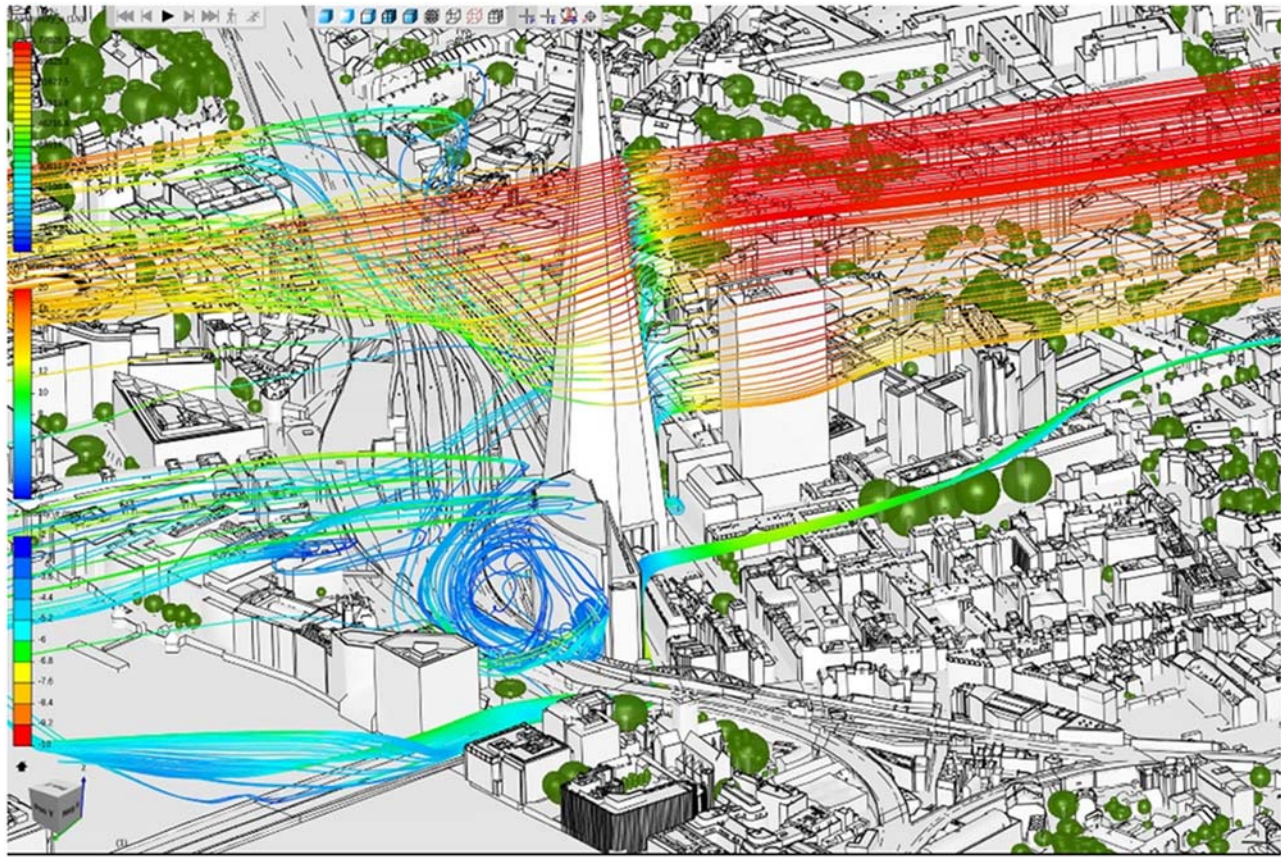


FIGURE 5.2 CFD local wind analysis for The Shard. *Courtesy of SimScale.*

5.1.2.2 Systems sizing

BPS tools commonly predict the energy performance of the building annually; however, software focused on system sizing, especially HVAC, base their calculations on the worst case scenario to enable the selection of the HVAC equipment size (design tools), then design the related MEP systems accordingly. Typically, the HVAC equipment is sized based on summer and winter design days that define the extreme conditions for the building, based on static calculations.

Conventional annual simulation tools (Trnsys, EnergyPlus) predict the annual energy performance of a building and its HVAC system, and often include a sizing functionality. These software are less streamlined and may require additional expertise and some trial and error to get the results but can predict differences in energy consumption for different design alternatives and typically include dynamic calculations based on various thermodynamic equations.

Overall, BPS workflow for system sizing can follow two levels of simulation detail:

- Level I: simulation mainly of the building envelope with simplifying assumptions regarding operation of the HVAC equipment;
- Level II: detailed transient simulation of the building envelope and the HVAC equipment and its control.

Due to increased complexity and need for additional performance and control system data, most designers employ the first approach; however, simulations of the “typical day operation” shall be carried out with advanced HVAC control system modeling to allow realistic prediction of yearly heating and cooling energy costs of different solutions.

A common approach involves the initial sizing of a basic HVAC equipment according to established industry standards such as DIN 4701, then a preliminary run of level I simulations with the actual shape and envelope configuration of the building. These produce the heating and cooling peak loads, which at a glance can be compared to the presized plant. In addition to the peak loads, it is useful to study the transient variation of loads during the cooling and heating seasons: by examining the whole season load trends, one can identify how many instances of higher loads occur, which

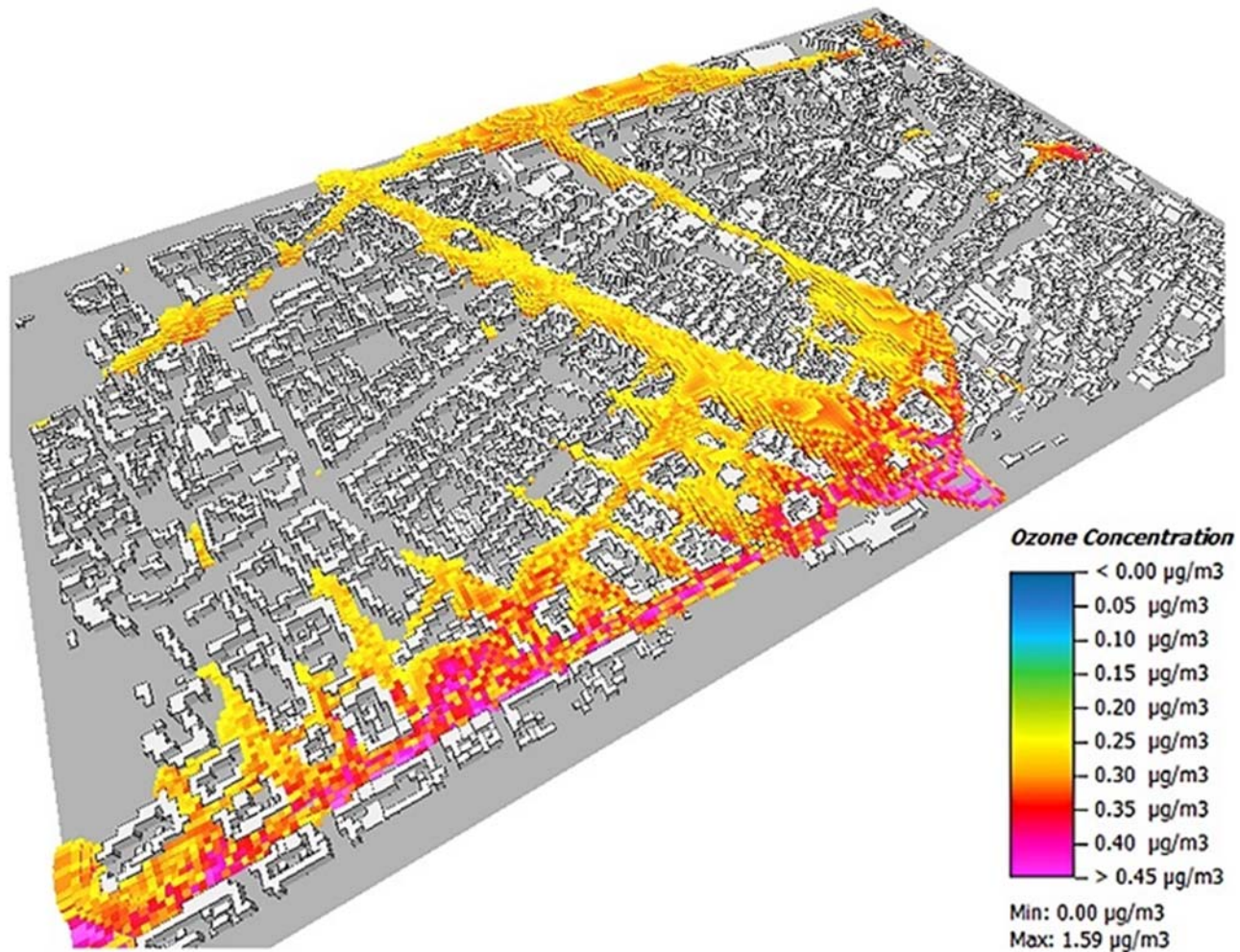


FIGURE 5.3 Ozone concentration analysis. *Courtesy of ENVI-met.*

factors drive them, and enact design changes to reduce those—for example, by minimizing the percentage of outdoor air, shutting off air-conditioning in unoccupied spaces, or changing envelope or shading configurations.

Level II simulations requires a much more detailed HVAC system, which can therefore be sized and configured in all its components (Boiler/chiller, cooling and heating system, control settings, ventilation strategy, supply fans, duct-work, and piping). Level II simulation can be readily employed to support heating equipment size optimization, for instance, by accurately linking performance and cost of undersized, correctly sized, and oversized generators over annual, monthly, or even hour energy loads. As a rule of thumb, building HVAC systems designers tend to overdimension the equipment, a practice that penalizes operation expenses, as well as installation and maintenance costs. “Level II” systems simulations allow optimal sizing of the equipment with good estimates of percentage of failure to cover heating and cooling load peaks (Zogou & Stamatelos, 2009).

In addition to these iterative HVAC sizing workflows, BPS tools such as Carrier HAP or TRACE 3D + use a system-based approach to design calculations, which tailors sizing procedures and reports to the specific type of system being designed, such as variable refrigerant flow (VRF), central air handling units (AHU), hydronic fan coils, ground source heat pumps (GSHP), water source heat pumps (WSHP) etc. This offers a more streamlined operation compared to load calculation programs, which require the engineer to apply calculation results to size system components. These programs provide features for quickly designing VRF, fan coils, WSHP, and GSHP systems, batching sizing results for many zone terminals in a single report and calculating required space, zone, and system airflow rates according to the specific system type, up to component loads, hourly load profiles, hourly performance data, and psychrometric charts.

These tools provide preconfigured building themes and preloaded and scalable libraries and templates, often from different manufacturers, and often feature wizards to configure systems and plants schematically. More evolved

products have built-in validations and intelligence based on systems knowledge to provide early detection of potential problems in the design, with defaults preprogrammed into the software to reduce errors and save design time.

Easiest line of work is to start from predefined prototype systems provided by the software, which are autosizable with respect to zone- and system-level equipment and controls. Both BPS levels are required in sequence to fully auto-size the system, with opportunity for user intervention between the two, and can also be applied to user-modified variants of prototype systems.

Finally, specific tools exist for certain HVAC and MEP applications such as photovoltaic and solar thermal systems, piping, ductwork, or geothermal loops design.

PV design tools (PVsyst, Bluesol) support a range of design activities, from array-system predimensioning to specification of all system subcomponents. Built-in wizards require the user to only input the location (from PVGIS or NASA databases), desired power or available area, and choose PV modules and inverter from the internal database to propose a system configuration and conduct preliminary simulations. Common features at this stage include automatic string insertion with optimal filling of areas, automatic insertion of inverters, panels, batteries and connecting cables, automatic predimensioning of electrical components, and microinverter management. The prototype project can then be modified in each part to obtain the desired configuration, with the embedded warning/errors messaging system highlighting possible mismatches and issues. Provided tools enable the evaluation of the wiring losses (and other losses like the module quality), far and near environmental shading, the mismatch between modules, ageing and soiling, thermal behavior according to the mechanical mounting, system unavailability, etc. These software allow to design both grid-connected and stand-alone systems, with a range of PV products and technologies (crystalline, thin-film as well as bifacial panels). Battery storage can be either AC-coupled or DC-coupled and can be optimized for enhancing the self-consumption of the PV system owner, for ensuring peak shaving when the possible power injected into the grid is limited, or for the continuity of the user's electricity feeding when the grid is weak and often unavailable. Simulation outputs include visual diagrams of total energy production (MWh/yr), performance ratio [PR (%)], specific energy (kWh/kWp), and energy gains/losses throughout the year, as well as the I/V curve of the PV array, together with the MPPT range, voltage, power, and current limits of the inverter. Lastly, economic evaluation tools calculate CAPEX (installation cost), OPEX (operating costs), yearly balance, payback period and return on investment rate according to defined feed-in tariffs, selling policy, and parameters for self-consumption economy.

Polysun is another simulation program which in turn allows to design and dimension solar thermal, photovoltaic, hybrid, heat pump and systems, as well as combined systems. The system designer can use and edit one of the preconfigured systems or create new systems by combining components from the built-in database such as storages, pumps, collectors, and pipes or designing arbitrary hydraulic topologies is especially useful for process heat applications. It is particularly suited for designing and sizing hybrid PV/thermal systems (see [Section 12.3.1.1](#)).

Transol is a tool for the design, calculation, and optimization of solar thermal and hybrid PV/T systems. It performs dynamic simulation based on TRNSYS engine, through a user-friendly interface. Within PV/T field it can be used for fast thermal performance determination at the system level, as it offers a wide range of installations as well as hourly energy data.

Ductwork design tools (VariTrane Duct Designer, IES VE IndusPro) focus on streamlining air ducts design by quickly sizing system components, determining the appropriate nominal duct size for equal friction applications, and identifying the optimal fittings and sizes for each duct section by comparing their efficiency and cost, allowing to optimize the design to obtain a minimum pressure system. These software are commonly based on engineering, procedures and tested data from code databases such as ASHRAE and United McGill.

Pipe design software (Trane Pipe Designer, IES VE PiscesPro) can be used to determine required pipe sizes, find the critical path for proper pump sizing, calculate pressure drops through valves/fittings or from elevation changes, and create bills of materials.

5.1.2.3 Life cycle analysis

Life cycle analysis (LCA) is a methodological framework regulated by ISO 14040 for estimating and assessing the environmental impacts attributable to the life cycle of a product, including the sourcing of raw materials, manufacturing, distribution, transportation, and end-of-life disposal. Applied to the construction sector, LCA can allow to understand the energy use and other environmental impacts associated with all life cycle phases of the building: procurement, construction, operation, and decommissioning.

LCA can be used in all different stages of construction decision-making, from city planning to architectural design, structural design, building commissioning up to the operational phase and building decommission and deconstruction. It

can be used to set impact targets, verify the results after the process, and learn from past cases. Concerning the design process, LCA can be applied at any stage, from programming and conceptual design to detailed development and can prove particularly helpful in supporting the following activities:

- optioneering building design alternatives and various building structural systems, assemblies, and products;
- identifying products, assemblies, or stages of building life cycle causing the maximum and minimum contribution to the overall environmental impact;
- mitigating impacts targeted at a specific environmental issue.

In particular, during the programming and early-stage design, LCA can help define the environmental goals of a project. LCA can be used to evaluate the building footprint among several options, or to steer basic decisions on the structural system. Trade-offs between impacts from the construction phase and operational phase can be evaluated to select assembly types. At the schematic design stage, LCA can support the selection of building products and assemblies and the assessment of energy conservation measures and environmental burdens. Finally, in detailed design LCA can help evaluate the life-long impacts of proposed lighting and HVAC systems or compare material finishes. The most crucial stages in a system's life can be identified in terms of environmental impact, and appropriate modifications to the system design can be proposed.

In the EU, the specific requirements for LCA in the construction sector are found in the CEN standard family TC/350 Sustainability of Construction Works, and in EN 15978 Sustainability of construction works—Assessment of environmental performance of buildings—Calculation method. Also, the EN 15978 standard is used in almost all of the Green Building certification systems in Europe and outside Europe, including LEED (United States), Green Star (Australia), and Konut (Turkey). In addition, the ISO 21930 Sustainability in buildings and civil engineering works is at the moment being aligned with the EN standards.

According to EN 15978, the building's life cycle can be broken down into five main stages (see [Table 5.4](#)): product stage (A1–A3); building construction stage (A4–A5); use stage (B1–B7); end of life (C1–C4), and benefits and loads beyond the system boundaries (D).

The product stage (A1–A3) includes extraction of raw materials, transportation of these materials to the manufacturing location, manufacture of finished or intermediate materials, fabrication of the building product, packaging and distribution.

The construction stage (A4–A5) covers the processes from the factory gate of the different construction products to the practical completion of the construction works. Typically, the following activities are included in this stage: transportation of materials and products to the project site, use of power tools and equipment during construction of the building, on-site fabrication, and energy used for site work.

TABLE 5.4 Stages of building life cycle.

Life cycle stage	Phases
Product	A1 raw materials supply extraction and processing A2 transport A3 manufacturing
Construction	A4 transport from the gate to the building site A5 construction-installation
Use	B1 use B2 maintenance B3 repair B4 replacement B5 refurbishment B6 operational energy use B7 operational water use
End of life	C1 deconstruction and demolition C2 transport C3 waste processing C4 disposal
Benefits and loads beyond the system boundaries	D reuse—recovery—recycling potential

The use stage (B1–B7) covers the period from the practical completion of the construction works to the point of time when the building is deconstructed/demolished. The system boundary includes the energy used by building-integrated technical systems during the operation of the building; all water used and its treatment (pre- and post-use) during the normal operation of the building (excluding during maintenance, repair, replacement, and refurbishment); the use of construction products and services for protecting, conserving, moderating, or controlling the building; scenarios for maintenance including cleaning, operation, and replacement of machinery; impacts and aspects of the building-integrated technical system and building-related furniture, fixtures, and fittings.

The end-of-life stage (C1–C4) of a building starts when the building is decommissioned and is not intended to have any further use. At this point, the building's demolition/deconstruction may be considered as a multi-output process that provides a source of materials, products, and building elements that are to be discarded, recovered, recycled, or reused. End-of-life stage includes the energy consumed and environmental waste produced due to building demolition and disposal of materials to landfills, as well as the transport of waste building material. Depending on the availability of data, recycling and reuse activities related to demolition waste can also be included in end-of-life stage.

Stage D quantifies the net environmental benefits or loads resulting from reuse, recycling, and energy recovery resulting from the net flows of materials and exported energy exiting the system boundary.

According to ISO 14040, LCA methodology consists of four components or steps: Goal definition and scoping, life cycle inventory (LCI), life cycle impact assessment (LCIA) and life cycle interpretation.

In the goal and scope definition phase, the product or service to be assessed, the functional unit, and the required level of detail are defined. The type of analysis, impact categories to be evaluated, and set of data that needs to be collected are identified. System boundary and functional unit definition are important elements of this component. The functional unit represents a description of the product or system being assessed, defined with great specificity so that the resulting LCA can be compared to the LCA of a similar product or system on an one-to-one basis. For a building LCA, the functional unit might be, for instance, “the entire building supplied from design to demolition for a 50-year service life,” or it might be computed on a per-square-foot basis and limited to one life cycle stage (e.g., construction). The system boundary dictates the breadth and depth of the proposed LCA. For example, if the LCA is completed on a building enclosure system, then the system boundary will likely exclude the primary building structure that supports the façade. The assessment might or might not include the clips, brackets, and lintels that are used to attach the façade to the building. If a comparative LCA is anticipated, then it is critical that the system boundary be established in the same way for the systems being compared.

In the LCI step, an inventory of all the inputs and outputs to and from the production system is prepared: the energy and raw materials used, the emissions to atmosphere, water, and soil, and different types of land use are quantified for each process then combined in a process flow chart and related to the functional basis. LCI results allow products and processes to be compared and evaluated. If the results of LCI are consistent, that is, a product performs well or poorly in all environmental burdens, there is no need to carry out the LCIA step. However, if the LCI results are inconsistent, this step becomes essential. In the inventory analysis stage, software tools and databases are critical. It is not possible to analyze each individual material and process from scratch each time an LCA is performed. Instead, software tools tied to extensive product and process databases are used to complete the inventory analysis. The simplest software tools are spreadsheets, in which material quantities can be entered. More complex tools act more like cost-estimating software, so that automated tabulation of material quantities from assemblies can be completed on a surface-unit basis.

In the LCIA step, inputs and outputs from a given product or process are translated into impacts on various human and terrestrial eco-systems. Several methods are used to convert the LCI analysis results (quantities of materials and energy used and resulting emissions) into environmental impacts. Some commonly used methods are Eco-indicator 99, EDIP 1997 and IMPACT 2002 + , CML, TRACI, and ReCiPe.

To aid in the understanding of impacts, the effects of the resource use and emissions generated are grouped and quantified into a limited number of impact categories, using specific indicators of potential impacts which may then be weighted for importance (see [Table 5.5](#)).

Finally, in the life cycle information step, LCA results are reported in the most informative way possible and the need and opportunities to reduce the impact of the product or service on the environment are systematically evaluated. LCA results can be presented in the form of tables or graphs, which is especially helpful when comparing two competing design options or products. Like any other design feedback tool, LCA can be an iterative process; the interpretation of the LCA can lead to changes in the proposed design, which then leads back to LCI in the process. Validation of results (comparing with results from other LCAs) and sensitivity analysis (checking on the reliability of variables for LCA) may also be conducted during this process.

TABLE 5.5 Main environmental impact categories and indicators for LCA.

Impact category	Impact category indicators
Climate change	kg CO ₂ equivalent
Ozone depletion	kg CFC-11 equivalent
Ecotoxicity for aquatic fresh water	CTUe (comparative toxic unit for eco-systems)
Human toxicity—cancer effects	CTUh (comparative toxic unit for humans)
Human toxicity—noncancer effects	CTUh (comparative toxic unit for humans)
Particulate matter/respiratory inorganics	kg PM _{2.5} equivalent
Ionizing radiation—human health effects	kg U ²³⁵ equivalent (to air)
Photochemical ozone formation	kg NMVOC equivalent
Acidification	mol H ⁺ eq
Eutrophication—terrestrial	mol N eq
Eutrophication—aquatic	Fresh water: kg P equivalent; marine: kg N equivalent
Resource depletion—water	m ³ water use related to local scarcity of water
Resource depletion—mineral, fossil	kg antimony (Sb) equivalent
Land transformation	kg (deficit)

The main effort required for LCA usually pertains the inventory analysis, in which materials and activities are analyzed and the emissions from them are accrued. Several organizations and LCA tool vendors have developed LCI databases that contain material, energy use, and emissions data for commonly used products and processes. These databases contain elementary flows (inputs and outputs) for each process unit for a product system and are specific to countries and regions within countries because the energy fuel mix and methods of production often differ from region to region. However, the modules do not contain data characterizing the full life cycles of specific products but generally account for raw material extraction, transportation to a manufacturing unit, manufacturing process, and packaging and distribution. Notable LCI databases are the EcoInvent Database, featuring global, European, and Swiss datasets, and the United States LCI database managed by the National Renewable Energy Lab, which provides individual gate-to-gate, cradle-to-gate, and cradle-to-grave accounting of the energy and material flows into and out of the environment that are associated with producing a material, component, or assembly in the United States. LCI databases are either integrated with the LCA tool or can be imported.

Data can be inferred from industry averages or be supplier-specific. For instance, the BEES LCA Tool is driven largely by product data provided by suppliers. Industry averages make more sense in whole-building LCA tools, as these tools are designed to support decisions about assemblies at the schematic design stage, in which specific suppliers are not usually identified yet. At the specification and procurement stages, if supplier-specific data are available, a decision to select the most environmentally sensitive supplier for a specific product could be assisted using LCA.

Depending on the goals, in the building sector LCA can be applied at the building product level, at the assembly level and at the whole-building level, and its scope can extend to various stages and processes of the life cycle (from cradle to grave, from cradle to gate, from cradle to cradle, or from gate to gate) (see [Table 5.6](#)).

To deliver reliable and consistent results, the choice of the right software tools becomes an essential aspect of LCA.

Today more than 50 LCA software tools are available on the market. Some are applicable to any industrial product or process from scratch (GaBi, SimaPro, OpenLCA, Umberto, etc.), whereas others are streamlined for the construction sector (BEES, Athena Impact Estimator, Tally, One Click LCA, etoolLCD, etc.). Some tools use proprietary datasets, others rely on external databases. Best known and most used software on the market are reported in [Table 5.7](#).

LCA tools optimized for construction sector can be classified based on the following:

- Levels of LCA application: Product, building assembly and whole-building LCA tools.
- User skills required: Tools for LCA practitioners and tools for general users such as architects.
- Data location: Tools containing LCI data for a specific country or region.
- Life cycle stages that can be evaluated using the tool.
- Design stage application.

TABLE 5.6 Life cycle analysis (LCA) scopes.

LCA scope	Description
Gate-to-gate (only one phase)	Gate-to-gate is a partial LCA that examines only one value-added process in the entire production chain, for example, by evaluating the environmental impact due to the construction stage of a building.
Cradle-to-gate (A1–A3)	Cradle-to-gate is an assessment of a product life cycle from extraction of raw materials “cradle,” to the factory gate before it is transported to the consumer. In this system boundary, only the processes used in the extraction of raw material, transportation of the harvested materials to the plant and manufacturing are included in the analysis. Cradle-to-gate assessments are sometimes the basis for environmental product declarations (EPDs).
Cradle-to-grave (A1–C4)	Cradle-to-grave is the full LCA from the extraction of raw materials “cradle” to the disposal phase of the building “grave.” In addition to the processes included in the cradle-to-gate boundary, cradle-to-grave also considers environmental impacts resulting from products manufacturing and from the building’s construction, occupancy, and demolition phase are considered.
Cradle-to-cradle (A1–D)	In addition to the processes included in the cradle-to-grave boundary, cradle-to-cradle LCA also considers what impacts, positive or negative, the disposed materials have on the environment. Cradle-to-cradle often implies that the product under analysis is substantially recycled, thus reducing the impact of using the product in the first place.

TABLE 5.7 LCA software tool.

LCA software tool	LCA tool type			Required user skill
	Whole building	Assembly	Product	
ATHENA EcoCalculator		■		General users
ATHENA Impact Estimator ^b	■	■		General users
BEES ^a	■		■	General users
Boustead			■	LCA practitioners
CAALA ^c	■			General users
ECO-BAT 4.0	■	■	■	General users
Eco-Quantum	■			General users
Envest ^a	■			General users
EQUER	■			General users
EtoolLCD	■			General users
GaBi			■	LCA practitioners
LCAid	■	■	■	General users
LCAit			■	LCA practitioners
LEGE ^a	■	■		LCA practitioners
LISA	■			General users
One Click LCA ^a	■	■	■	LCA practitioners
OpenLCA ^b			■	LCA practitioners
PEMS			■	LCA practitioners
SBi LCA tool			■	LCA practitioners
SimaPro			■	LCA practitioners
Tally ^c	■	■		General users
TEAM			■	LCA practitioners
Umberto			■	LCA practitioners

^aAlso a life cycle cost analysis tool.^bOpen source.^cPlug-in.

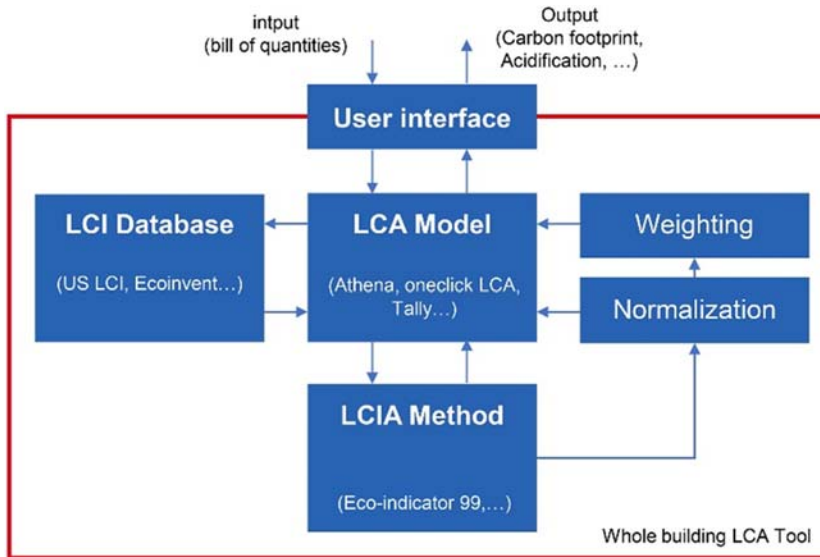


FIGURE 5.4 Configuration of a typical whole-building LCA tool.

The most basic LCA tools take inputs in the form of material take-offs (in area or volume) and convert them into mass. Then they attach this mass value to the LCI data available, resulting in quantities of inputs and outputs of a product system. The inputs and outputs may include the use of resources and releases to air, water, and land associated with the system. Fig. 5.4 depicts the basic configuration of a whole-building LCA tool.

Main data can be inputted in a spreadsheet format, or through a geometric computer model. Geometric based input uses the 3D model software platform to extract information about the building's materials and quantities. Tools such as One Click LCA and Tally use the Revit 3D model platform, while CAALA developed plugins for both Sketchup and Rhino. EToolLCD and Athena do not support a 3D model, even though the former attempted to develop a Revit plugin. In Athena, all data must be entered manually and the material volumes are calculated by the program based on assumptions. Normally, LCA software do not calculate the building operational energy use themselves and allow the user to input this information, as well as the electricity and fuel grid characteristics. CAALA software can estimate the final and primary operational energy requirements according to DIN V18599 for apartment buildings or single-family houses. However, because it calculates operational energy, there are many other variables considered in the assessment, such as the thermal properties of materials, thermal bridges, airtightness, climatic zone, as well as shading devices and on-site shading obstacles.

Some LCA tools have an LCI database locked to them and are not compatible with other databases, which limits their application since LCI databases are region-specific. For example, ATHENA Impact Estimator has the ATHENA and United States LCI databases embedded in it, which are specific to North America so it can only be used for building locations in Canada and the United States. Other tools, such as like SimaPro and One Click LCA, are more adaptive in their linkages to different databases and thus are not region-specific. Not all LCA tools are capable of conducting a full cradle-to-grave LCA analysis, nor contemplate all impact categories cited in EN ISO 15978. All software tools normally allow the user to perform a sensitivity analysis, comparing the results after changing any parameter. Software such as eToolLCD and One Click LCA also provide result examples from other buildings, like residential dwellings or multiple story office buildings. The validation happens when the results of the building assessed are contrasted with the outputs of a building with similar characteristics (baseline). For primary energy demand, primary energy nonrenewable (PENRT) and global warming potential (GWP), CAALA instead provides reference values based on German standards.

Building product LCA tools, such as BEES software, evaluate and compare competing building products. Such tools can be useful in comparing products that are sufficiently similar in their basic composition as well as in their function within a building context and allow supplier-to-supplier comparisons as opposed to material-to-material comparisons.

Building assembly LCA tools, such as ATHENA EcoCalculator, evaluate complete assemblies for their environmental footprint by considering the combined effect of all the products that make them up. For example, a wall would consist of several elements, all of which are needed to erect, weather-proof, and finish it. These tools are wider in scope and less specific in analysis results than building product tools.

Whole-building LCA tools (WBLCA), such as ATHENA Impact Estimator, EtoolLCD, One Click LCA, and Tally, assess the environmental impact of the building by bringing together all its systems and assemblies. These tools are

generally capable of comparing several design options for a building program and are generally helpful during initial design phases. WBLCA tools take input in terms of building geometry and building assemblies. The result is aggregated for the entire building and presented in the form of environmental impacts due to different life cycle stages or the contribution of the building toward a particular impact (see [Fig. 5.5](#)). They can be used to evaluate an initial design and then be updated to capture how design changes affect environmental outcomes, and provide reports that fully meet the documentation requirements of the LCA credits of most building rating systems (see [Table 5.8](#)). Plug-in tools like Tally do not need to manually enter the bill of materials since quantities of materials are imported directly from the Revit software. WBLCA tools have a simplified interface in which the user is prompted for inputs and does not need to structure the analysis. The tool may ask for a building location region to determine aspects like electrical grid, source of building products, and transportation modes and distances. The model breaks down the selected assemblies into their respective products, converts it onto a bill of quantities, and applies LCI datasets to it to get the inventory of consumed resources and emissions and impact assessment. Databases are often locked and cannot be modified by the user, limiting the LCA to the building products, materials, and activity stages available (often a serious drawback). In other cases, they can be integrated with LCA of individual products and assemblies made by the user using more general LCA tools like Simapro, Gabi, Umberto, etc.

5.1.2.4 Code compliance verification

Building energy code compliance is the crucial link between the actual energy savings and the efficiency prescribed in energy codes, as the energy savings from stringent energy codes cannot be delivered unless buildings are constructed or retrofitted to completely comply with the required standards. Although severe energy requirements have demonstrated effective savings worldwide in the last decades, noncompliance of buildings is still an issue in both advanced economies and developing countries ([Xie et al., 2020](#)).

BPS is increasingly recognized in wide-scale promotional programs as well as in legislation around the world; examples are LEED (Leadership in Energy and Environmental Design) and EPAct (Energy Policy Act) in the USA, and EPBD (Energy Performance of Buildings Directive) in Europe. The development, evaluation, use in practice, and standardization of the models and tools is therefore of growing importance ([Djunaedy et al., 2006](#)). At the same time, there is significant focus on the development of new and improved building codes and standards to address current challenges in context of designing buildings. As codes and regulations grow more stringent, precise, and oriented on actual building performance in addition to compliance to prescriptive terms, manual checking of requirements becomes harder, more time-consuming and error prone. Therefore energy code compliance tools with integrated performance simulation engines, capable of automatic checking of codes and standards, are becoming essential for successful design delivery ([Maile, Haves, & See, 2015](#)). United States energy codes, for example, are based on the DOE-2 building energy performance simulation software, and often provide the possibility of either following the conventional prescriptive requirements or an alternative performance-based compliance path with the latter showing an upward trend in recent years. The increasing stringency of the prescriptive path is considered the key driver behind the trend toward performance-based compliance, with more projects taking advantage of trade-offs allowed by the performance path in lieu of meeting some of the prescriptive requirements: for instance, many projects pursuing the performance path have higher fenestration areas than allowed (some states prescribe maximum 30% WWR) and poor opaque envelopes, or do not meet the ERV and lighting power density requirements. In these cases, performance-based compliance allows to make up for the poorly performing envelopes, excessive glazing, and increased lighting power density by utilizing on-site renewables or cogeneration systems ([Karpman, 2016](#)).

Today, most energy and sustainability certifications, both code mandatory and voluntary (e.g., LEED, BREEAM, ESTIDAMA, etc.), can be attained only with BPS tools certified to comply with the related calculation methodology. For instance, whole-building BPS programs certified for code or LEED verification in the United States shall comply to ASHRAE Standard 90.1–2010, Appendix G, which includes the following minimum modeling requirements:

- 8760 hours per year;
- hourly variations in occupancy, lighting power, miscellaneous equipment power, thermostat set points, and HVAC system operation, defined separately for each day of the week and holidays;
- thermal mass effects;
- ten or more thermal zones;
- part-load performance curves for mechanical equipment;
- capacity and efficiency correction curves for mechanical heating and cooling equipment; and
- air-side economizers with integrated control ([ANSI/ASHRAE/IES, 2019](#)).

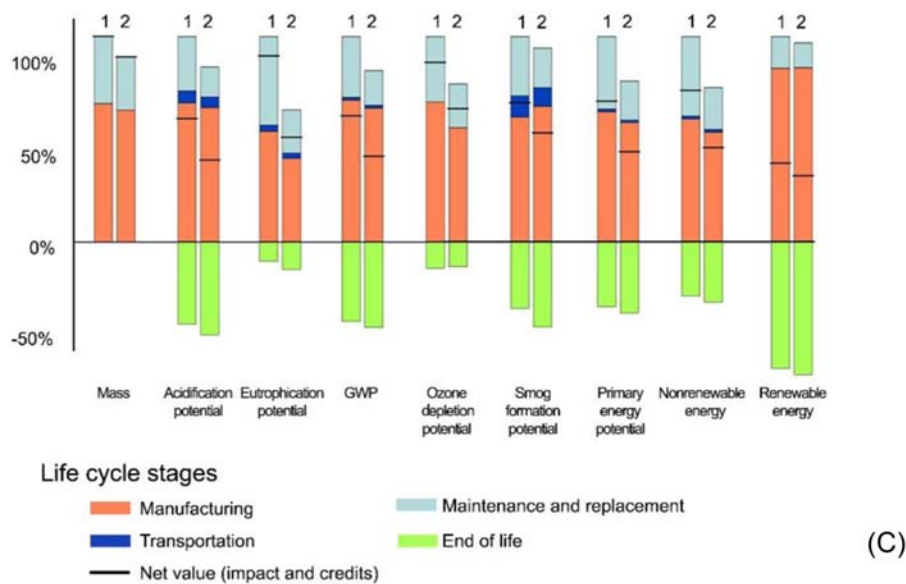
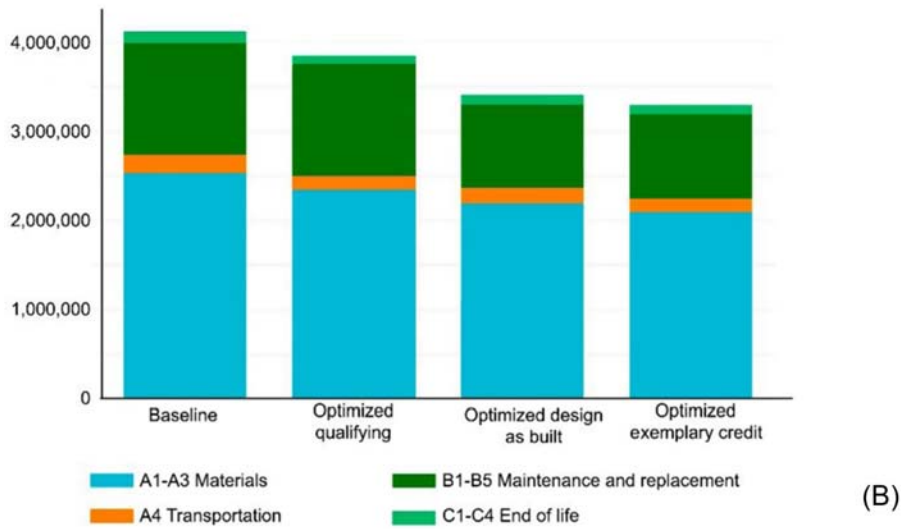
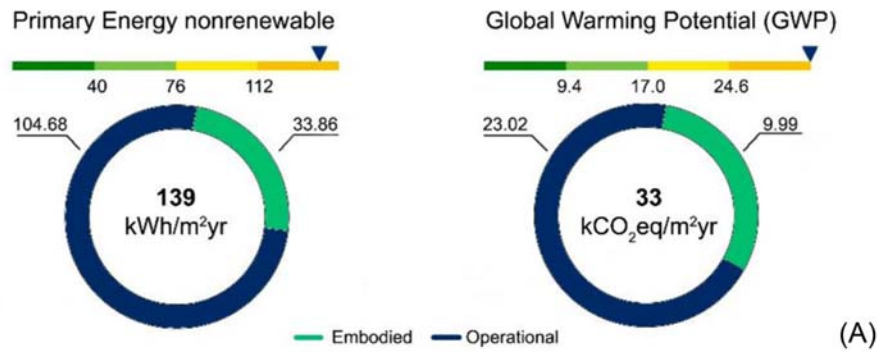


FIGURE 5.5 Examples of graphical outputs representations. (A) Share of embodied and operational impacts in CAALA; (B) comparison between design options in One Click LCA; and (C) comparison between design options in Tally.

TABLE 5.8 Whole-building LCA results. Example from Athena impact estimator LEED report.

Life cycle assessment impact measures	System boundary: cradle-to-grave (from A to C stages)			
	Baseline building	Proposed building	Units	Difference (%)
Global warming potential	157,343.34	118,007.50	kg CO ₂ eq	(-) 25.0
Stratospheric ozone depletion	0.00	0.00	kg CFC-11 eq	Not mean.
Acidification of land and water	910.67	796.16	kg SO ₂ eq	(-) 12.5
Eutrophication	77.10	72.47	kg N eq	(-) 6.0
Tropospheric ozone formation	13,789.23	11,307.16	kg O ₃ eq	(-) 18.0
Depletion of nonrenewable energy resources	1,987,895.78	1,441,224.46	MJ	(-) 27.5
Number of measures with at least 10% reduction(a reduction corresponds to a negative value percent difference)				4

European energy codes are instead based on an energy balance computation model that takes into account the internal and external temperature variations and a utilization factor of the dynamic effect of internal and solar heat gains (Energy Performance of Buildings Directive 2010/31/EU). In particular, the European EPBD, and its subsequent amendment Directive (EU) 2018/844, was primarily designed for use in judging compliance with regulations expressed in terms of energy targets but was also intended for use in comparing the energy performance of various design alternatives for a planned building, or for assessing the effect of possible energy conservation measures on an existing building (Reichard & Papamichael, 2005). EU member states are required to adopt national calculation methodologies, hence certified BPS tools, following ISO 52000 family of standards emanated in 2017 which replaced the conventional quasistationary monthly average calculation method with a more refined dynamic model which contains both hourly and monthly calculation procedures, closely linked. The effect of specific system properties is also taken into account, such as the maximum heating or cooling power and the impact of specific system control provisions, leading to additional system-specific energy loads and needs, on top of the basic energy loads and needs (Dijk & Spiekman, 2016). The main objective of this transition is to leverage energy compliance as an instrument for policy targets and driver for innovation. In the past, in fact, energy performance requirements were prescribed at the component level—minimum thermal insulation levels and minimum efficiencies of products. This, however, led over time to suboptimal solutions and created a barrier to technology transitions. The new set of standards is instead based on a holistic or systemic approach: the assessment of the overall energy performance of a building considering all types of building-related energy uses (heating, lighting, cooling, air-conditioning, and ventilation) and outdoor climatic and local conditions, as well as indoor climate requirements, including the sometimes complex and dynamic interactions between these various aspects. This implies that any combination of technologies can be used to reach the intended overall energy performance level, at the lowest cost, promoting technological innovation and change (Dijk & Hogeling, 2019).

Regardless of the specific energy code or standard enforced, the challenge for most existing tools, however, is their limited data exchange capabilities, which requires to reenter data from the project to the simulation engine and thus more preparation time and error possibility than necessary. At the same time, this discourages code compliance verifications right from the early stages of the design process and often relegates them at the final design delivery, when eventual compliance issues may require costly and time-consuming redesigns.

A recent DoE-funded study estimated that 50%–60% of LEED models are developed using either eQUEST or Trane/Trace (Barbour, Zogg, Cross, & Clark, 2016).

5.1.2.5 Traffic and pedestrian simulation

The simulation of people behavior for design purposes has been a staple of urban planning and infrastructure design, with several traffic simulation tools and software developed over the years and applied to highways, local roads, railway design, airports or seaports layout, or logistic centers planning.

Current software tools such as Bentley Cube can support multiple modes of transport, implementing a multimodal approach able to consider interactions between different modes (pedestrians, bikes, cars, freight, buses, bus rapid transport, rail, air, water, among others), and commonly entail different level of simulation, either macroscopic or microscopic, according to the specific application.

Macroscopic level simulation (large population) is used for strategic and multimodal planning and is typically employed to study major roadway networks and public transport systems. A macroscopic model treats the entire volume of traffic traveling between an origin and destination as a single unit to evaluate the lowest cost path for the aggregated traffic volume and compute congestion effects on a strategic scale, using volume-capacity ratios and estimating resulting speeds.

Microscopic simulation (small population) instead explicitly models each agent, either vehicle or pedestrian, capturing detailed movements and interactions such as vehicle acceleration and lane merges. Most of the currently existing microscopic traffic simulators are based on the family of car-following, lane changing, and gap acceptance models to model the vehicle's behavior. This higher level of detail is suitable for studying infrastructure geometry, traffic control systems and parking, or for studying multimodal projects such as the interactions between pedestrian and vehicle flows. The aim of microscopic models is to emulate the flows and interaction of the complete street, including vehicles traveling through the area, cars circulating and parking, trucks making stops and deliveries, buses, rail vehicles, and circulators making stops and preempting the traffic control as appropriate as well as bicycles and pedestrians interacting with all the other vehicles and the environment.

Some software also claim to operate at an in-between level, called mesoscopic model, which allows to model and simulate corridor-level projects based on maximum highway capacities and apply dynamic traffic assignment methods to understand how traffic varies by time of day and at a higher resolution than what is possible in macroscopic models.

Traffic modeling software can be used to analyze the effects of new projects and policies on a city's transportation network, land use, and its population. As part of a city's digital twin (see [Chapter 12](#)), they can be employed to develop and apply predictive multimodal transportation models in order to simulate how changes in infrastructure, operations, technology, and demographics will impact movement and accessibility of a given area.

Parallel to vehicular traffic simulation, pedestrian, or crowd simulation has seen remarkable development in the last years, with several specialized software (Oasys MassMotion, Bentley Legion, Anylogic, InControl Pedestrian Dynamics, Vadere Crowd Simulation) available for outdoor and, in particular, indoor microscopic simulation of people dynamics. Crowd simulation analysis tools are now widely used in design decision-making to assess building performance and are expected to provide relevant information indicating building behavior in crowded scenarios ([Boje & Li, 2018](#)).

These tools are particularly suited to support design and improvement of public facilities subject to large flows of users, including shopping malls, airports, railway and subway stations, stadiums and theme parks, museums, or hotel lobbies. In particular, by running crowd simulations, it is possible to explore how pedestrians and crowds interact with infrastructure with the following main objectives:

- optimization of the size and placement of elevators, ramps and staircases;
- evaluation of building or rooms capacity;
- identification of potential bottlenecks such as kiosks, cashiers, ticket halls or security checks;
- assessment of evacuation plans, even in multistory buildings, based on the diverse and complex behaviors of people in an emergency;
- visualization of customer traffic in shopping areas;
- evaluation of parking, roadway, and public transportation accessibility;
- preparation of emergency or limited operation schedules to allow minimal distancing between users, such as for epidemic containment measures.

Pedestrian simulation tools are agent-based, meaning that rather than treating the entities in the simulation as a homogenous mass—such as the particles in a CFD simulation—each pedestrian is modeled as an individual, allowing the user to customize their personality with any extra explicitly designed behavior. They may be preassigned with individual properties, preferences, and states. Each agent moves according to a social force model, choosing the shortest route, avoiding collisions with other objects by analyzing the current environment, and making decisions on further movements. Intelligent agents can also respond dynamically to evolving operational conditions and user-defined triggers. Algorithms driving these simulators are commonly developed studying pedestrian behavior, including video techniques to collect empirical crowd data which is then systematically analyzed and combined with mathematical modeling to create the simulation engines.

Leading software is already compatible with an array of file formats including industry foundation classes (IFC)-converted AutoCAD, MicroStation, SketchUp, Rhino, or Revit BIM models, as well as featuring built-in 3D modeling capabilities to create or edit the building geometry within which the people will be moving. The BIM file already identifies building elements such as walls, doors, columns, and stairs, allowing to integrate the environment with design

components from the software built-in library such as ticket counters, turnstiles, gates, barricades, signs, retail stores, kiosks, and restrooms that will directly impact how people will move within the space. Entrances and exits are designed to define the pedestrian flow, as well as areas where interim activities such as queuing or waiting will occur. Other inputs for simulation is the types of people who will be using the space, selected from profiles differentiated by size, gender, age, walking speed, nationality, personal space requirements, as well as specific behavior profiles based on the type of project—for instance, when simulating a train station, people can be tourists (who will tend to linger and may carry luggage) or commuters (who are in a rush).

Different scenarios can be created for testing the design in different demand situations such as for rush hour, time of year, match day for stadiums, or to test different variations of the floor plan to fine-tune its layout.

Simulations can include up to hundreds of thousands of agents and take several hours for most intensive applications. The output statistics of the model can allow to assess facility capacity and throughput, count pedestrians in different zones, measure wait and service times. Pedestrian flow density can be shown with people as dots on the floor plan or in the form of heat maps, which allow at-a-glance visualization of the areas of overcrowding, congestion, and delays. Results come as reports in a variety of formats, charts, and tabular data-driven outputs, maps, and graphs as well as fully rendered 3D graphics and animations which can be experienced also via extended reality (see [Chapter 6](#)).

5.1.2.6 Building energy prediction

In addition to supporting all stages of the building design process up to project delivery to the client/contractor, BPS is also finding application in the building's operation and managements phase, as a tool for improving the building control systems or for evaluating its operational performance.

Concerning building control, the same simulation tools employed to calculate performance metrics useful for building design and compliance verification can, in fact, be used to predict the daily heating and cooling loads of the building before they occur, allowing the BAS to anticipate the building's energy needs and operate the HVAC and energy systems accordingly. This approach to building control is known as model predictive control (MPC) (see [Fig. 5.6](#)). Contrary to conventional building control logics, which prescribe corrective actions based on environmental values as measured by sensors (e.g., raising the supply air temperature if the temperature inside a room decreases), MPC aims at performing anticipatory control actions based on the conditions predicted in a definite time interval.

In particular, a MPC controller consists of two main technologies: a prediction model to anticipate the dynamic behavior of the control subject, and an optimization solver to find the best control input to set in order to meet the desired result. The prediction model foresees the dynamic response of the outputs of a system as affected by the manipulable variables (temperature set points, HVAC controls, windows, and shading actuators) and uncontrolled inputs

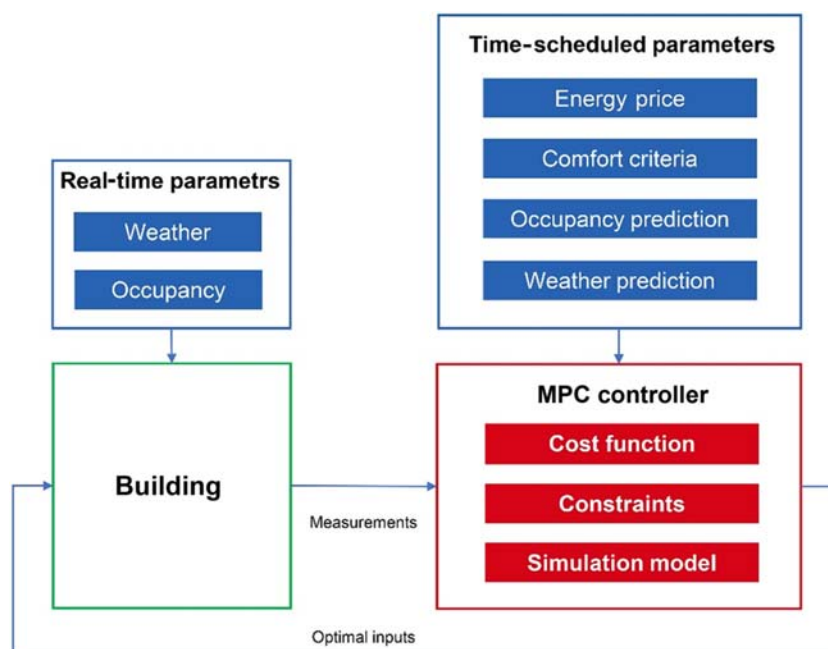


FIGURE 5.6 Basic principles of MPC for buildings.

(constraints set by the designer, weather forecast, expected occupant behavior). The optimization solver then identifies the best strategy to achieve the expected targets (energy saving, thermal and visual comfort, cost reduction) which is enforced until the next round of predictions (normally in intervals of 30 minutes or 1 hour). MPC employs the same simulation engines used in the design phase (e.g., EnergyPlus, DOE-2, etc.), which are applied on an as-built model of the building and can be further calibrated on measured operational values. Building control systems, and MPC in particular, are investigated in more detail in [Section 10.4.3](#).

In building operation, BPS can be used for conducting what-if scenarios useful for management decisions, for instance, to evaluate the effect of specific actions or modifications within the building before they actually take place. This is particularly effective when BPS tools are applied on the building's digital twin, that is, a virtual structured model of the building that is continuously updated with real-time data from its sensors network and at the same time can be replicated on its real-world counterpart. An accomplished building digital twin provides an accurate testbed on which to monitor the ongoing status, recognize internal and external complexities, detect abnormal patterns, reflect system performance, predict future trends and optimize operation. In particular, when paired with BPS tools it allows to simulate what would happen if adjustments are made that might be too expensive, dangerous, or uncertain to try out in a real-world scenario. By altering the variables under which the digital twin is operating, the changes can be predicted in the digital world without any risk in terms of cost or safety. For more information on digital twins, see [Section 11.4](#).

5.2 BPS software tools

The ultimate aim of BPS is to support building's design by providing a representation of the dynamic, interconnected and nonlinear physical processes that define the building's performance. The output will in turn indicate if buildings and their related energy supply systems are able to meet the designer's objectives in terms of energy efficiency, thermal, and visual comfort of occupants as well as overall cost reduction ([Clarke & Hensen, 2015](#)). It is therefore evident that BPS alone does not provide engineering solutions or design answers, but results which have to be interpreted and analyzed to extract knowledge to put back into buildings design, in an iterative workflow.

BPS activity is based on two integrated but distinct paradigms, the modeling and the simulation, which are however often wrongly used as synonyms. According to Becker and Parker, the model is the description, commonly a mathematical-physical one, of the system that is to be simulated, which in turn consists of objects that interact with each other. A model describes the system at a particular level of abstraction to be used, in such a way that it can be understood by any technician or software who can read the description. The actual simulation enacts, implements, or instantiates that model ([Becker & Parker, 2009](#)).

Most BPS programs formulate models using imperative programming languages, which assign values to functions, declare the sequence of execution of these functions, and change the state of the program. In such programs, model equations are tightly intertwined with numerical solution methods, often by making the numerical solution procedure part of the actual model equations. This approach originated in the 1970s and is today largely tailored for the use case of building energy performance assessment to support building design and energy policy development. Imperative modeling language impose rules that determine for example where inputs that compute HVAC, building, or control equipment are received from the internal data structure of the program, when these inputs are updated, when these functions are evaluated to produce new output, and what output values may be lagged in time to avoid algebraic loops. However, this rigidity makes it difficult for developers to add new functionalities to software without inadvertently introducing an error in other parts of the program, allowing little flexibility in terms of implementing emergent use cases such as controls design and verification, coupled modeling of thermal and electrical systems, and model use during operation require different numerical methods ([Wetter, Bonvini, & Nouidui, 2016](#)). Examples of BPS tools based on imperative programming languages include DOE-2 and EnergyPlus.

More recent alternative technologies for BPS are instead based on equations-based, object-oriented modeling languages. Differently from imperative programming, equation-based languages do not require to specify the sequence of computer assignments needed to simulate a model. Rather, the developer can specify the mathematical equations, package them into graphically represented components and store them in a hierarchical library. Any user can then assemble these components in a schematic editor to create the desired system model. Lastly, a simulation environment analyses these equations, optimizes them using computer algebra, translates them to executable code and links them with numerical solvers. In particular, the translation for equations to executable code involves analyzing the system of equations to detect, for example, algebraic loops and zero-crossing functions for state events, and converting the equations to a form

that can be solved efficiently. Compared to established imperative programming, equations-based modeling can be orders of magnitude quicker in computation and allows a much greater degree of flexibility, making it suitable for applications beyond the BPS at the design stage and involving, for instance, fluid systems (e.g., steam power generation, hydraulics, etc.), automotive applications (especially powertrain), up to MPC of constructed buildings (See [Chapter 10](#)). However, developing the object-oriented model requires further expertise and time investment compared to off-the-shelf BPS tools; hence, additional development is required to advance translators and solvers and make them more readily accessible to a wider range of users. Main equation-based modeling languages for BPS is Modelica, especially using the Dymola and IDA Indoor Climate and Energy (IDA ICE) simulation environments.

Whether imperative language-based or object-oriented, accomplished modeling and simulation shall take into account different domains to represent the interactions, often conflicting, that take place between the parts of the problem and to indicate performance compromises and trade-offs. Model domains to couple include, for instance, thermal loads, lighting, HVAC, etc. Integration of different domains adds complexity, in particular if mathematical modeling is still inadequately represented, for example, concerning integrated renewable energy generation, occupants' behavior, or natural ventilation. To facilitate more effective performance explorations, BPS tools have traditionally been simplified to a level that preserves the essence, however, defined, of some domains while excluding those that are not expected to affect the answer. At the same time, research has been undertaken to evolve mathematical models of several building processes, including nonsteady airflow regimes, daylight flow, moisture flows, uncertainty and fuzzy logic models, renewable energy supply, adaptive materials such as PCM or smart windows ([Clarke & Hensen, 2015](#)).

Today, several BPS software tools are available on the market, with both commercial and free, open-source licenses. To conduct whole-building simulations, multidomain and dynamic BPS software is required, which would be able to effectively factor in how different subsystems of the building and its context interact and affect each other. In addition, specific optimized tools can be used to investigate definite aspects of building performance, such as artificial and natural lighting, plant sizing, thermal bridges, windows and shading design, etc., at a level of detail and granularity which may not be achievable with whole-building simulators.

Whole-building BPS tools are able to output KPI of the overall quality of the building, which include heat balances and temperature trends (in building zones, construction layers, facades, water supply, etc.), indoor environment (humidity, CO₂ concentration, thermal comfort according to PMV/PPD methods, radiant temperature asymmetry, etc.), energy demand (for HVAC, lighting, building equipment, appliances), building load profiles, visual comfort (daylight availability, artificial light uniformity, glare control). These KPIs provide insights that can inform design activities at different levels applications, from analyzing the performance of existing buildings to identifying the major areas for improvement, to comparing different design options to find the optimal solution, to accurately size HVAC systems according to the actual thermal loads. Concerning the latter, some BPS also have built-in functionalities to support HVAC systems sizing or building control systems optimization. Crucially, whole-building BPS tools are also required by most regulations and building codes to demonstrate buildings' performance-based compliance with relevant standards in terms of energy efficiency and livability of spaces.

BPS tools, either for specific systems or whole-building simulations, can be classified into two main categories:

- solutions which include both the modeler application and the simulation engine;
- solutions that provide only the modeler application and rely on external simulation engines.

Solutions from both categories can come as stand-alone tools or as plug-ins for other software, such as 2D or 3D CAD or BIM programs, often as cloud computing services.

In particular, the modeler application provides the graphical user interface for data input, allowing the user to translate project and climate data into the input file for the simulation engine to solve. The engine then produces output data, which the modeler application or another visualization tool in turn presents to the user. Modeler applications often include libraries of components, each of which models the performance of one part of the system ranging from single fixtures, building elements or HVAC equipment to multizone buildings, weather data processors or economics routines. These models are constructed in such a way that users can modify existing components or create their own, extending the capabilities of the simulation environment.

Regarding whole-building simulations, main BPS solutions include (see [Table 5.9](#)):

- DOE-2 simulation engine, used by eQUEST modeler and by Autodesk Green Building Studio plugin for Revit BIM;
- EnergyPlus simulation engine, which can be integrated with several modeler/interfaces such as OpenStudio SDK, DesignBuilder, Trimble Sefaira, Autodesk Insight 360, Bentley OpenBuildings Designer and Hevacomp Simulator, BuildSimHub, FineGREEN, Simergy, CityBES, GEnergy;

TABLE 5.9 Main whole-building building performance simulation tools.

Simulation engine/modeler	Additional modelers and GUIs
DOE-2	eQUEST, Autodesk Green Building Studio plug-in for Revit
EnergyPlus	OpenStudio SDK, DesignBuilder, Trimble Sefaira, Autodesk Insight 360, Bentley OpenBuildings Designer and Hevacomp Simulator, BuildSimHub, FineGREEN, Simergy, CityBES, GEnergy
APACHESIM	IES Virtual Environment
IDA ICE	ESBO
ESP-r	OpenStudio SDK
TRNSYS	Simulation Studio Modeler and TRNSYS3D plug-in for SketchUp
PHPP	DesignPH plugin for SketchUP

- IES virtual environment with its proprietary APACHESIM simulation processor;
- IDA ICE, an equation-based modeler and simulator which can be integrated with tools such as ESBO;
- ESP-r simulation engine and modeler, used also in OpenStudio SDK;
- TRNSYS simulation engine with Simulation Studio Modeler and TRNSYS3D plug-in for SketchUp;
- Passive house planning package PHPP, with its own calculation tool and designPH plugin for SketchUp;
- Energy Evaluation tool for Archicad.

Each of these whole-building simulation tools is characterized by its own advantages and disadvantages in terms of usability, accuracy, and capability in factoring different building parameters and external factors, and may be more or less suitable for specific applications. For instance, built-in energy simulation engines in BIM authoring tools (Autodesk Insight and GBS for Revit, Energy Evaluation for Archicad) are heavily geared toward early-stage design support and are not robust enough for detailed energy simulation at subsequent design phases.

Some of these are open-source and have found wide diffusion in both the academic community and in professional practice, whereas other are commercial licenses and are largely employed by architecture and engineering firms. Most widely used simulation tools are DOE-2 and, in particular, EnergyPlus, which have been available for free for the longest time and have developed a wide range of both free and commercial modelers and add-ons. Of these two, DOE-2 is the oldest and lacks some of the more advanced features present in EnergyPlus, of which it can be considered a founding element. Nonetheless, both require third party user interfaces to be used, which also integrate modeling capabilities, CAD-BIM interoperability, and other additional functions. Other open-source BPS tools such as ESP-r are used mainly as research tools and have seen little professional application.

Concerning commercial products, adoption is more piecemeal worldwide as the ability to verify local code compliance becomes a central requirement and not all are compatible with specific regulations and sustainability programs. Among these software, IES VE is one of the most successful in view of its wide range of additional services (systems autosizing, LCC and pedestrian simulation, compliance to several national codes).

Regarding system-specific simulations of single building subsystems, several BPS solutions are available for different applications, with the main ones reported in [Table 5.10](#).

Following is reported the common design workflow indicating for each design phase the parameters being simulated, the detail level of the model and the main software that can be used to run the simulations (see [Table 5.11](#)).

In addition to advanced, desktop-based BPS tools, web applications for simple simulations can be adequate for quick comparisons of design options. Prior experience with the tools is often not required and climate data for different geographical zones are already integrated within these applications. Even if they produce less accurate results, they can provide some effective guidance for decision-making on design, especially at the beginning of a project, and are more interesting for students or smaller offices with less financial or human resources, as well as for project developers and prospective building owners. Depending on the tool, planners can either set default climate and building parameters or add building information via a simple design interface, obtaining rough calculations on energy performance, environmental impact, and potential savings. Such tools include the Interactive Guide for Energy Efficiency in Buildings (Brazil), the CBE Thermal Comfort Tool (United States), ECO-NIWAS, THESIM 3D, or the Building Material Scout (Binz, Bourgault, Gruner, & Zinecker, 2019).

TABLE 5.10 Main application-specific building performance simulation tools.

Building service/system	Building performance simulation software
Urban microclimate	ENVI-met
Daylighting and artificial lighting	Radiance, AGI32, Accelerad, ClimateStudio (Rhino plugin), UrbaSun, DL-Light, LightStanza, Groundhog (SketchUp plugin), Sun Study (Archicad plugin)
Electrical systems	PowerCalc, Demand Response QAT
HVAC sizing	Modelica Buildings Library, Looplink PRO, EVAP-COND, Trane Pipe Designer, VariTrane Duct Designer, PUMPCALC, HVACSIM + , SimulationX, HAP.
Acoustics	Trane Acoustics Program (TAP), AcousticCalc
Photovoltaics	PVsyst, BlueSol
Solar thermal systems	TRANSOL, Kalkener
Windows	Berkeley Lab Window, AERCalc, RESFEN, COMFEN, EFEN
Thermal simulation	THERM, AnTherm, UcanPsi
Airflow simulation	LoopDA 3.0, Tas Ambiens 2D, UrbaWind, CONTAM, TRACE 700, SimScale, COMIS
LCA/LCC	ATHENA Impact Estimator, BEES, CAALA, Enves, EtoolLCD, LEGEP, LISA, One Click LCA, Tally
Traffic and pedestrian simulation	Oasys MassMotion, Bentley Cube and Legion, Anylogic, InControl Pedestrian Dynamics

TABLE 5.11 BPS design workflow.

	Conceptual design	Design proposal	Final design
Design subject	• Massing • Orientation • Space layout • Openings • Landscaping • Access	• Construction • Materials • Functional layers • Thermal performance • Noise insulation • VLT and SHGC • Shading systems • Systems sizing • Renewables integration	• Detailed design • Project certification • Design for digital fabrication • Budget • Construction site planning
BIM LOD	• LOD100	• LOD200	• LOD300
Simulations	Pre-analyses • Climate analyses • Energy analysis • Daylight analysis • Wind analyses • Shadow analyses • Visual analyses • Flows analysis	Parallel analyses • Visual comfort • Thermal comfort • Natural ventilation • Electrical loads • Thermal loads • Renewable energy production • Systems sizing • LCA and LCC	Post-analyses • Code compliance • Energy certification • Wellness certification • Green building certification • LCA certification • Cost estimation • Works scheduling • Quantity take-off
BPS tools	Early-stage • ENVI-met • Insight • Sefaira • Cove.tool • Bentley cube • Oasys Massmotion	Whole-building • EnergyPlus • IES VE • DOE-2 System-specific • PVSyst, Bluesol, Transol • Radiance • Trace 3D + , Carrier HAP • VariTrane, IndusPro • Tally, One Click LCA • Bentley Legion	Whole-building • EnergyPlus • IES VE • DOE-2 System-specific • Naviswork • Synchro • Bexel manager • Tally, One Click LCA

5.2.1 DOE-2

The DOE-2 software was developed in collaboration with Lawrence Berkeley National Laboratory mostly under funding from the United States Department of Energy (USDoe). First released in the late 1970s, DOE-2 is a freeware building energy analysis program used to predict the energy use and cost for all types of buildings. At its core, DOE-2 is a command prompt program which requires to input via text the description of the building layout, constructions, operating schedules, conditioning systems (lighting, HVAC, etc.) and utility rates, along with weather data, and uses this information to perform an hourly simulation of the building and to estimate utility bills.

The calculation engine of DOE-2 is based on four simulation subprograms: Loads, System, Plant, and Economics. The three main parts of the model, building zones, air handling system, and centralized generation plant, are simulated sequentially, without any feedback between them. The sequential solution starts with the zone heat balance which updates the operating conditions of the zone and determines the heating-cooling load at each simulation step according to the weather data provided. This information is then transferred to the simulation of the air handling unit to determine the system response, which is in turn transferred to the centralized generation plant. Lastly, the Economics module evaluates operational costs based on consumption and fuel prices. The heat transfer between two rooms with different temperatures is evaluated with a weight factor method which takes into account the capacitive effects of the thermal mass but does not rely on thermodynamic equations. Such technique is ill-suited for more complex simulations such as those focused on dynamic behavior, like PCM and green roofs, which require to simulate better the contribution of thermal inertia and mass. More complex HVAC systems and solar thermal systems are also difficult to model, and advanced functions such as natural ventilation, opening windows or surface temperatures (needed for thermal comfort estimation) are not supported.

DOE-2 text-based interface requires substantial experience to learn to use effectively; hence, graphical interfaces such as eQUEST have been developed over time to improve usability.

In particular, eQUEST is an easier to use, freeware building energy analysis tool which combines an improved DOE-2 building energy simulation program with a building creation wizard, an energy efficiency measure wizard and a graphical results display module. The building creation wizard walks a user through the process of creating a building model and has a detailed building description interface mode that includes 2-D and 3-D display of the building geometry (including limited CAD file import for point-and-click layout drawing), graphical display of HVAC equipment layout, and access to all DOE-2.2 input parameters and summary/hourly report data. The detailed interface also includes the capability to describe and perform parametric runs and the graphical display of results includes multirun comparison graphics. Within eQUEST, the DOE-2 engine performs an hourly simulation of the building based on walls, windows, glass, people, plug loads, and ventilation, and of the performance of fans, pumps, chillers, boilers, and other energy-consuming devices. eQUEST allows users to create multiple simulations and view the alternative results in side-by-side graphics. It offers energy cost estimating, daylighting and lighting system control, and automatic implementation of energy efficiency measures.

eQUEST is qualified for Energy Code compliance and commercial building tax deduction in the United States according to ASHRAE 90.1 and California Title 24.

DOE-2 is also employed as the simulation engine within Autodesk Green Building Studio (GBS) application, which enables energy analysis within Autodesk's own Revit BIM modeler and FormIt sketch modeler. GBS is a cloud-based program, focused on providing the designer with useful results to guide the design activity from an energy point of view, especially in the early stages of the design process, allowing the comparative evaluation of some aspects that govern the energy response of the project. The energy analysis workflow is defined as follows: modeling of the project to be analyzed, generation of the energy model, upload of the energy model via gbxml format to the GBS cloud service for analysis, consultation of the simulation results through a web interface or through Autodesk Insight 360, and definition of alternative scenarios for the study of the hypotheses for improving the energy performance of the building. Being mostly an early-stage energy analysis tool, some project data such as the HVAC system are filled in automatically according to the chosen building type, with the sole purpose of forecasting energy consumption or other performance metrics based on the current design alternatives.

5.2.2 EnergyPlus

EnergyPlus is a whole-building energy simulation program able to model both energy consumption—for heating, cooling, ventilation, lighting, and plug and process loads—and water use in buildings. EnergyPlus development was funded from 1996 by the United States Department of Energy (DoE) and was carried out in collaboration with National

Renewable Energy Laboratory (NREL) and various National Laboratories including Berkeley Lab and Oak Ridge: first release was in 2001, with subsequent continuous updates. EnergyPlus derives directly from the DOE-2 and BLAST programs, which were conceived following the energy crisis in the early 1970s and were developed and released between the late 1970s and early 1980s, and updates them to overcome their main limitations. In particular, the calculation method for the BLAST heat balance used in EnergyPlus is based on the resolution of the actual thermodynamic equations, producing better results than the weighted heat balance method used in DOE. Other notable functions of EnergyPlus include the modeling of the air flows between various thermal zones, the definition of more realistic HVAC system controls and radiant-type heating and cooling systems, as well as self-sizing of many specific parameters for each component, making the results more accurate and consistent than DOE-2. Being a powerful, free and open-source software, EnergyPlus has become a de-facto industry standard for both academic researchers and building professionals.

EnergyPlus implements detailed building physics algorithms for heat transfer—radiation, convection, and conduction—air and moisture transfer, light distribution, and water flows, allowing to model a broad range of building and mechanical system configurations and conditions, and includes advanced simulation features such as subhourly time steps, simultaneous solution of zone conditions and HVAC system actions, a modular HVAC structure, and a runtime scripting language for user-defined control strategies. In addition to energy simulations, EnergyPlus is certified for code compliance verification according to ANSI/ASHRAE/IES Standard 90.1–2010, Appendix G as well as USGBC LEED certification.

Like DOE-2, EnergyPlus simulation engine has a built-in modeler which is console-based, reading input and writing output to text files. A number of utilities allow for creating input files using a simpler spreadsheet-like interface, for managing input and output files and performing batch simulations, and for graphically comparing different results. Nonetheless, the core EnergyPlus graphical interface is not very user-friendly, as data tables used to manage the building's inputs and outputs do not have automations or intuitive graphic elements. To overcome this problem, several external graphic interfaces and modelers have been developed that use EnergyPlus as the simulation engine and facilitate the creation of the thermal model of the building and the insertion of its characteristics. These modelers and plugins include Autodesk Revit with Insight, Rhino and Grasshopper with Honeybee, SketchUp with OpenStudio, direct modeling and editing building energy model (BEM) in OpenStudio, DesignBuilder, etc. (Chang, Yang, Yamagata, & Tobey 2020).

In particular, Openstudio is a free collection of software tools to support whole-building energy modeling using EnergyPlus and other engines, developed by NREL and other DoE laboratories with the aim of reducing the effort required to build and maintain BPS applications. OpenStudio facilitates application development by presenting EnergyPlus inputs and outputs as a dynamic, object-oriented data model with an application programming interface, a much easier construct for applications to deal with. In addition to low-level model and result access, OpenStudio also provides common high-level abstractions like space types, functionality like instantiation and configuration of standard HVAC systems, and data import from standard schemas like gbXML. Finally, in addition to EnergyPlus, OpenStudio also exports inputs for and import results from other engines like the Radiance lighting engine and the CONTAM air-flow engine, supporting multiple analyses from a single model. Graphical applications include OpenStudio SketchUp plug-in that allows users to quickly create geometry needed for EnergyPlus and import gbXML and IFC for geometry creation, the OpenStudio Application, which provides a graphical interface to OpenStudio models including envelope, loads, schedules, and HVAC, and ResultsViewer, which enables browsing, plotting, and comparing simulation output data, especially time series.

DesignBuilder is a popular commercial, third party modeler and interface for the EnergyPlus simulation engine. DesignBuilder comprises a core 3D modeler and additional modules to provide further functions, including visualization of rendered images and site shading analysis, local code and LEED certification, daylight factors and illuminance reporting using Radiance, early-stage building cost estimation, multicriteria optimization, customization of EnergyPlus simulations using EMS or functional mockup units (FMU) scripting, and CFD analysis of distribution of air properties in and around buildings. The 3D modeler allows data entry and storage for most environmental calculations including activity, constructions, glazing, lighting, HVAC, renewables, cost etc, and the definition of inner zones geometry using actual construction layer thickness for individual surfaces. BIM models can be imported from Revit, Microstation, Archicad, and SketchUp using gbXML, and 2D CAD geometries can be traced over to create blocks and to partition blocks up into zones.

Sefaira is a modeler for EnergyPlus which is closely integrated with Sketchup 3D tools and is heavily geared toward early-stage analysis of building form, orientation, fenestration, and shading. Sefaira interface and analysis is simplified enough to support conceptual and schematic design and provide quick, even real-time performance results, starting with only two inputs (location and space use). Real-time analysis plugins (see Fig. 5.7) can provide constant feedback on

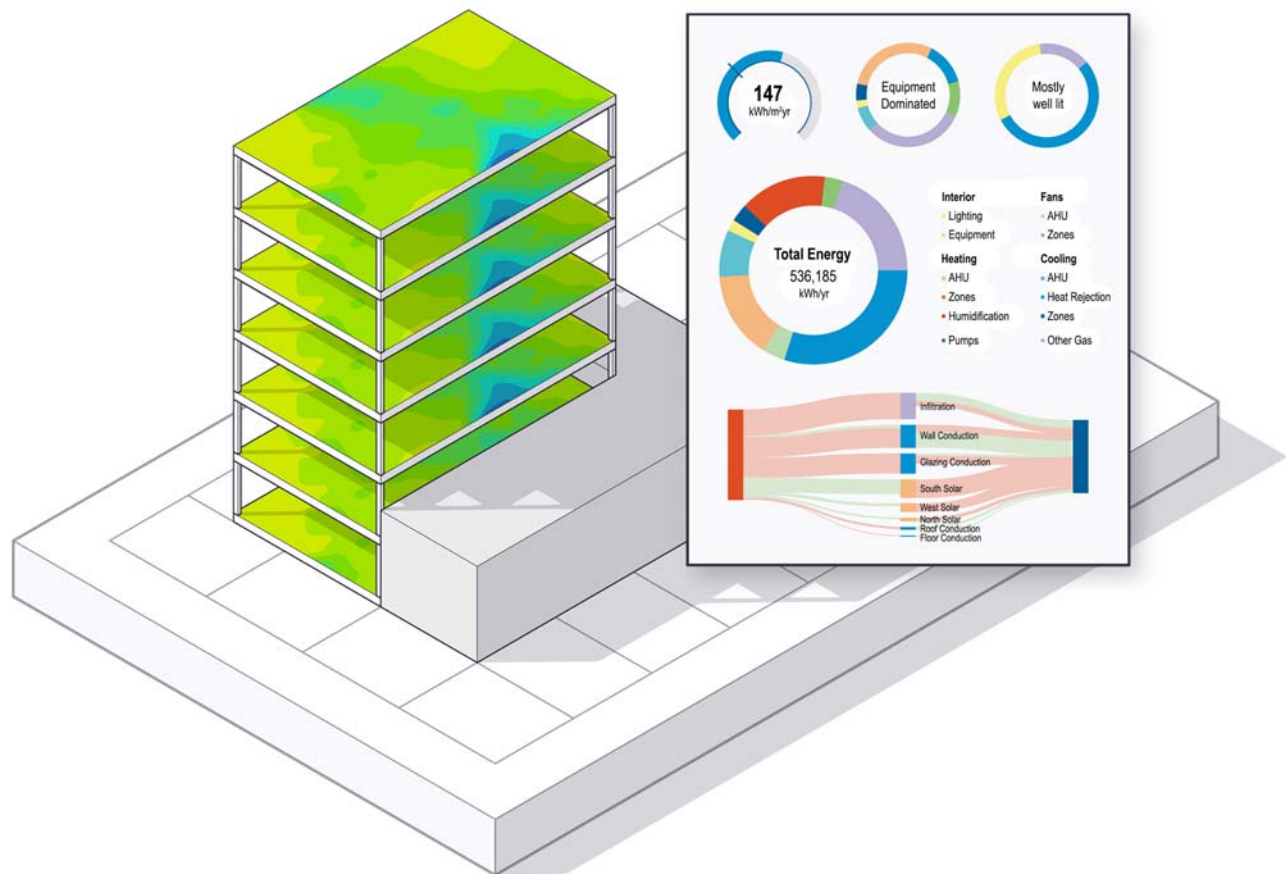


FIGURE 5.7 Early-stage simulation with Trimble Sefaira. *Courtesy of Trimble.*

energy and daylighting metrics as architects work, allowing to test multiple design options at once. Built-in tools allow easy comparison of massings, layout, envelope options, natural ventilation, and HVAC systems for all project types to shortlist the right concepts and strategies for subsequent design development (see Fig. 5.8). Sefaira offers both SketchUp and Revit real-time plugins, as well as a cloud-based platform and web apps for comparative and parametric analysis. Concerning energy simulation, hour-by-hour annual simulations using EnergyPlus can provide energy cost and CO₂ emissions, measure the impact of renewable systems, shading and window openings on thermal comfort, and assess the impact of the architectural features on HVAC sizes and generate preliminary sizes to improve cost estimation. Regarding daylighting, Sefaira integrates the Radiance simulation engine to calculate Daylight Factor, Direct Sun Exposure, and Annual Daylight outputs (including sDA).

Autodesk Insight 360 is a plugin for Autodesk Revit BIM platform and FormIt sketch tool. Insight 360 allows to create energy models from both detailed BIM and early concept projects, and enables rapid, real-time feedback on energy and daylight analysis as design activity proceeds. In particular, Insight 360 focuses on early-stage energy analysis, which is carried out directly from the Revit or FormIt interface via cloud computing using Autodesk GBS. The 3D model is populated with the required or available information (location, building type, HVAC systems, materials, glazing) to create an energy analytical model that is exported to the cloud service for the energy analysis. Insight 360 returns an interactive dashboard that allows the user to compare the effects of different design scenarios—that is, different WWR and glazing solutions, shades, building orientation—with relevant benchmarks (building code or sustainability target) and metrics without affecting the actual work model. Several scenarios using the dashboard graphs as visual references can be created and compared to show clients and team members options for their building design. Specifically, whole-building energy analysis from Revit and Insight 360 is powered by GBS, which runs in the cloud to perform the calculations using the DOE-2.2 engine run, whereas Insight 360 Heating and Cooling loads module uses the EnergyPlus engine for HVAC calculations. Illuminance analysis employs the Perez All-Weather Sky Model. Lastly, Insight 360 map interface shows available weather stations, from which it is possible to pull up statistics about relevant weather data.

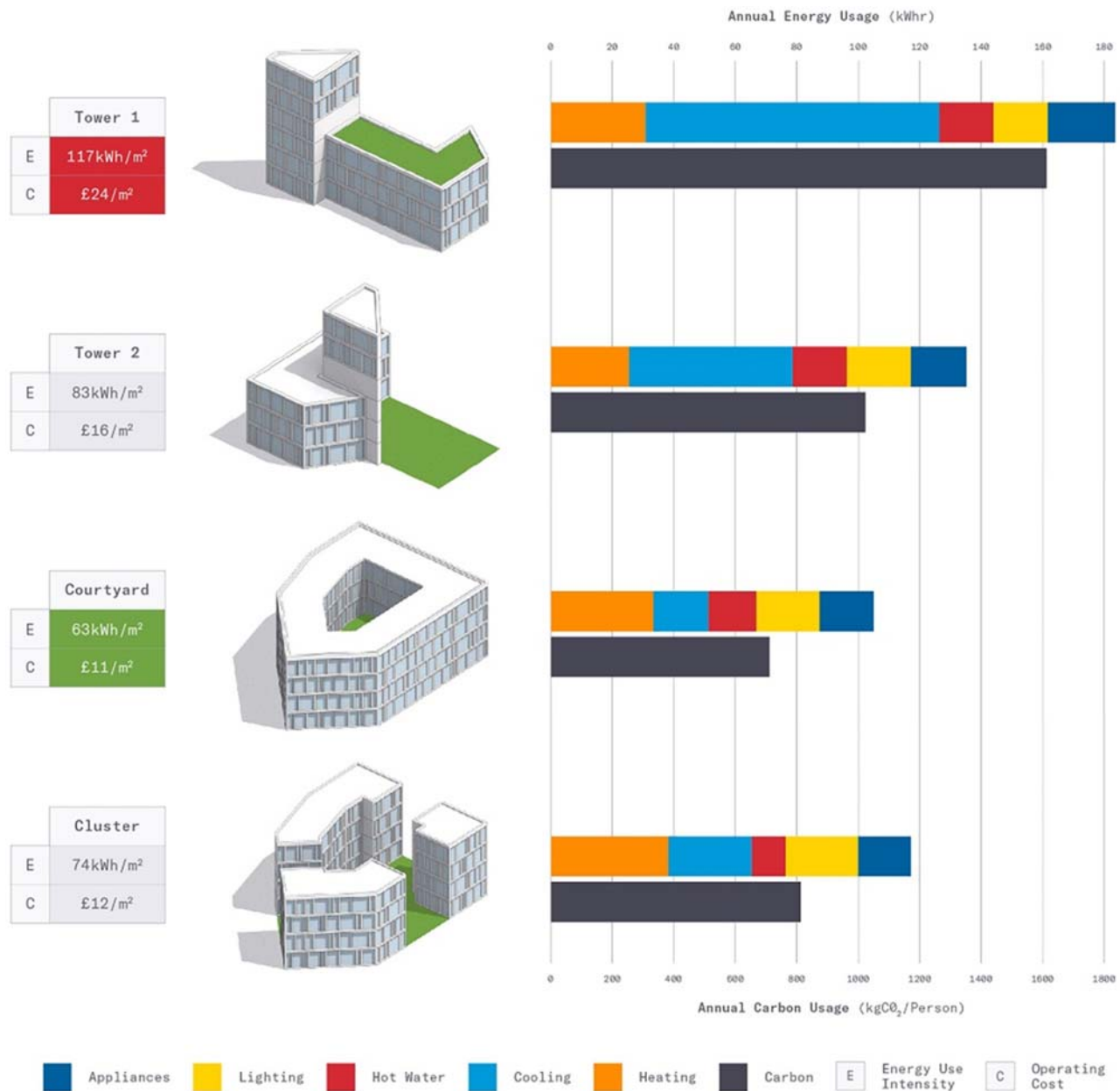


FIGURE 5.8 Massing options comparison with Trimble Sefaira. *Courtesy of Trimble.*

At the end of the analysis, a report is produced on the amount of energy and electricity consumed per annum by various factors such as area light, external usage, miscellaneous equipment, space cooling, vent fans, pump aux, and hot water, as well as efficiency factors achieved through glass type, lighting, green roof, wall type, orientation, and PV panels window-to-wall ratios, and window shades, among others.

5.2.3 IES virtual environment

The IES virtual environment (VE) is an all-in-one, proprietary suite of building performance analysis applications. It is a commercial software comprising of a range of built-in modules for accomplishing various simulation tasks including daylighting, artificial lighting, thermal behavior, or airflow (Geetha Ramesh & Ramachandraiah, 2021). IES VE can be used by designers to test different options, identify passive solutions, compare low-carbon and renewable technologies, and draw conclusions on energy use, CO₂ emissions and occupant comfort. The VE contains an integrated central data

model interoperable with most BIM processes, which has direct links to SketchUp, Revit, Vectorworks and allows gbXML, IFC & dxf imports. Differently from other mixed modeler/engine solutions, IES VE employs its own simulation engines in the different modules that deal with various aspects of modeling.

In particular, whole-building energy simulation is carried out via the ApacheSim central simulation processor, which is certified in the United States for ASHRAE 90.1 and LEED Energy Modeling as well as UK and Ireland code and BREEAM compliance, French standard RT 2012, Honk Kong and Malaysia OTTV, Singapore Green Mark system, Australia Green Star and Estidama Pearl Rating System. ApacheSim is a dynamic thermal simulation program based on first-principles mathematical modeling of the heat transfer processes occurring within and around the building and is capable of solving problems of thermal insulation (type and placement), dynamics and thermal mass, building massing and orientation, glazing properties, shading, solar gain and solar penetration, casual gains, airtightness, natural and mechanical ventilation, HVAC systems including mixed-mode systems. The conduction, convection and radiation heat transfer processes for each element of the building fabric are individually modeled and integrated with models of room heat gains, air exchanges, and systems. The simulation may cover any period from a day to a year, and the time-evolution of the building's thermal conditions is traced at intervals as small as one minute. Simulation outputs include comfort statistics (using PMV/PPD Analytical, Adaptive Thermal Comfort and Direct Solar Radiation Methods), energy consumption, carbon emissions, room load statistics, plant sizes, hourly room temperatures (air, mean radiant and dry resultant), humidity, plant loads, casual gains and air exchanges, as well as surface temperatures for comfort studies or CFD boundary conditions.

Lighting simulation is carried out using RadianceIES or FlucsPro modules, which allow to perform both quick early-stage analysis and greater detail simulation of natural and artificial light, to assess visual comfort related to brightness and glare, to determine daylighting metrics (Daylight factor, UDI, sDA, ASE), to calculate the number of electric light fittings required in a room and the energy potential for daylight and artificial light dimming, and to produce photo-realistic rendering images based on physically accurate lighting simulations.

Solar shading simulations are carried out by the SunCast module, which can determine how solar rays pass through both external and internal openings and track solar rays across rooms and atriums throughout the building interior, allowing to optimize passive solar heating, solar gains, daylighting and PV panels placement (see Fig. 5.9).

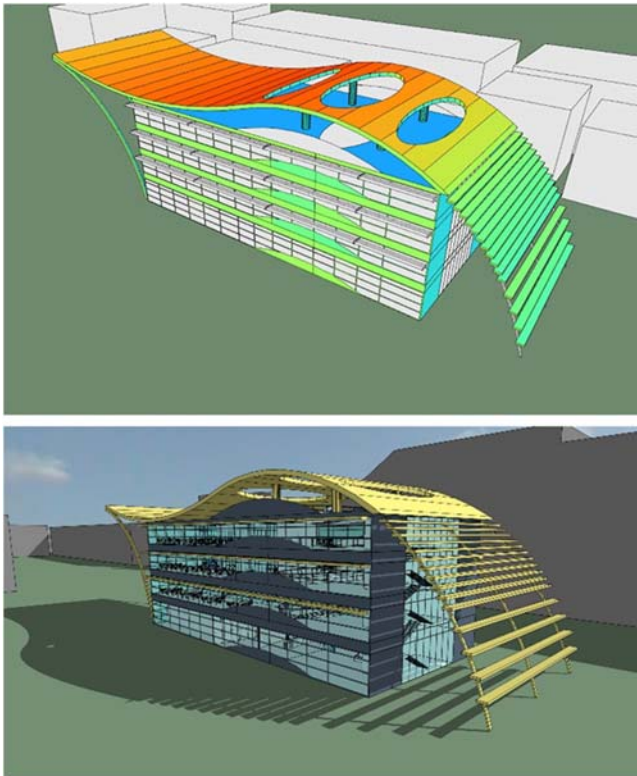


FIGURE 5.9 Solar analysis in IES VE. *Courtesy of IES.*

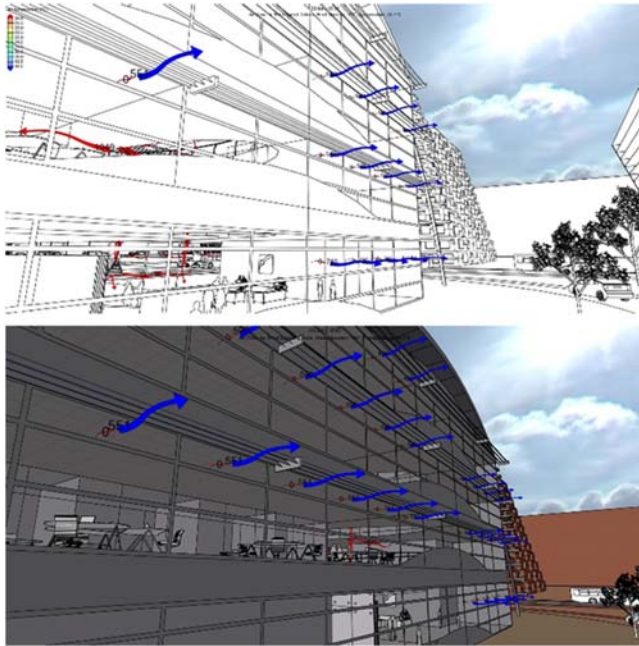


FIGURE 5.10 Airflow analysis in IES VE. *Courtesy of IES.*

Airflow can be simulated by the MacroFlo and MicroFlo modules either using quicker multizone thermo-fluid solvers or more accurate CFD analysis. This allows to investigate natural and mixed-mode ventilation, overheating, infiltration, optimal vents placement, daily and yearly thermal comfort, and evaluate feasibility of strategies such as single-sided ventilation, cross-ventilation, whole-building ventilation, chimneys, dynamic façade, and window opening controls (see Fig. 5.10).

HVAC systems can be assembled with the ApacheHVAC module, which, in addition to system modeling and simulation, features plant equipment and autosizing wizards. The IndusPro model allows drafting and designing the air-duct network for supply and extract systems directly in the 3D model of the VE, using constant friction, constant-velocity or static-regain methods, balancing the system either using dampers only or by resizing nonindex runs, and accounting for duct-heat pickup and the consequent volume-flow changes through the system. The PiscesPro module, in turn, enables drafting and sizing the pipework system of heating/cooling networks including single-pipe, two-pipe and reverse-return systems. The modeler allows the possibility of balancing the circuit using valves only or by resizing nonindex paths in the network, as well as defining velocity limits for the system, and automatically assigns fitting types at each junction.

Life cycle assessment (LCA) and LCC analyses can be carried out within IES VE through the LifeCycle and One Click LCA modules, which allow to predict the building's LCC and LCA into early-stage design and help compare the optimum long-term strategies by interrogating operational cost implications using dynamic thermal modeling directly from the building model. These tools also make IES VE compliant with BREEAM, LEED, and other Voluntary Emission Reduction (VER) credits

Finally, IES VE can be integrated with the Simulex module to define building occupants and simulate movement, egress, elevators in day-to-day and emergency situations. The processor shows how the population evacuates (including queuing, congestion, overtaking etc.), monitoring the number of people left in the building at any time, and predicting how long it will take all the occupants to reach the exits, separately for each floor plan and staircase.

5.3 Data and accuracy for building performance simulation

BPS programs can be powerful tools to predict future building performance; however, their accuracy largely depends on the quality, representativeness, and significance of input provided by the user. In particular, BPS software require hundreds or thousands of inputs, which may be assigned manually by the user or by importing data from CAD models, shared schemas (BIM), and databases of constructions, HVAC components, load and user profiles, weather data, etc. It is apparent that, regardless of the modeling and mathematics/physics approach of the simulation tool, input data and the assumptions taken in order to simplify building's parameters play an important role in terms of modeling time and reliability (Østergård et al., 2016). In addition to physical parameters related to building construction (shape and geometry,

materials), which are inherently exact by nature, many input parameters required in BPS are more variable and stochastic in nature. These are often assumed imprecisely or oversimplified, and the variety of uncertainties is often ignored in order to allow the deterministic prediction of buildings' performance. These uncertainties are recognized as the main reason of the performance gap registered between simulated and operational results and depend mostly on the inadequate characterization of operational schedules and occupants' behavior (OB) and on the quality and reliability of data contained in weather files, assuming that the modeling of building components and the simulation algorithms are up to the task (Erba, Causone, & Armani, 2017). In particular, the bidirectional interactive relationships between occupants' behaviors and building performances are the most important linkages between human and building: different occupancy patterns, inhabitants' lifestyle/habits, comfort preferences and associated actions may all lead to distinct building system performances even for buildings of the same type (Xie et al., 2021).

5.3.1 Occupant behavior

The category of OB encompasses all phenomena that concern the response of building occupants to factors which depend on the physical properties of the building, the indoor and outdoor environmental conditions, the predicted state of building systems, the time of day, as well as their personal characteristics (e.g., gender and age), and physiological, psychological, social and random factors (Xie et al., 2021).

In particular, environmental and time-related factors may play a crucial role on the behaviors of inhabitants (see Table 5.12). For instance, window opening behaviors in residential buildings are strongly related to the daily routine activities of occupants, such as sleeping, cooking, and studying. In an office building, window open/close actions are usually affected by arrival and departure activities (i.e., open on arrival and close before departure) and daily working schedule. Generally, occupant behaviors in office buildings are more regular and constrained than in residential buildings (Day et al., 2020).

TABLE 5.12 Driving factors influencing occupant behavior in buildings (Xie et al., 2021).

Behavior	Drivers	Details
Window use	Environmental Time-related	Outdoor temperature Indoor temperature CO ₂ concentration Time of the day
Light switching	Environmental Time-related	Work plane illuminance Illuminance Arrival and departure time
Shading and blind use	Environmental Time-related	Illuminance Solar radiation Glare Outdoor and indoor temperature Season Time of the day
Air-conditioning use	Environmental Time-related	Outdoor and indoor temperature Weekday and weekend Time of the day
Thermostat use	Environmental	Outdoor and indoor temperature
Fans and doors	Environmental	Outdoor and indoor temperature
Daily routine (kitchen, toilet, relax)	Time-related	Weekday and time of the day
Housework, interior cleaning, laundry, plant repairs	Time-related	Weekday and time of the day
Irrigation	Environmental Time-related	Outdoor temperature Sun radiation Humidity Rain Season and time of the day

Commonly studied behaviors in OB models include occupancy presence/absence, lighting and blinds control, windows opening, plug-load usage, and other user interactions, which may have a substantial impact on actual building performance. Current BPS tools, however, provide only a simplistic representation of OB and its effect on simulation outputs and have limited built-in features for OB modeling (Azar et al., 2020). In fact, OB is commonly represented by standardized schedules or predefined inputs which are oversimplified versions of complex reality, making it difficult for practitioners and stakeholders to make more rational decisions on selecting energy saving technologies, especially in cost-optimal analysis and LCA (Li, Yu, Haghighat, & Zhang, 2019).

Occupants influence their built environment through both their sheer presence (e.g., heat release and carbon dioxide emissions) and their interactions with buildings (e.g., lighting, windows, blinds, HVAC set points, and plug appliances), and energy-related OB can also include unconscious physiological adjustments such as sweating and shivering, or individual adjustments such as clothing changes (Schweiker, Carlucci, Andersen, Dong, & O'Brien, 2018).

Currently, the most popular sources of plug load profiles are from the ASHRAE 90.1 User Manual, often used for LEED Energy Modeling or Code Compliance Modeling, which define the typical occupant's behavior in terms of equipment use as weekday and weekend subhour power consumption profiles. Plug loads are one of the main contributors to overall modern building power consumption, accounting up to 50% of the total electricity consumption of buildings with high efficiency HVAC systems (New Buildings Institute, 2012) and are therefore determinant in building load calculations for accurate sizing of HVAC equipment. ASHRAE standard 2017, 29.17 provides guidance for evaluating internal heat load due to appliances, both latent and sensible.

Concerning BPS tools, DesignBuilder considers energy behavior in the "activity" section of the software, which includes occupancy (to modify the density of people within each zone), activity factor, gender adjustments, clothing, and use of computer and other equipment. EcoDesigner plugin for Archicad, as well as Insight for Revit, have less occupancy inputs limited to occupant's presence schedule and type of activity that determines the human heat gain. Thus most designers rely on default occupancy schedules of energy simulation software for energy analysis. However, input occupancy data in those do not necessarily reflect reality, as it is limited to occupants' presence in fixed and scheduled patterns, and, in residential buildings, the default occupancy is measured based on the floor area (Delzendeh, Song, Lee, & Zhou, 2017).

This unreliable representation of occupancy patterns, as well as the lack of knowledge in terms of how occupants actually interact with buildings, pose significant challenges in improving BPS accuracy and reducing the performance gap versus measured performance. It is widely recognized that there is a need to understand the actual process of occupants' energy-related behavior, and research has developed various mathematical models with this scope. In this picture, the International Energy Agency (IEA) Energy in Buildings and Community (EBC) Programme Annex 66 has established a scientific methodological framework for occupant behavior research, including data collection, behavior model representation, modeling and evaluation approaches, and the integration of behavior modeling tools with BPS programs (Yan et al., 2017).

OB models can be classified into four main categories: statistical models, stochastic/probabilistic models, data mining models, and agent-based models. Statistical models commonly use regression methods or generalized linear methods to construct the numerical connection between influencing factors and the behavioral metrics—for example, regression models can correlate window opening and closing behavior with indoor/outdoor temperature or both. Stochastic/probabilistic models (mainly Bernoulli process, Markov chain, and survival analysis) capture and describe the probability that a specific behavior occurs based on historical or statistical data and can be used to represent both occupancy and the actions occupants take to control their indoor environment. Data mining models apply machine learning methods on large databases of residential and office buildings operation to extract patterns and insights on the way occupants behave and are being increasingly used due to their good accuracy and the recent availability of more and more robust datasets from real-world observations. Lastly, agent-based methods separately create, analyze, and manipulate the models that constitute the agents interacting with a specified environment, each computed as a real-world individual with their own features and capabilities and have recently become the most popular method for the OB modeling approach in the built environment (Uddin, Wei, Chi, & Ni, 2021; Zhang, Bai, Mills, & Pezzey, 2018).

These OB models can be integrated into BPS tools to improve the real-world accuracy of their results in four main methods:

- Direct input or control, in which occupant-related inputs are defined using the semantics of BPS programs as the other model parameters (geometry and construction, HVAC, heat gains, etc.).
- Built-in OB models, already implemented in the BPS software normally using linear or logic regression functions to model occupant movement, window operation, and lights switching.

- User function or custom code, in which users write their own code to implement new or overwrite existing or default building operation and supervisory controls. Several EMS scripts and Openstudio libraries are available to be directly applied to EnergyPlus for typical OB models.
- Cosimulation, in which building performance and OB simulations are carried out in an integrated manner, via running modules developed by different programming languages or in different physical computers (Hong, Yan, D'Oca, & Fei Chen, 2017; Taveres-Cachat, Favoino, Loonen, & Goia, 2021).

Among these methods, cosimulation has received considerable interests due to its flexibility in offering a cooperative way of different programs and address the interoperability issue of OB modeling in BPS tools (see Section 10.4.3.1 for additional information on cosimulation). Two notable examples are the OB modeling tools developed under IEA EBC Annex 66, named obXML and obFMU. Specifically, obXML is an XML schema that standardizes the representation of energy-related OB models for BPS. These obXML files, available in libraries and developed from literature, can be exchanged between different BPS programs, different applications, and different users. Conversely, obFMU is a modular software component represented in the form of FMUs, enabling its application via cosimulation with BPS programs using the standard functional mockup interface. The obFMU tool reads the OB models represented in obXML, including lighting control based on visual comfort and daylight availability, temperature set points, HVAC system control, occupancy-based plug load control, and window opening and closing based on indoor and outdoor environmental parameters. It functions as a solver of these OB models and runs in parallel with BPS tools like EnergyPlus and ESP-r via cosimulation to improve the modeling of OB (Azar et al., 2020).

5.3.2 Weather data

BPS strongly depends on boundary conditions to input its mathematical/physical equations and drive its simulation runs, and data concerning weather is one of the most significant for its impact on produced results, as it dictates simulation parameters such as outside temperature and humidity, wind intensity and direction, sun irradiation, etc. At the same time, the concept of climate-adapted buildings is becoming crucial, and there is a growing need to investigate passive techniques able to harness the local climate and weather characteristics effectively. For simulation purposes, weather data can be sourced with varying degrees of fidelity, granularity, and reliability, from built-in and online weather databases or from local data collection by the users, according to the intended use of the simulation.

It is apparent that, to ensure maximum simulation accuracy, environmental input data should ideally be observed exactly at the project site, subject to all local conditions, with observations made at intervals consistent with the modeling being undertaken. At the same time, such an activity requires considerable effort, which may not be proportional to the specific application and can greatly reduce quality of the simulation results if done without the necessary care. Recommended methods to collect local weather data employ one or more aptly positioned weather stations featuring sensors for the following minimum parameters: global solar radiation (W/m^2), diffuse solar radiation (W/m^2), air temperature ($^{\circ}\text{C}$), wind speed (m/s), wind direction (degrees), relative humidity (%), rainfall (pluviometric mm), and sunshine duration. The weather station is completed with an environmental data logger to initiate the readings, control the sensors, and store data related to the observation range (typically 10 minutes). The measured weather data are then processed to produce the required input parameters (e.g., monthly average values) before being implemented in the BPS tools subroutines (Ciobanua, Eftimie, & Jaliu, 2014).

The go-to resource for weather data for simulation is, in the great majority of use cases, constituted by file repositories built in the BPS tool of choice or available online, in which weather files can be sourced for the chosen location. Historically, large-scale (national) weather data observation programs have supported various activities such as general forecasting, aviation, and agriculture, with limited consideration for engineering applications, although this situation is improving as technology lowers the cost and increases the sophistication of data observation, management, and modeling. Traditionally, weather data for simulation are represented in files of values for the 8760 hours of a year, a level of detail that allowed a practical enough reporting cycle of manual observations, which would also be short enough to capture behaviors of interest in buildings but long enough to allow reasonable simulation run times. Current formats of weather files include Typical Meteorological Year (TMY) and EnergyPlus Weather (.EPW) file. A TMY file is a set of meteorological data with data values for every hour in a year for a given geographical location, reported as text values separate by commas or in tabular form. The data are selected from hourly data in a longer time period (normally 10 years or more) with each month selected from the year that was considered most representative for that month—for instance, January might be from 2007, February from 2012, etc. to allow estimation of long-term (multiyear) performance from a single year analysis. Last release of TMY files, dubbed TMYx, is derived from hourly weather data

TABLE 5.13 Information included in TMY simulation file.

Element	Unit
Year	TMY/TGY/TDY2017 1998–2017
Month	1–12
Day	1–28, 1–30, or 1–31
Hour	1–23
Minute	0
Dew point	°C
Diffuse horizontal irradiance (DHI)	W/m ²
Direct normal irradiance (DNI)	W/m ²
Global horizontal irradiance (GHI)	W/m ²
Temperature	°C
Pressure	mbar
Wind direction	Degrees
Wind speed	m/s
Surface Albedo	Ratio

through 2017 in the ISD (United States NOAA’s Integrated Surface Database) using the TMY2/ISO 15927–4:2005 methodologies, and is available in the more flexible CSV file format. Typically, the TMY grid reports location data (city, state, country, latitude/longitude, time zone, elevation) as well as the actual hourly environmental data as reported in [Table 5.13](#).

EPW format is further optimized for use in BPS, allowing inclusion of design conditions, extreme period sequences, and subhourly data, and can be read or translated by more than 20 building simulation programs. Weather data files commonly refer to airports or air force bases, which are often far from the building site and may experience different local conditions compared to urban centers, in particular regarding increased winds from low ground rugosity and lower temperatures due to the lack of heat island effect.

TMY and EPW files are best suited for energy design and compliance analysis of fully conditioned buildings. In this baseline simulation application, energy savings information is derived by comparing results for design variants and benchmarks; hence, there is little need for absolute accuracy as errors partially compensate, short-time inaccuracies are not significant, and the mechanical HVAC system will ensure actual building comfort. Similar comparison procedures are used in energy code compliance and building labeling programs.

However, using TMY files in building simulation for “what-if” analyses of designs or more specific applications returns only the response of the building or design strategy to typical climatic conditions, for the period of record of that file. Therefore simulating with typical weather provides little information about the sensitivity of a building or design strategies to variations in the climate itself ([Rastogi & Andersen, 2015](#)). With a methodology similar to TMY, extreme years files can be considered for simulation. These consist in one-year weather data files which either include an extreme summer (e.g., Design Summer Year [DSY]) or winter (e.g., Extreme Cold Year) or combination of both (e.g., Extreme Meteorological Year).

In particular, TMY files are less adequate for the following use cases, which may require alternative weather data for deeper and more accurate investigation:

- performance simulation of un- or semi-conditioned buildings, in which overheating analysis, passive solar design, and other problems involve non average weather conditions—for example, a comfort simulation for a building without mechanical cooling might require weather data from a particularly warm summer chosen over multiyear analysis;
- natural ventilation studies, which strongly depend on local wind conditions, hence cannot rely on historical data from airport stations alone but require on-site measurement;

- determination of maximum heating or cooling demand for HVAC sizing, which is typically based on design-day or short period calculations using near-extreme conditions that may not appear in TMY tables;
- model calibration, control optimization, actual savings estimation, and other applications involving the performance of existing buildings, which require weather data observed during the study period at or near the building site.
- Simulation of renewable energy systems, in which standard hourly data may produce unreliable results for systems that have nonlinear characteristics such as photovoltaics and wind turbines which output depends on incident radiation or wind velocity (Crawley & Barnaby, 2019).

In addition to the established quality requirements of buildings in terms of energy efficiency and thermal and visual comfort, the concept of climate-resilient building has emerged in the last years, that is, buildings that are designed to cope with the extreme or unforeseen weather conditions which occurrence is expected to become increasingly common in the coming years due to the climate change disruptions. When aiming at climate-resilient buildings, future weather data are needed for simulation to consider the various possible climate realizations. In the last years, several methodologies have been developed to implement future weather files/datasets (Ramon, Allacker, van Lipzig, De Troyer, & Wouters, 2019). A first method, known as analog scenario method, is to use a weather file from a different location which currently has similar climate conditions as expected for the building location in the future. A second option is to select a year from the past that is warmer than normal to represent the future climate. In both these methods, however, the important role of solar radiation makes it hard to find suitable weather files, as it strongly depends on the latitude of the location, and its change is underrepresented in current climate change scenarios.

Ongoing research about future weather data for building simulations make in general use of a third method based on General Circulation Models (GCMs) to construct possible trajectories of the future climate. These models aim at simulating the state and evolution of the atmosphere, including the atmospheric circulation and energy exchanges in terms of radiation, heat and moisture, the processes related to cloud formation and precipitation, and take into account the interaction with the ocean and the land. GCMs provide climate information on the global scale with a typical spatial resolution of 150–600 km; hence, they must be downscaled at the local level to consider location-specific factors such as urban heat island effects (Jacob, Petersen, & Eggert, 2014).

5.4 Integration with BIM

BIM models provide an excellent starting point for conducting BPS analyses, as they can include and integrate information about the building geometry, envelope components, materials, costs, HVAC system, electrical systems, and thermal properties of materials (Kamel & Memari, 2019), as well as incorporate relevant information for conducting LCA and LCC studies. At the current state, however, BIM is mainly employed in the architecture and engineering sector as a mean for faster development of 3D geometric models and to improve the accuracy of construction documents, the communication among parties in design and construction process and to reduce field coordination problems, and its utility in BPS applications is still limited to a repository of project data which often have to be reentered in the energy models. Nonetheless, the integration of BIM and BEM, known as BIM-BEM, is a growing trend in both research and commercial applications, with notable initiatives such as the IEA EBC Annex 60 project which focused its Activity 1.3 on the specific issue of transforming a digital model of a building and its HVAC systems into semiautomatically generated models for BPS (in this case, Modelica code) (Pinheiro, Wimmer, O'Donnell, & Muhic, 2018).

5.4.1 BIM-BEM interoperability

BIM-BEM integration offers multiple benefits, greatly easing the handling data and allowing automation in energy modeling, better presentation of output, capability of storing and organizing new building data. Usually, in fact, more than 70% of the information needed for BPS is already stored within the BIM model (Choi, Shin, Kim, & Kim, 2016). Further progress in BIM-BEM interoperability would translate into major improvement of BPS usability, as seamless data migration between BIM and BEM would save time and effort and reduce human errors and open BPS even to less specialized professionals.

As an added benefit, BIM provides the building team with a substantial amount of information in an early stage, favoring the enhancement of building performance since the first phases of design, when the cost of changes in the project is relatively low. Ideally, in fact, BPS should be used throughout the design process to carry out various tasks at corresponding periods, as the building and energy model are developed from a preliminary one to a detailed one. At the concept design stage, the rough energy model needs only simplified thermal zones, and already allows to evaluate

design concepts such as site location, building massing and envelope, building orientation, and renewable energy sources. Although at this stage major assumptions are required for the energy model (e.g., fixed internal loads for all design alternatives), it does help the design team to weight the performance of one design alternative relative to another one. Progressing through the design stage, the building information becomes more detailed and BPS can help the design team optimize choices involving various layouts, HVAC systems, construction types, and basic architectural features. When finalizing design and engineering development, BPS moves on to the parametric analysis of the selected design based on a much more detailed energy model. These simulations can determine the relative impact of insulation values or HVAC subsystems and control (Gao, Koch, & Wu, 2019). Accomplished interoperability between BIM and BEM removes the main barriers to this performance-based process, which is the lack of time, money, and information that causes the BPS activities and results to always lag in time behind the timing of decision-making.

BIM-BEM integration can be implemented at various levels. A common workflow involves three main steps. First, BIM model is simplified within the BIM authoring software, removing unnecessary information and streamlining the building geometry, internal loads and equipment systems. Second, the simplified model is exported in interoperable-friendly formats, such as gbXML and IFC. Third, these BIM files are imported into the modeler GUIs of most BPS tools (Designbuilder or Openstudio for EnergyPlus, eQuest for DOE-2 or IES VE for Apachesim) which convert building information therein into data usable by the respective simulation engines. Both gbXML and IFC formats are suitable for BEM as they provide material properties, limited data for HVAC systems, and thermal zone data. Of these two, IFC is more flexible in nature and can be applied also to building construction or building operation domains, whereas gbXML is more geared toward the energy simulation domain, for instance by including data about the project location. Moreover, IFC is object oriented with a top-down structure, and all information is illustrated in an organized approach, whilst gbXML is a bottom-up structure and is easy to comprehend. Overall, gbXML is considered a better performing format for BIM-BEM integration, and it has been estimated that there are almost five times as many energy modeling programs which support data transferring to gbXML than the ones that support IFC. Ideally, BIM models should successfully transfer the following data to the BEM software: location and weather file, geometry, construction and materials, thermal zones, HVAC systems, and occupancy operating schedule (Elnabawi, 2020).

However, often BIM authoring tools might not be able to properly transfer required data to BIM files, and even if BIM files carry the required information, the BEM tools reading such files might not be capable of retrieving these data properly, requiring the use of corrective middleware tools to improve this process (Kamel & Memari, 2019). A common example of middleware is the Space Boundary Tool that eases BIM transfer to EnergyPlus by generating space boundaries that could be missing from the model and are necessary for BPS.

As an alternative integration path, some BPS tools such as DesignBuilder and IES VE, in addition to their ability to import and export in the gbXML file format, feature their own Revit plug-ins that should simplify and automate gbXML export procedures, which still cause errors in the exchange of data between the BIM and BEM. Nonetheless, studies have evidenced that satisfactory synchronization of BIM-BEM tools is still a long way ahead, and the data flow between the two programs tend to be one-way, meaning that any modification in BEM cannot be recognized in the BIM model. At the moment, it is still advised to differentiate the capabilities of the two approaches: BIM tools do not provide many options for customization, such as the operation schedule or HVAC, and might be a very helpful tool for early design analysis to support decisions such as building form, mass, orientation, and fenestration in which BIM sourced geometry and construction accelerate deployment, whereas BEM may be the best options for a validated energy analysis at the later phases of the project life cycle (Elnabawi, 2020).

5.4.2 Parametric energy modeling

An emerging solution to the current issues of BIM-BEM interoperability consists in parametric design. Parametric design consists in linking determined design activities within the BIM or 3D authoring tool to user-defined scripts, allowing to automate these tasks according to the specific parameters. This allows to automate menial tasks (e.g., placing lighting fixtures or doors in corridors at specific intervals), but, more importantly, enables to correlate design actions to parameters which in turn result from user specific equations or proper performance simulations (e.g., creating windows or awnings of the right size to ensure daylight requirements). Moreover, a parametric approach to specific design problems enables iterative comparison of different solutions procedurally generated by a specific algorithm, allowing the modeler to evaluate numerous potential designs to produce guidance that design teams can use as an informed starting point in the design process. In fact, the analysis and simulation workflow commonly still revolves around a set process: a single instance of a building (i.e., without changing parameters) is modeled in a software and analyzed in a separate program, making iterative evaluations unnecessarily cumbersome and time-consuming. The use

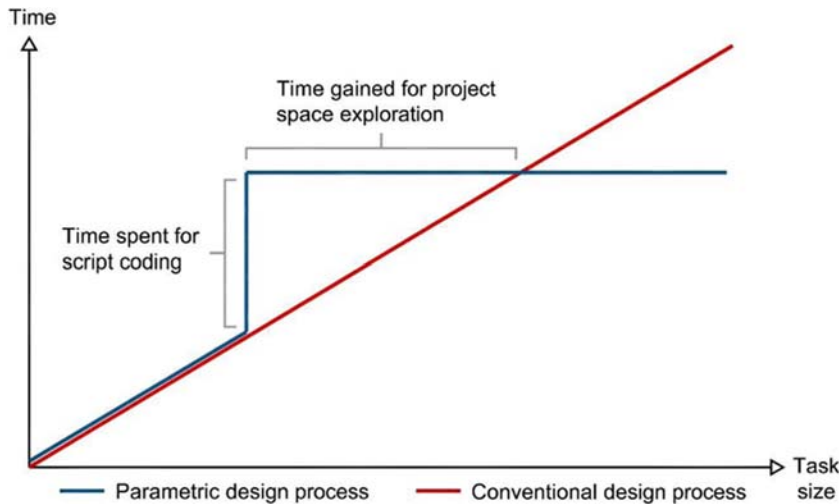


FIGURE 5.11 Comparison between time spent in parametric and conventional simulation processes.

of a parametric, easily manipulatable and responsive model base for analysis/simulation instead of a static one greatly eases testing the effects of multiple design choices (Fig. 5.11). Furthermore, parametric modeling allows to assess each system's compensation and responsiveness for introduced variables (sensitivity analysis): by perturbing one or more parameters of the model and keeping the others constant, the designer understands how the target performance metrics are affected by each design factor (e.g., EUI may be particularly sensitive to WWR rather than orientation) (Samuelson, Claussnitzer, Goyal, Chen, & Romo-Castillo, 2016). In some cases, it is capable of identifying autonomously the best ones (generative design). Parametric and generative design are explained in more detail in Chapter 6 concerning Advanced Digital Design Tools and Methods.

Main software tools for augmenting 3D and BIM modeling with parametric design include Autodesk Dynamo, a visual programming environment integrated in Revit, and Grasshopper, a graphical algorithm editor which enables parametric 3D modeling within Rhinoceros 3D modeling tool. Both provide visual programming interfaces for intuitive scripting of design parameters without learning special syntax and facilitate the link between model and analysis/results in a way that allows the designer to keep manipulating parameters on the model until a desired analysis result is achieved (Toutou, Fikry, & Mohamed, 2018).

The parametric BIM or 3D model is interfaced with BPS software (EnergyPlus, Radiance, Therm/Window etc.) through specific middleware tools. The most prominent of these is the Ladybug Tools suite, compatible with both Dynamo and Grasshopper, which consists in the following plugins for different applications: Ladybug, Dragonfly, Honeybee, and Butterfly.

Ladybug performs analysis of climate data to produce customized, interactive visualizations for environmentally informed design. It can import standard EPW files into Grasshopper and Dynamo and provides 2D and 3D interactive climate graphics, solar radiation studies, view analyses, sunlight-hours modeling to support decision-making during the early stages of design. Integration with parametric design tools allows instantaneous feedback on design modifications and a high degree of customization. Main features include solar diagram plotting, shadow studies and masks, solar access study, psychrometric and adaptive comfort charts, and renewable energy integration. Ladybug is integrated by the Dragonfly application that models large-scale climate phenomena such as urban heat islands, climate change projections, and local topography influence on the project.

Honeybee supports detailed daylighting and dynamic energy modeling and is more geared toward mid and later stages of design. It runs simulations and visualizes the results by linking the parametric model to Radiance for daylight simulations, EnergyPlus/OpenStudio for energy modeling, and Berkeley Lab Therm/Window for heat flow through construction details. Honeybee allows to simulate illuminance, daylighting, glare, artificial lighting, heating and cooling energy use and peak loads, energy balance, indoor thermal comfort and microclimate mapping, as well as heat flow and condensation through building envelope elements.

Butterfly plugin performs CFD simulations using OpenFOAM engine allowing to integrate airflow into building design. Applications include indoor airflow to assess ventilation, outdoor airflow to model wind patterns in urban settings, buoyancy and stack effect phenomena, as well as HVAC-generated drafts and air currents.

Another common BPS plugin is ClimateStudio, which links Rhino/Grasshopper to the EnergyPlus and Radiance simulation engines to create, simulate, and visualize results for building models directly within the 3D modeler, giving

the designer free-form control and instant in-program feedback, as well as optimizations, sensitivity analysis, and automated model generation. Concerning lighting design, ClimateStudio provides sun path and shadow analysis, LEED day-lighting compliance of the sDA metric, annual glare calculation, dynamic shades and smart windows simulation and scheduling, and electric lighting sizing. Regarding energy modeling, the software allows multizone simulation, spatial thermal comfort maps, natural ventilation simulation.

The integration of BPS and parametric tools from the first stages of the design process provides insight and guidance toward the quantifiable targets specified in the planning and programming phase. In particular, different simulations and tools are best employed in each design step of the BIM model development, according to workflows such as the following.

In the predesign stage, corresponding to BIM level of development (LOD) 100, it is possible to perform climate alignment and solar radiation analyses on preliminary massing box-like shapes, to obtain first energy projections and to set the sustainability goals of the project. In this stage, tools built in the BIM authoring software may suffice (e.g., Autodesk Insight for Revit, Archicad Energy Evaluation), as well as climate analyses tools such as Ladybug plugin.

In the preliminary design stage (LOD200), it is possible to analyze massing and orientation of the building, to assess PV and wind power capacity according to the weather data and to investigate facade options in terms of thermal properties, WWR, daylight, and heat gain/loss tradeoff. Results support design choices in terms of space configuration, lighting power density, and HVAC types. Suitable BEM software in this stage include energy and daylight plugins such as Honeybee, with some contributions from built-in energy analysis tools.

In the detailed design stage (LOD300), the design choices identified in the previous stage are optimized to the specific objectives. With spatial geometry fixed, envelope construction parameters such as insulation thickness, solar shades, fenestration geometry, and transparency can be optimized using parametric and generative approaches to identify the best solution in terms of energy saving, thermal and visual comfort as well as LCC and sustainability. PV systems can be optimized in terms of tilt, orientation and layout, and their capacity, efficiency and payback are calculated on real PV modules, dynamic context shading, and effective system loss factor. Thermal zones, occupancy schedules, and activities can be factored in to select and optimize HVAC options (plants and room units, control logics, sensors). In this stage, parametric design and energy simulation tools are necessary for elements optimization (Honeybee with Dynamo/Grasshopper), whereas HVAC sizing, controls and code compliance assessment may require a dedicated BEM software tool (Designbuilder, IES VE, etc.) to which the building model is exchanged via IFC or gbXML file formats.

Lastly, in the project delivery stage (LOD400, construction documentation), all building information is gathered and packaged for transmission to the client/contractor. Glazing and wall configuration, lighting fixtures, HVAC equipment characteristics are illustrated and integrated with their schedule documentation. Space and rooms' schedule documentation is also provided. For this final phase of design, only the BIM authoring software is needed (Revit, Archicad).

5.4.3 BIM and life cycle analysis integration

As reported earlier, LCA is becoming an increasingly important aspect of holistic design, and only its integration in the design process since the early stages can ensure the inclusion of the environmental impact in all decision-making. However, LCA process, as well as LCC analysis, requires considerable effort in data collection in terms of both materials and quantities, if sufficient accuracy is expected. The process of re-entering the data in environmental assessment software is time-consuming and typically not done by the specialists involved in the creation of the BIM models, leading to errors and misreadings which jeopardize the accuracy of LCA (Naneva, Bonanomi, Hollberg, Habert, & Hall, 2020). This makes it difficult to effectively include LCA iterations whenever design choices are made, especially in concept and preliminary design stages in which multiple technological and geometry solutions shall be compared at the same time.

In this picture, BIM-LCA integration can greatly help to make the design process of a sustainable building more efficient and to optimize the management of the necessary data, providing LCA results and insights in a short time compatible with the decision-making process. Indeed, whereas traditional design environments typically provide less support for visualizing the feasibility of initial design decisions, linking the BIM model to a LCA tool enables detailed environmental compromise analyses to be conducted in the early stages of design. Since BIM programs allow to simultaneously manage both the graphical and nongraphical aspects of the project, they provide an effective tools for designers to quickly manage the amount of information needed to perform the LCA analysis (Mora, Bolzonello, Cavalliere, & Peron, 2020).

In particular, the 3D BIM model represents a repository of parametric objects improved by semantic information and data that, once extracted, can be used to conduct analysis on the model. BIM can reduce the time-consuming nature of the LCA for collecting data as it allows for performing quick quantity take-offs. Ideally, BIM-LCA integration would enable designers to conduct whole-building LCAs during design and to use LCA data to run comparative analyses of various design options that show their differing environmental impacts.

In order to achieve this, the information flow between BIM and LCA tools can be streamlined by either simplifying the data input (BIM information extraction) or by implementing the environmental information into the digital model itself (BIM inclusion of environmental properties).

The first approach entails the use of automatic take-off tools that extract information directly from the BIM model, using IFC as a data-sharing format or converting them into Bill of Quantities (BoQ) to import as xls spreadsheets. LCA is then performed by combining the quantity building data obtained from the BIM model with the life cycle inventory data in order to obtain the desired environmental indicators. This approach avoids data re-entry in the LCA tool and can be used for real-time assessment and comparison of different alternatives with sufficient accuracy. However, as the performance of the LCA is not developed in the BIM software itself, any changes in the BIM model can only be made by going back to the BIM software and then re-importing the model into the LCA platform. Furthermore, interoperability between BIM models and LCA tools is still not perfect, therefore extracted information may be prone to semantic or reading errors that may hinder the LCA accuracy (Antón & Díaz, 2014).

The second approach, on the other hand, aims at automating the link between the BIM model and the environmental information present in LCA databases. This way, the environmental properties are incorporated into the parametric BIM objects themselves: as the building is modeled in the BIM authoring tool, designers assign materials and quantities to create a Bill of Materials for the full building or constituent parts. This Bill of Materials automatically updates as the design changes, allowing to see in real-time the impact the design choices have on the buildings' overall sustainability. However, the resulting assessment will be mainly material oriented, since it is based on information referring to different materials and components. Some studies consider this as an estimation for use up to the construction phase, rather than to evaluate the entire life cycle, as the issue of calculating and automatically including the information related to transportation of the different materials and elements to the construction site, considering the different characteristics, location, and features of each project is still unresolved (Antón & Díaz, 2014). This approach may also involve the use of LCA plug-in tools for BIM for greater convenience. These enable fast results, but have the limitation that in most cases they use generic data. Therefore these tools are often used in the early design stages to identify the most important impacts.

One of the most used LCA plug-ins is Tally, an Autodesk Revit application that allows whole-building analysis as well as comparative analyses of design options. While working on the BIM model, users can define relationships between BIM elements and construction materials from the Tally database (GaBi data from thinkstep). The resulting LCA-on-demand can become an additional layer of decision-making information within the same time frame, pace, and environment that building designs are generated. If the impacts of the operational phase are also assessed, then Tally can be combined with Green Build Designer, which is also a Revit plug-in (Obrecht, Röck, Hoxha, & Passer, 2020).

LCA plugins for the Rhino3D and Grasshopper platforms include Tortuga, which evaluates the LCA and GWP (CO₂e) by accessing either Quartz Project LCA Data (United States/GaBi) database or Ökobau.dat (DE) database, and BOMBYX, a plugin developed by ETH Zurich which focuses on the assessment of embodied impacts using the Swiss LCA database for building materials.

For both approaches, the BIM LOD is a key concept of BIM-LCA integration and is closely related to the design stage set for the case study. A low level (LOD100 or 200) already allows to estimate the environmental impacts in the earlier design stage. This in turn leads to the effective comparison of the different buildings design scenarios from the environmental point of view and can support the selection of more sustainable materials for different building assemblies and the modification of the detailed building design (LOD300 or above) to reduce the environmental impacts, especially concerning the production and construction phases (phase A). In the case of LOD300 or above, the evaluation of the usage stage (phase B) should be absolutely considered for an accurate LCA assessment of the whole building (Mora et al., 2020).

Similarly to LCA, web-based embodied carbon calculators such as EC3 allow to import project material quantities from BIM models interfacing with Autodesk's BIM 360 modeling software and Tally. The tool features its own database of EPDs provided by manufacturers to populate the model and calculate the project's embodied carbon estimate. Users can set project specific reduction targets, and after products have been procured, select utilized products to document the project's actual reductions against the targets set. The project's embodied carbon baseline estimate, reduction target and as-built results can be visualized as a Sankey Diagram for quick representation.

5.5 Conclusion and future trends

In the last two decades, performance simulation of buildings has assumed ever greater importance within the design process, today reaching the full integration into the design workflow thanks to a wider availability of accurate, mature, flexible, and easy-to-use software tools. Indeed, BPS allows to reduce environmental impacts, improve indoor quality and productivity, and facilitate future innovation and technological progress in construction. BPS draws on many disciplines, including physics, mathematics, material science, biophysics and human behavior, environmental and computational sciences. Performance simulation itself is continuously evolving and maturing, as improvements in model robustness and fidelity are constantly being made and new simulation domains, such as massing, traffic, and pedestrian patterns, or life cycle costing are being added.

Initially dedicated only to the final phases of the design to support systems sizing, code compliance, benchmarking, or quality control, BPS has now expanded both to the early stages of design and to postconstruction activities, such as commissioning, operation, and management, and today finds full application in the complete building life cycle, from conception to demolition.

Overall, in fact, the goal to design high performance buildings requires the optimization of a large number of aspects, such as energy demand, indoor environment, materials, LCC, etc., which are often conflicting. Only the integration of BPS into all phases of the design process, from planning and programming, to early-stage decisions, up to systems sizing and energy code compliance verification, can allow to implement the informed and performance-based design approach that enables optimization of all factors and requirements.

Very important in this sense is developing the integration of BPS and BIM that today represents a growing trend in both research and commercial applications. BIM models provide in fact an excellent starting point for conducting BPS analyses, as they can include and integrate information about the building geometry, envelope components, materials, costs, HVAC system, electrical systems, and thermal properties of materials as well as incorporate relevant information for conducting LCA and LCC studies.

For early design stages, specific BPS tools are available on the market, often integrated into the main 3D sketching, massing, or conceptual modeling tools. Comparative analysis software can be used to calculate the cost-effectiveness of energy-efficient measures against a base case, allowing to test different building design concepts and assess the ecological and economic savings of efficiency measures regarding energy and water use as well as embodied carbon.

BPS can also be further enhanced through parametric design, which enables iterative comparison of different solutions procedurally generated by a specific algorithm, allowing the designer to quickly compare and evaluate numerous potential solutions to produce guidance that design teams can use as an informed starting point in the design process.

Lastly, in order to better align the simulated results with the actual performance measured in the real conditions of use, an important research trend is represented by the integration into BPS tools of occupant behavior models that can provide a more plausible representation of both occupancy patterns and the modalities of interaction of occupants with buildings in relation to their preferences and climatic conditions. Among the different OB methods, cosimulation has received considerable interests due to its flexibility in making different OB modeling and BPS programs interoperate.

Once the building is operational, BPS finds strategic application as a tool for improving the building control systems or for evaluating its operational performance (MPC). BPS can support management decisions by conducting what-if scenarios, for instance, to evaluate the effect of specific actions or modifications within the building before they actually take place. This is particularly effective when BPS is applied on the building's digital twin.

Thanks to the ever-increasing amount of data made provided by the diffused adoption of IoT and BAS, future trends on BPS regard the development of statistical and algorithm-based tools as an alternative method to predict the future behavior of buildings in the first stages of design, in which conventional physics-based models struggle with the limited project values available. Such black-box methods take advantage of the availability of a wealth of historic data concerning design and operation of multiple buildings (Big Data) as well as advanced AI and ML techniques to draw correlations between inputs from the projects and expected performance in operation and to extract interrelationships and patterns of interest from a large database.

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Chapter 6

Advanced digital design tools and methods

6.1 Advanced survey systems

The reliable reproduction of the project site, be it a cadastral plan, a boundary outline, a satellite image, or a reconstructed 3D model, is the paramount element on which to base every urban planning or construction activity. The level of accuracy and detail of base documentation, in fact, influences directly how informed will be the decisions taken at every step of the design process: whereas early stage planning and context analysis may require only a shallow knowledge of the site dimensions and characteristics, for subsequent phases of the project much deeper investigation of the local topography and geographical elements is needed to prevent redesign and reworks to occur with the associated increases in time and budget. Therefore, it is universally recommended to introduce site surveys since the start of the project workflow.

6.1.1 Aerial mapping

In most cases, the first step toward an accurate and comprehensive survey of the site and the surrounding context of the project, be it an urban redevelopment plan, a large-scale infrastructure, or a new building, concerns gathering and browsing the geographical data pertaining both the physical and legislative/social characteristics of its location. Traditionally, this research phase involves aligning data from multiple sources to first grasp an overall picture of all the factors that play a role in defining all the constraints, and all the potential, that will constitute the input for the subsequent design choices that will take place over the project lifecycle. In particular, topography and physical features of any project should be considered since the preconstruction design and planning phases, as they also influence the layout of temporary facilities, the best points of access for heavy vehicles, and the construction site safety planning. In fact, some of the major causes of schedule delays and increases labor costs in any construction project stem from unexpected construction site conditions resulting from insufficient preconstruction site surveys.

6.1.1.1 Satellite imagery

Aerial imagery, either from aero photogrammetry or, in more recent years, satellite pictures, has always been the baseline resource from which designers could visually glance the site characteristics as well as extract some information (lot size, distances from buildings, road access). Aerial imagery, once properly scaled, also provides a valuable tool for subsequent site investigation concerning local measurements, utilities connections, terrain and vegetation features, etc., as well as constituting a base layer on which to manually superimpose relevant data maps, such as urban zoning.

Today, satellite imagery of varying quality, both orthographic and isometric, is largely available for free on web platforms such as Google Maps, Microsoft Bing Maps, Zoom Earth, and others. These data are also retrievable via free software tools like Google Earth, which provide additional functions such as 3D topography with z axis elevations, 3D modeled buildings in some cities and the possibility of linear, areal, and vertical measurement.

These web-based platforms are some of the most widely used services on the Internet and allow decent quality data free of charge, and in the last years have significantly lowered the barriers to accessing good resolution satellite images. However, they come with some drawbacks that limit their full integration into the design workflow, including the following:

- images are not always corrected for lens distortion, camera tilt, perspective, and topographic relief to obtain a proper, uniformly scaled orthophoto;
- images are not always up to date and service providers have no publicly available schedule of updates;

- rural or coastal areas are imaged less frequently and in lower quality than populated areas;
- downloaded maps are not georeferenced, preventing them from seamless overlay with additional data;
- multispectral band combinations are rarely provided and cannot be adjusted to reveal additional insights.

A more robust integration of aerial imagery into the project survey and design workflows needs more detailed, customizable, and geospatially reliable datasets. These can be purchased from specialized companies as single payment or subscription-based services. Main commercial service providers of aerial imagery include European Space Imaging, UP42, Airbus OneAtlas, and Nearmap Ltd.

Compared to free satellite image sets, commercial services provide very high-resolution (VHR) optical satellite imagery, which resolve up to 30 cm on the ground and can be delivered in different combinations of multispectral bands to capture data not visible to the human eye, such as IR radiation, and extract information on material composition, vegetation health, water depth, and roof types. Even higher resolution can be provided by aerial orthophotos with a pixel level detail as little as 7.5 cm and horizontal measurement accuracy of 15 cm. High revisit rates are ensured, meaning that satellites recollect imagery over the same area within a short time frame, allowing additional insight on evolving contexts or works progress. Images can be ordered from historical datasets, or new collections can be requested at a specific location (satellite tasking). The possibility of precise timing of satellite and aerial imagery allows to view seasonal context and optimize data capture according to the intended use: for instance, images taken at the end of winter allow to see details in roofs and outbuildings after they have been covered by snow and before they are occluded by trees canopy. The same sets of images may include both orthophotos and multidirectional oblique views that allow precise vertical measurement of buildings' height, facades, roof pitches, and areas. Furthermore, oblique views also allow streamlined generation of 3D models of a terrain's surface in digital format from triple stereo data acquired through VHR satellite imagery or tilted aerial pictures, outputting digital elevation models that can be imported in most 3D modeling software.

The use of georeferenced imagery is crucial to associate geometric coordinates to every object ensuring that, when placed or printed on a map, it is inserted at the proper geographical location and is well aligned with the other map features. This in turn allows to integrate and overlay additional data from different sources using Geographic Information System (GIS), enabling a multitude of features to be projected on a map that uses a common coordinate reference system, or datum (Diakite and Zlatanova, 2020). Most common worldwide datum is WGS84, which approximates the overall shape of the Earth to an ellipsoid, however, localized datum can give a more accurate representation of their specific area of coverage (for instance, NAD83 for North America, ETRS89 for Europe, GDA94 for Australia, or PZ90.11 for Russia).

6.1.1.2 Low altitude aerial mapping

In addition to satellite imagery, low-altitude aerial mapping, either taken by airplanes or unmanned aerial vehicles (UAVs, or drones), is a suitable method of survey that consists in taking pictures of the site from the air with the prescriptions required to provide so called orthophotos, that is, images geometrically corrected for lens distortion, camera tilt, perspective, and topographic relief to obtain an uniform scale across the image (ortho-rectified) in order to properly represent the geometry of an area and its terrain (see Fig. 6.1). Unlike a simple aerial photograph, an orthophoto can in fact be used to measure real distances and is georeferenced, meaning that every pixel of the image has its own spatial coordinates and can therefore be overlaid on other cartography data. Several orthophotos can be merged in an orthomosaic to cover large areas, a process which requires color-balancing and seamlines blending to minimize disruptions at image boundaries. Orthophotos and orthomosaics production has conventionally been extremely costly and time-consuming, requiring airplanes, helicopters, kites or balloons equipped with expensive large format analog cameras with rectified optics, making it mainly used by public authorities or large-scale secondary industries such as mining or agriculture, with a reduced market for custom orthophotography. The advent in the last years of digital photography first and then of UAVs has greatly reduced time and cost investment required for professional grade aerial photography, therefore opening the market to many more commercial actors and allowing many architecture, engineering and construction (AEC) firms to obtain the required imagery completely in-house. UAV-based survey is discussed in detail in Section 9.2.2.

The first step to carry out the aerial survey of the subject site is to determine the expected information in terms of actual data and resolution. For most uses in AEC, pictures taken in the visible range of light in RGB format are sufficient; however, aerial imagery taken with IR or multispectral cameras allows to extract additional information on temperature (thermal imagery) or vegetation health (via Normalized Difference Vegetation Index). Ground resolution depends instead on the camera/lens equipped and the altitude of the flyovers, with higher resolutions requiring low



FIGURE 6.1 High-res orthophoto from UAV survey. Courtesy of Pix4D SA.

altitude and therefore more passages to cover the same areas. Field resolution of orthophotos is known as Ground Sample Distance (GSD) and is determined by the corresponding size of a single image pixel in the real world: commercial aerial photos have conventional GSD of less than 10 cm, and custom site specific low-altitude surveys conducted with UAVs can have a GSD as low as 1 cm.

If more than a single orthographic image is needed, a flying path with a parallel pattern is programmed to ensure that sufficient pictures are taken and that each photo of the “strip-run” overlaps at least 60% with the other to allow ortho-rectified mosaic combination without edge distortion. Adjacent strip-runs shall also overlap by at least 20%. The aircraft then proceeds with the flight plan taking the desired pictures automatically, blocking exposure and white balance to ensure visual consistency across the final mosaic. After the flyover, images are downloaded and fed to specific software such as 3DR Sitescan, Pix4D, Bentley ContextCapture or Agisoft Metashape for postprocessing, which includes geo-tagging and georeferencing orthophotos with Global Navigation Satellite System (GNSS) data recorded in-flight.

In addition to orthophotos and orthomosaics, aerial imagery can produce isometric views of the terrain and its features (including buildings and vegetation) by combining aerophotos taken with the camera tilted sideways from the four directions. These require additional flyovers or multicamera set-ups. Conventional GSD of isometric views is up to 1 cm horizontal and 2–3 cm vertical. These isometric views can moreover be used to create 3D models via 3D photogrammetry, which in turn can be either exported as a point cloud or a 3D mesh compatible with most 3D modeling software. 3D photogrammetry is detailed in [Section 6.1.3.3](#).

Finally, both orthomosaics and point clouds can be automatically converted to CAD drawings with advanced tools based on artificial intelligence (AI), such as Airworks, with equal accuracy compared to manual tracing at a fraction of the time. Feature extraction employ computer vision to accurately identify topography, roads and railroads, buildings,

vegetation, down to utilities such as manholes and drains, as long as sufficient GSD is provided in the source material (at least 3 cm).

6.1.2 Geographic information system

Topographical work on georeferenced documentation is carried out using GIS, which is essentially a framework for gathering, managing, integrating, and analyzing data by organizing layers of information into visualizations using both two-dimensional (2D) maps and 3D scenes. GIS is currently integrated into software tools that link typical database operations to geographic analysis, combining alphanumeric and spatial data to obtain georeferenced information. Main GIS commercial software on the market include Esri ArcGIS, Autodesk MapGuide, Bentley Map, and MapInfo Professional, with many more open source GIS projects available for free.

GIS allows to present geographic datasets as a series of dynamic, stacking maps that cover a given extent (area) depicting virtually any object (fixed or moving), boundary, event, spatial phenomenon, or abstract information (see Fig. 6.2). This geographic information is commonly accessed through three primary items: layers, maps, and scenes (Harder and Brown, 2017).

Layers are logical collections of geographic data, which is organized and combined to create maps and scenes. They can represent geographic features (points, lines, polygons, and 3D objects), imagery, surface elevation, cell-based grids, or virtually any data feed that has a specific location. Georeferenced layers are the key characteristics of GIS that enable to display, combine and analyze in a common geographic space disparate types of data, regarding both physical and abstract information (see Table 6.1).

Concerning maps, they constitute the primary user interface (UI) by which work is carried out using GIS software. They contain the payload for GIS applications and are the key delivery mechanisms used to share geographically referenced information on GIS platforms. A GIS map contains, in 2D, a basemap (called the “canvas”), plus the set of data layers one wants to work with.

Regarding scenes, instead, they are the 3D counterpart to maps. They also combine basemap layers with the chosen operational overlays, but bring in the third dimension, the z-axis, to provide additional insight to study certain phenomena (see Fig. 6.3).

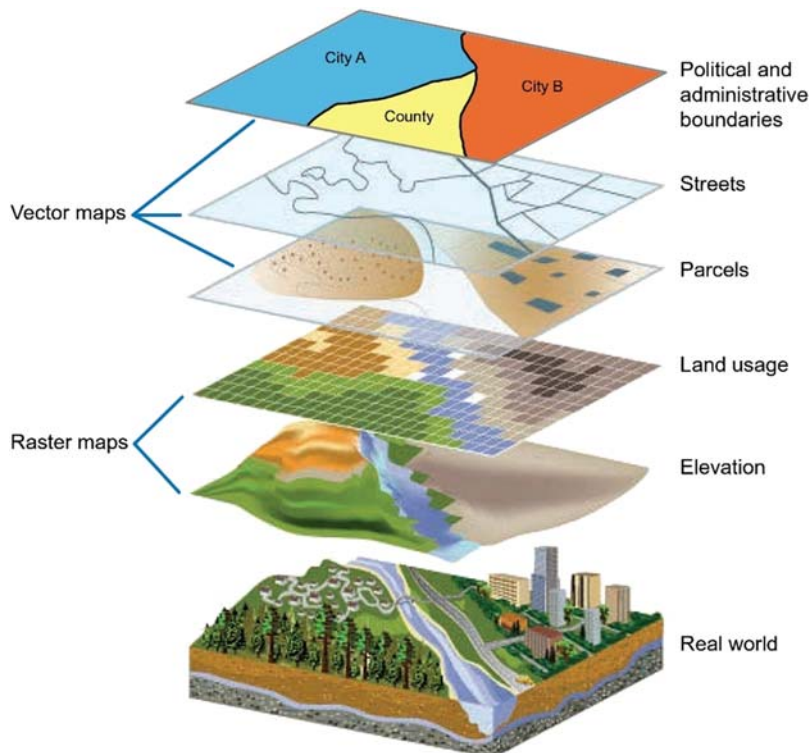


FIGURE 6.2 GIS layers composition. *Courtesy of Esri.*

TABLE 6.1 Main geographic data for GIS visualization.

Physical information	Abstract information
Aerial imagery	Land use
Terrain	Cadastral parcels
Buildings	Demographic data
Roads and infrastructure	Socioeconomic data
Utility networks	Social services
Spatialized data from sensors and IoT	Protected and restricted areas
Weather data	Agriculture and vegetation
Air quality	Historic preservation
Noise	Wildlife
Traffic congestion	Administrative borders
Pollution	Urban planning
Water resources	Geology

**FIGURE 6.3** 3D scene in GIS (credit: Daniele Masi).

6.1.2.1 GIS spatial analysis

Once the desired map or scene is assembled with the relevant information layers, data can be analyzed spatially to obtain insights useful for orienting project decisions. GIS software suites provide a large set of modeling functions that

produce analytical results, typically in the form of new data layers and associated tabular information, allowing to model a multitude of spatial problems. Analysis functions are built into the systems, and additional models and tools can be created or retrieved from GIS libraries, further expanding the level of analysis sophistication.

Spatial analysis is the process of looking at a map and turning it into information by analyzing its contents, finding patterns, and assessing trends. This allows to solve complex location-oriented problems by going beyond mere mapping to study the characteristics of places and the relationships between them, lending new perspectives to decision-making. Many independent sources can be combined applying a set of spatial operators and analysis tools to derive new sets of information (results), and further statistical analysis can determine whether the patterns that emerge are significant beyond the scope of simple visual analysis. Spatial analysis allows the following outcomes:

- determine relationships;
- understand and describe locations and events;
- detect and quantify patterns;
- find best locations and paths;
- make predictions ([Harder and Brown, 2017](#)).

Spatial data analysis involves working with both interactive maps and tables, charts, graphs, and multimedia to integrate the geographic perspective with statistical information, in an iterative process of interactive exploration and visualization of maps and data. All data and measurements that can be associated with locations can therefore be placed on the map to show what is present and where it is. Information can be represented either as discrete data, stored by its exact geographic location (“feature data” or “vector data”), or continuous data represented by regular grids (“raster data”). Raster grids are usually employed to represent the natural environment (elevation, temperature, precipitation), whereas built environment (roads, buildings) and administrative data (countries, census areas, demographics) tend to be represented as vector data. Further information that describes what is at each location can be attached (“attributes”). In addition to locational and attribute information, spatial data are characterized by geometric and topological properties: geometric properties include position and dimensions such as length, direction, area, and volume, and topological properties represent spatial relationships such as connectivity, inclusion, and adjacency.

In GIS, each dataset is managed as a separate layer and can be graphically combined using analytical operators (overlay analysis) obtaining a weighted overlay to explicit emerging patterns and explore answers and alternatives to one’s queries. A basic workflow to GIS spatial analysis concerns the following main steps (see [Fig. 6.4](#)):

- input dataset is digitized into a vector or raster layer for each information (source layers);
- source layers composed of continuous values are reclassified into meaningful value intervals (reclassification);
- the content of each source layer is ranked according to a common suitability scale, which signals its response to the proposed inquiry, assigning for instance a dark color for high suitability and a light color for low suitability (suitability layer creation);
- finally, suitability layers are aligned and overlaid, with each one given a weight or relative importance (weighted overlay calculation).

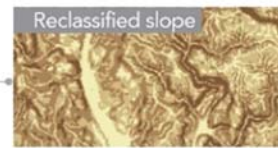
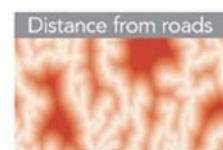
What results is a new map that gives each point or cell its overall suitability rating to the query required, allowing multifactorial evaluation of the whole investigated area with a glance. A variety of additional models and algorithms can be integrated to refine the analysis, including filters or tabulate groupings, circular buffers/bands, location tools, density grids, hot-spot mapping, gravity centers, shortest path calculations and routing tools, drive time/distance bands, balancing or clustering tools, desire lines, or spider diagrams.

In the AEC industry, the use of GIS instruments, including GIS-based spatial analysis, enables the creation, management, visualization, and sharing of valuable project data and gives a holistic perspective of the surrounding environment to enable informed design decisions. GIS allows for a better understanding of the geographic context, enabling to review design plans with a complete perspective of the external impacts of any design choice or change. Moreover, GIS format enables better collaboration between project teams and stakeholders, providing flexible deployments to deliver information products, and allows improved workflows in connecting field operations with the office through real time mapping applications.

Because of their excellent capabilities for processing spatial data, GIS can be used in a wide range of applications, not only for regional planning, landscaping, and infrastructure maintenance, but also for land surveys, cadastral management, environmental management, and other purposes. In addition, the emergence of GIS-based simulation models can solve environmental and planning problems in a more accurate way, for instance, to test the impact of urban layouts and building types on energy performance, carbon emissions, and solar availability ([Wang, Pan, & Luo, 2019](#)).

Collect source layers

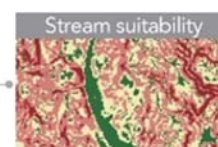
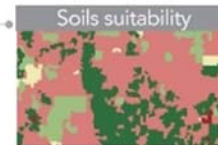
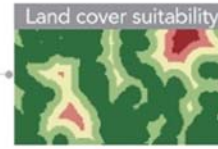
Data is first digitized into either polygon or raster layers. This housing suitability data is raster.



Reclassification
Source layers composed of continuous values (such as slope and distance layers) are first reclassified into meaningful ranges of values.

Create suitability layers

Each layer is now classified to use a common suitability scale: for example, low suitability could be assigned a value of 1 (dark red) and high suitability a value of 5 (dark green).



Calculate weighted overlay

Suitability layers are overlaid so that each cell gets an overall suitability rating. Weights of relative importance are assigned to each layer.

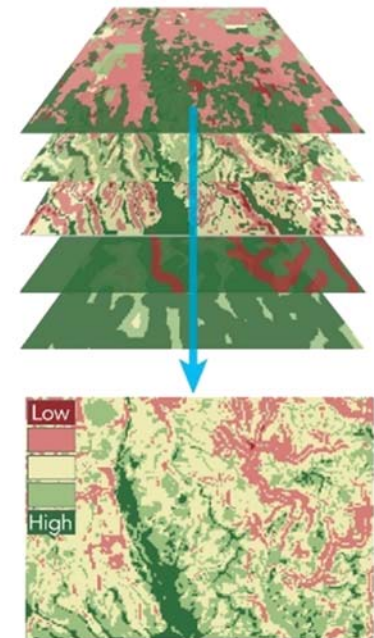


FIGURE 6.4 Example of GIS spatial analysis workflow to identify the most suitable place for a housing development *Courtesy of Esri.*

6.1.2.2 Integration with BIM

As explained above, GIS technology allows to manage and visualize georeferenced datasets by integrating real-world objects and locations with relevant information and providing users with an encompassing platform from which to seamlessly retrieve and analyze information. This approach to information management shares a common foundation with the building information modeling (BIM) process of digital representation of building assets characteristics, as described in [Chapter 4](#).

Actually, GIS and BIM can be described as two types of data-driven models, both providing digital representations of architectural or environmental entities, but each work at different scales with mostly different focuses. In particular, BIM focuses on buildings themselves, paying more attention to construction projects and their internal details, whereas GIS is specialized in geospatial information outside buildings and is mainly used to generate macrolevel information such as topographical plots. It is evident that neither BIM nor GIS can fully facilitate project management and decision-making in the construction industry by themselves, but they need to plug into each other to look into both buildings inside and buildings outside, providing integrated data for construction projects and their surrounding environment ([Wang et al., 2019](#)). By integrating GIS with BIM, it is possible to build a data model that includes geographic layers (such as soils, geology, and vegetation), built layers (such as land use, buildings, highways, and infrastructure), and social layers (such as social data and code requirements), enabling project teams to design in full accordance with the context of the site's geographic information.

GIS and BIM integration is beneficial for activities throughout the entire lifecycle of the project, from the planning and design (P&D) to construction, up to operation and maintenance (O&M) as well as final dismissal.

Regarding P&D stage, BIM-GIS integration can support the following main activities:

- site selection, by importing reference BIM models into the GIS geospatial environment to compare building's requirements with site blocks characteristics (maps, urban planning, land registration) or to make initial assessment of the building's volume;
- energy and environmental design, by linking energy-related features and indicators to different scales (from single rooms to the district level) via GIS to optimize energy performance and to check compliance with urban development schemes, by importing GIS climate data into BIM energy model for more accurate simulations, or by importing traffic data around the site to plan and simulate impacts accordingly;
- structural design, by integrating site characteristics such as soil and seismic category from GIS into the BIM design workflow and returning design choices and revisions to the geographical database to better inform future designs;
- interior acoustic design, by extracting outdoor traffic noise sources as input for indoor acoustic comfort evaluation;
- design authorization, by populating GIS with BIM models of as-built buildings to enable city-scale visualization and ease architectural authorization of the proposed design in context;
- building renovation, by integrating preretrofit BIM data into GIS to perform building data mapping and evidence existing issues and corresponding solutions;
- postoccupancy evaluation, by integrating obtained results such as indoor air temperature, humidity and lighting levels into GIS for visualization, spatial analysis, and reference to promote continuous improvement of performance.

Concerning, in turn, the construction stage, BIM-GIS integration can benefit project management as follows:

- supply chain and schedule management, by combining early-stage quantity take-off from BIM to geospatial analysis of logistics delivery via GIS to track materials provision status and provide warnings in case of disruption;
- progress tracking, by importing BIM-based time control models and scheduling into GIS to visualize and manage the progress of repetitive construction projects in distributed sites.

Regarding the O&M stage of the project, BIM-GIS integration has the following main applications:

- energy management, by connecting BIM and GIS data into district information models to facilitate calculation, monitoring, and control of energy consumption of buildings and their surroundings and optimize energy flows at the urban scale;
- facility management, by integrating BIM models of MEP systems and sensors/IoT data into GIS geospatial systems to visualize building facility information through interactive queries;
- heritage protection, by leveraging both architectural information from BIM models and historical semantic data from GIS databases to document and analyze cultural heritage sites for preservation purposes;
- fire response, by integrating BIM models, road network, and fire brigade locations into GIS to guide interventions by identifying the shortest routes to the emergency site, the best window to break in or the most suitable position for ladder deployment, as well as increasing responders' perception of indoor areas, decreasing reaching times, and optimizing route finding.

Finally, GIS and BIM can work together during final dismissal and demolition of buildings by integrating materials and quantity take-off from BIM models with GIS database transportation networks to allow precise waste sorting and estimation and accurate routing and planning of truck trips via spatial analytics (Ma and Ren, 2017).

At present, however, seamless integration of GIS and BIM data is still challenging at the technical level, as both are created, managed, analyzed, stored, and visualized in different ways considering the coordinate system, range of focus, and data structure, creating incompatibilities between the two sets of data. In particular, Industry Foundation Classes (IFC) and City Geography Markup Language (CityGML) are the two major data models currently used to represent BIM and GIS models, respectively, with CityGML being the standard model for modeling urban areas, and IFC the reference model for modeling buildings and infrastructure. These BIM and GIS datasets differ fundamentally in terms of their semantics, geometry, and level of detail, and because of their different modeling approaches, there is not an optimal nor uniform conversion between them yet. For instance, the basic concept of level of development (LOD) in BIM and GIS is different, and a conversion between the two databases needs a full matching between them. As IFC contains much more detailed information than CityGML, a complete mapping between IFC and CityGML is quite challenging; therefore, the geometry conversion is mainly conducted to lower LODs losing relevant data in the process (Wang et al., 2019). Furthermore, the issue of georeferencing BIM data is one of the main problems in bringing information from the BIM domain into a GIS environment. Even when properly aligned, a deeper spatial integration, both semantically and topologically, of BIM features with the GIS map features is still required to allow more advanced analysis and

information enrichment of both models. Overall, in order to improve accuracy and ensure full data interoperability of BIM-GIS integration, IFC and CityGML models still need to be upgraded substantially.

The ultimate goal is to leverage GIS to fully extend the application of BIM modeling concept from separated individual projects up to the entire city, thus introducing the city information model (CIM) paradigm. With CIM, urban planners, policy makers, and designers will be able to divide the city system into several submodules: buildings section, roads section, piles section, drainage section, etc. Conventional BIM-tech would be used to build these parts into information models, then GIS-tech would be used to locate and interrogate every part of city seamlessly and in real time. BIM software vendors such as Autodesk and Bentley have expanded their technology offerings to CIM by supporting modeling for smart city implementation, with case studies in Copenhagen, Barcelona, Korea's U-Cities, Montreal, and Helsinki. One of the most advanced cities in regard to CIM implementation is Singapore, where owners and contractors are already required to provide building data to a municipal server for this very reason.

Once fully implemented, CIM will consist in an integrated, semantically enabled "super-BIM" 3D city model able to connect users to any contextual project data source or analysis tool—static or dynamic, spatial on nonspatial—from buildings, to roads and public spaces (open data), to streetlights (sensors/IoT), up to people on the street (social media). Furthermore, CIM constitutes the technological bedrock of fully implemented Cities Digital Twins by working in conjunction with big data, Internet of Things, real-time sensors and more, and can assist in the planning, design, analysis, maintenance, and improvement of cities (see [Section 12.2.2.](#)). Architects and planners will therefore be able to run city wide simulations of various aspects such as traffic, congestion, energy, impact of natural disasters such as earthquakes or hurricanes, flood control, etc. Lastly, as with BIM, CIM will put collaboration, coinnovation and inclusion at the forefront by joining together all different systems and stakeholders of the future smart cities.

6.1.3 On site survey

On-site surveying consists in the precise science of determining the positions of points in 2D and 3D space and the distances between them, and can be carried out with different methods according to the characteristics of the site and of the project to be carried out within. Compared to aerial surveying, on-site survey allows much greater accuracy of dimensions measured, in the order of millimeters, making it a mandatory activity to ensure the best correspondence between the design space and reality. Site measurements are aimed at the most accurate reconstruction of the physical environment into a digital document, either as a database of points and coordinates, a 2D drawing or even a 3D mesh or point cloud, ready to be integrated in a BIM-based design workflow. Conversely, on-site survey is also used crucially to translate project information to the work site during the actual construction phase, an activity also known as construction staking or site layout survey. Site survey can be carried out both outdoors, to precisely map the terrain over which building or infrastructure is to be built, and indoors to allow the meticulous recognition of the geometrical dimensions and physical characteristics of a building before carrying out renovations or demolition works. According to the method and tools employed, on-site surveying can be carried out either with mechanical/robotic total stations, with LiDAR stations, or with ground level or aerial 3D photogrammetry, all of which have been introduced, or vastly improved, by the evolution of electronic distance measurement (EDM), GNSS surveying, 3D scanning technologies, and advanced imaging software.

6.1.3.1 Total stations and global navigation satellite system survey

Mechanical total stations are a staple of surveying work, as their operation dates back to the older mechanical-optical theodolites of which they are considered the modern evolution. Main manufacturers of total stations include Leica Geosystems, Hilti, Trimble, Topcon, and Sokkia. A total station is centered on a EDM laser range finder and an integrated electronic theodolite to measure angles, which through trigonometry allow to locate exact points with millimeter accuracy up to a few kilometers away from the instrument ([Rick, 2018](#)). Robotic total stations automate most functions to allow faster, single operator surveys with no loss in precision.

Mechanical total stations

A mechanical total station consists of a rotating head containing the telescope capable of sighting the target and the EDM, as well as an on-board computer to input user specifications (coordinates, program commands, target codes, etc.) and to display visual/numeric information. For use, the total station is first firmly placed above a known point, or datum, blocking the instrument's height and its orientation in that plane—with respect to the direction of north or to another benchmark point (polar method). Once this setup is verified, the total station can sight, measure, and record

visible target points within coordinate space at high levels of accuracy and precision, usually to an internal memory or to external memory devices of varied capacity. For each point to measure, the user collimates the telescope sight and manually adjusts the horizontal and vertical screws to align the crosshairs to the target, then the EDM emits a laser beam and calculates the distance according to the total time taken to reach the target and bounce back. Together with the elevation and horizontal angles, this allows to identify spatial coordinates and elevation of all points visible from the station and to store them in the internal logger for retrieval.

Targets are commonly signaled by a mirror-like retroprism reflector mounted on a vertical, usually manually held and leveled rod which returns the laser pulses. This mode of operation has the best range (up to 10 km) but needs a second operator to move the reflector from point to point. More recent instruments add the possibility of reflectorless function, in which the laser pulses are reflected off the actual object of interest without the need of the reflector. Reflectorless operation enables measuring locations in which a reflector cannot be easily placed, and allows single-user operation, with the drawback of a more limited measuring distance (under 1000 m).

Surveys with the total station can be performed both outdoors and indoors, as long as free line of sight from the instrument's head to the target object or reflector is available. Once all desired measurements are carried out from that position, the station can be moved to a second location, with another set-up procedure to ensure consistency of subsequent measures. In all cases, all measured points are calculated relatively to the station's own position, which has to be a fixed point easily retrievable during coordinates extraction. If no definite points are available for positioning the total station above them, its location can still be fixed by measuring directions, slope distances, and vertical angles with respect to at least two external reference points (Free Station Method) (Irineu Silva and Poleszuk, 2018). Most advanced total stations include a GNSS receiver to allow precise determination of their position (Leica SmartStation).

Robotic total stations

To improve productivity of total station surveying, station head movement can be motorized to look to the reflector autonomously, obtaining a robotic total station (see Fig. 6.5). These advanced survey tools, such as Trimble S9, can automatically turn the telescope position and search, aim to and follow the reflective target as it is moved around the site. This allows no delays in waiting for the instrument operator to manually aim and measure each time because the instrument can be operated remotely by the same operator holding the reflector with a remote display integrated in the pole or with a remote controller such as Trimble TSC7. In reflectorless operation, the head displays the telescope view directly on the screen and can be manually adjusted to the nonreflective target using touch input, without needing the



FIGURE 6.5 Robotic total station (photo by the author).

user to look repeatedly through the telescope. Additionally, when it is needed to measure or scan a grid of points on a building, it is sufficient to define the area to be measured and the robotic total station can automatically measure hundreds or even thousands of points within few minutes and then export them into a CAD or BIM-based software to produce digital drawings and models of the surveyed site.

To avoid loss of contact between base-station and prism caused, for example, by the interruption of the signal by a passing vehicle, software is used that predicts the prism's path. To quickly re-establish contact after loss, either the station makes a quick laser scan of the broad environment (Leica PowerSearch), or the system makes use of active prisms able to generate themselves signals that are received by the base-station and direct targeting toward them. Using active reflectors also avoids faulty auto-aiming at reflective objects, such as traffic signs, windows or vehicle mirrors, but these solutions inherently increase complexity, cost and weight.

Global Navigation Satellite System Survey systems

An alternative to mechanical/robotic total station survey is the use of GNSS survey systems such as Trimble R12, which allow to precisely identify the location of points of interest in the site via their WGS84 coordinates and elevation (see Fig. 6.6). In order to ensure survey-grade accuracy, these systems employ real-time kinematic (RTK) operation which ensures precision of positioning at the centimeter-level, much higher than conventional, non-RTK satellite positioning systems (1–4 meters). An RTK system consists of a base station, which stays fixed in a known reference position, and one or more portable GNSS antennas (rovers). The base station calculates its location by using the signal received from the satellites based on a technique known as carrier phase measurement and then compares this result to its known location to identify any errors and generate a correction signal. This correction signal is transmitted in real time via UHF to the rovers, that in turn use it to improve their own computed position from the GNSS constellations (such as GPS, GLONASS, Galileo and BeiDou) to achieve centimeter precision. Best accuracy is ensured in a range within 20 km from the base station, with precision up to 8 mm horizontal and 15 mm vertical plus 1 additional mm of error for each kilometer away from the base station.

Compared to total stations, even robotic ones, GNSS survey is faster and more straightforward, as it is sufficient a single operator to move the GNSS rovers to each interest point and seamlessly identify and record their elevation and coordinates, without needing continuous line of sight toward the base station. The main limitation of GNSS survey is the necessity for both rovers and base station to have uninterrupted communication with at least four satellites, which prevents its application indoors or in places with obstructed view to the sky such as woods, valleys, or dense urban areas.

Leading manufacturers of survey equipment such as Leica Geosystems and Topcon have been integrating their total station and GNSS survey systems toward a unified workflow. By combining rover antennas and target reflectors in a single survey pole, it is possible to enable constant dual communication to both devices from the control software and to seamlessly switch between GNSS and robotic mode according to the situation at hand. For instance, it is possible to perform millimeter measurements with a robotic total station, then switch to GNSS measurement whenever line of sight is unavailable.

Construction staking and site layout surveys

In addition to land surveying, total stations and GNSS systems are also widely used for performing precise construction staking, also known as a site layout survey, which is the process of translating the engineering design plans to the work-site by marking the location of the proposed new structures before construction starts. An accurate site layout allows to build the project according to the design with the maximum precision and is a critical factor in ensuring it is completed on schedule and on budget. The land surveyor extracts discrete points and benchmarks from the design plans and places (stakes) their correct location on the ground, so that buildings, roads, sewers, electrical systems, and other underground utilities will be made in their envisaged location. In particular, construction staking may consist of rough grade staking to map the general location of improvements at a site, and more precise site layout surveys for actual construction purposes.

Rough grade staking defines the location of slopes, building outlines, parking lots, and roadways and enables the contractor to grade and prepare the site for the next works. This activity usually takes place outdoor and requires only centimeter-level accuracy; hence, GNSS positioning is commonplace in view of its increased speed compared to total stations.

Site layout staking instead is used to outline actual building construction and features within, therefore requires best accuracy. It typically begins with tracing underground preparatory features such as sanitary sewer lines, storm drain



FIGURE 6.6 Trimble R12i GNSS survey system. *Courtesy of Trimble.*

lines, water lines, electrical lines, etc. Once all underground utilities are installed, the above ground features are staked for construction, starting from laying out positions and levels for excavations and formwork for foundations and piles. Building corners are staked along with any interior grid lines throughout the building. Site layout has been traditionally performed with manual operation of strings and tape measuring, processes that have proven time-consuming, inaccurate, and prone to human errors. The introduction of total stations in the actual construction phase, in addition to performing survey duty, is greatly simplifying and streamlining the construction layout process, as design data can be taken directly from the office to the field via the layout instrument. In fact, contractors and land surveyors are able to upload the project coordinates directly from 2D plans and 3D BIM models to the total station, allowing to trace the layout of electric lines, drywalls, columns, ceilings, and other building features with extreme precision. Using integrated workflow software such as Topcon Magnet Field, Trimble Field Points, Hilti PROFIS Layout Office, or Autodesk Point

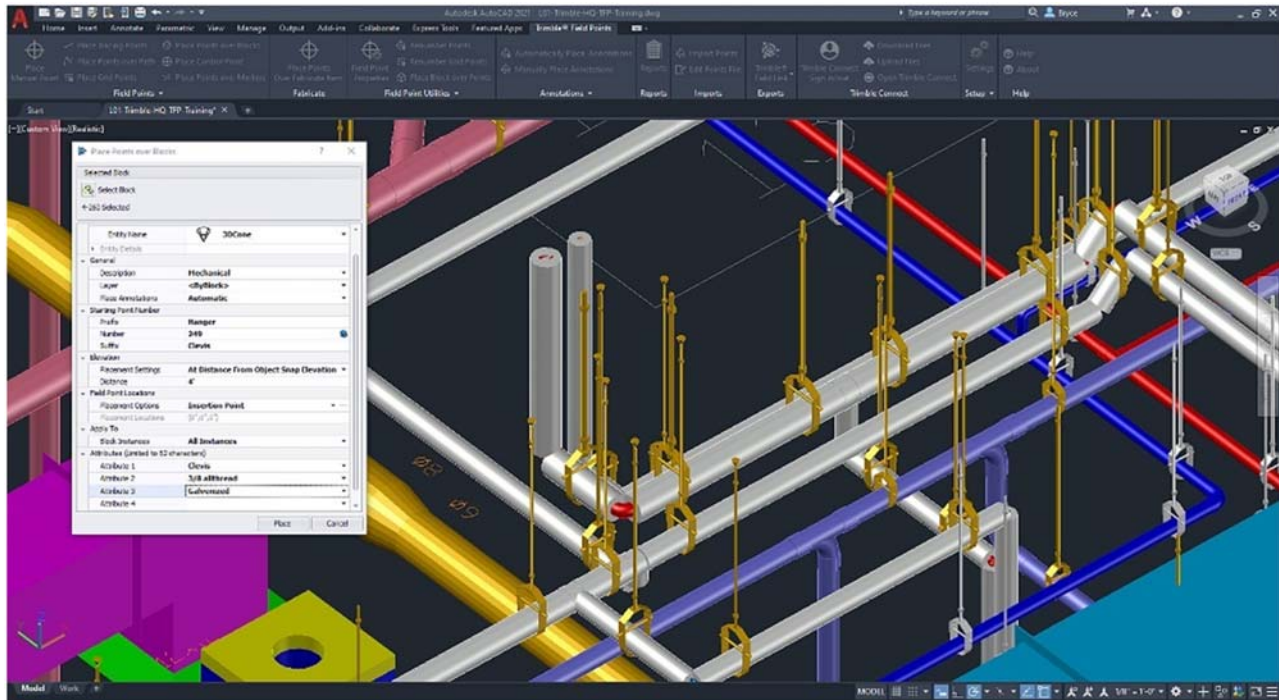


FIGURE 6.7 Setting up 3D control points in Trimble Field Points. *Courtesy of Trimble.*

Layout, contractors are able to import and display a digital drawing, such as a DXF/DWG, or a model, such as an IFC file of the project (see Fig. 6.7). As a result, they can work directly from the drawings or the model, choosing the control point from the screen or remote tablet to laser guide an operator holding the retroreflector in its expected position with millimeter accuracy. Robotic total stations also allow one-person operation to further increase productivity and reduce communication errors. This process is also more time and cost efficient as it eliminates the need for a surveying/engineering assistant on site and negates the need to have people manually inputting data for setting out into the instrument or data logger, which in turn reduces the capacity for further errors on site. Improvement over conventional manual methods is remarkable: whereas a two-person crew can lay out an average of 75 points per day using tapes and strings measurements, the same crew can lay out 150 points using a mechanical layout station, and a single worker can lay out 300 points per day with a robotic station.

During structural works, especially for tall buildings, GNSS and total station hybrid systems are best suited to track building progress and ensure floor by floor geometry compliance and overall verticality (Irineu Silva and Poleszuk, 2018).

6.1.3.2 Light detection and ranging 3D site scanning

An even more advanced application of EDM in construction is constituted by so-called 3D scanning, also known as laser-scanning or LiDAR (light detection and ranging or laser imaging, detection and ranging), which builds on the concept of robotic total stations described above to provide unparalleled quick and streamlined survey operation. As with conventional total stations, 3D scanners determine the exact position of a point by calculating the time between the emission of an eye-safe laser beam and its return to the starting point after bouncing off the detected object, as well as the relative horizontal and vertical angles of the instrument head. Differently than those, however, 3D scanners are able to perform this operation for up to two million points per second, pivoting automatically the instrument head on the horizontal and vertical axes to map all visible objects 360° around its position, instead of few discrete points. Operation is further streamlined: it is sufficient to place the 3D scanner on the preferred position and activate it to automatically trace all visible surroundings with a direct line of sight to the instrument head. What results is a dense cloud of 3D points, each with its x,y, and z coordinates in space. The 3D laser scanner can capture both exterior and interior structures, which will also include mechanical, electrical, plumbing, and fire protection installations as well as temporary elements such as furniture, vehicles, and people. If there are survey areas not visible from that position, it is sufficient

to move the instrument to another location and perform additional 3D scans, with on-board software taking care of aligning the different point clouds. By themselves, these point clouds are colorless, hence more advanced LiDAR scanners integrate high dynamic range cameras to provide spherical image capture to colorize 3D scans.

A ground level 3D survey-grade scanner is very similar to a total station, being composed by an instrument head able to rotate on the vertical axis and the laser EDM that pivots on the horizontal axis to ensure 360° coverage, all supported by a tripod base. High level products such as Trimble X7 and TX8 (see Fig. 6.8), and others by Leica Geosystems, Faro, and Riegl have ranges between 100 and 200 m up to 1 km, accuracy in the millimeter range, and typical high density scan time as low as 2 minutes. Teleoperation by mobile devices allows to preview and fine-tune scans on the go (see Fig. 6.9).

Other LiDAR applications are optimized for quick scanning, performing as many as 250 scans per second. This allows to move the 3D scanner while in operation to seamlessly cover large areas without incurring in any blank spot. Mobile 3D scanners can be obtained by mounting a conventional field scanner on a trolley to move around the site (Leica ProScan, FARO Focus Swift), or can be miniaturized to fit in a backpack (Viametris bMS3D LD5 +, Leica Pegasus Backpack) or even to allow handholding while walking the survey space (Leica BLK2GO, Gexcel Heron Lite Color, FARO Freestyle 2), tracking the operator's trajectory via simultaneous location and mapping (SLAM) and enabling the 3D mapping of an entire house in mere minutes, as opposed to more than an hour with fixed field scanners, at the cost of a reduced accuracy (20 mm absolute) and a less uniform or dense 3D point cloud. For infrastructure or urban district mapping, special LiDAR devices can be mounted on cars or rails to perform 3D scanning in all directions with the vehicle moving even at highway speed (data mapping works up to 110 km/h). These mobile mapping solutions (Trimble MX2 and MX9, Topcon IP-S3, Leica Pegasus Two, FARO Road-Scanner C) employ single or double LiDAR systems equipped with a microelectromechanical systems (MEMS) mirror to direct the laser in all directions with a rate of 700.000 pulses per second, and integrate inertial measurement units (IMUs), GNSS receivers and vehicle odometers to compensate vehicle attitude and provide precise positioning and georeferencing of produced data (see Fig. 6.10). Multicamera systems provide 360° spherical panoramas precisely matched to the LiDAR 3D point clouds by an internal timing unit.

Moreover, LiDAR systems have been miniaturized to the point of their possible integration in UAVs, which provide a vantage point capable of covering large areas with unparalleled velocity (see Section 9.2.2. for additional details on LiDAR equipped UAVs). LiDAR equipped drones allow to survey area not accessible with terrain 3D scanners, with the added benefit of being able to cross tree foliage and effectively map the ground even in densely vegetated areas.

Finally, biomorphic robots such as BostonDynamics Spot can mount LiDAR systems on their back to perform autonomous surveys in place of human operators. In particular, Spot has been integrated with Trimble X7 and FARO Focus Trek field 3D scanners to streamline and automate laser scanning workflows for construction sites (see Fig. 6.11). The scanner-robot duo autonomously navigates busy or dangerous sites, capturing accurate point clouds in predetermined locations or on demand (additional information on biomorphic robots is available in Section 8.2.2).

As stated above, the result of a 3D scan is a dense point cloud, which may integrate color information according to the LiDAR system employed. A survey-grade, 360° point cloud taken from a single field instrument may amount to more than 35 million points alone, and many more points are produced in composite point clouds obtained by multiple or mobile scans (see Fig. 6.12). By themselves, these dense point clouds are hardly usable, and the millions of points



FIGURE 6.8 Trimble X7 (left) and TX8 (right) ground-level LiDAR scanners. *Courtesy of Trimble.*

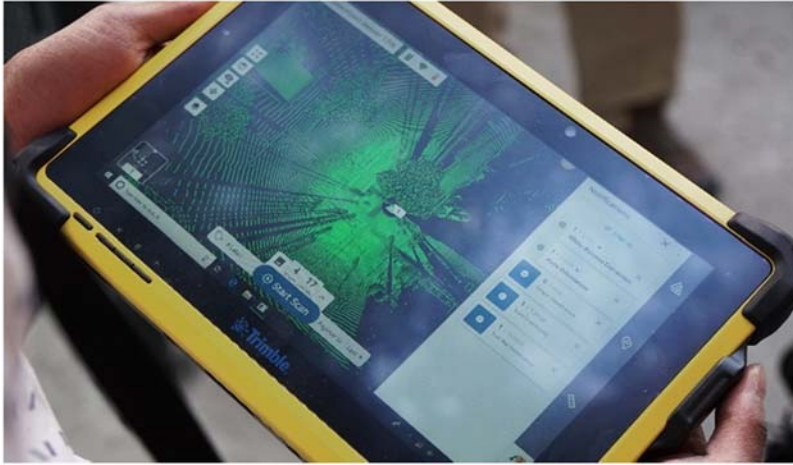


FIGURE 6.9 Trimble mobile app for LiDAR scanner control. *Courtesy of Trimble.*



FIGURE 6.10 Trimble MX9 vehicle-mounted LiDAR scanner. *Courtesy of Trimble.*

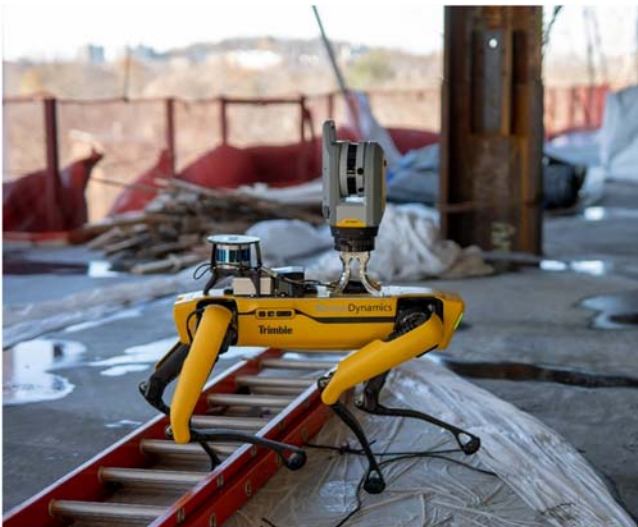


FIGURE 6.11 Trimble X7 LiDAR scanner mounted on BostonDynamics Spot. *Courtesy of BostonDynamics.*



FIGURE 6.12 3D point cloud of Notre Dame Cathedral. (credit: Dr Andrew Tallon).

and measurements captured by the scanner need to be registered to create a composite point cloud for use by designers and detailers in modeling and BIM applications. Specific point cloud processing software is required to register, visualize, explore, and manipulate as-built data collected from any 3D laser scanner and convert them into usable 3D models. Point cloud modeling applications are provided by all main LiDAR manufacturers, including Trimble RealWorks and Edgewise, Leica Cyclone REGISTER 360, TopCon MAGNET Collage, and FARO SCENE, but there are also suites that are not hardware specific, such as Autodesk ReCap Pro or Euclidean UdStream. These software tools include more advanced functions such as noise cleanup, moving objects filtration to remove unwanted people, vehicles of machinery captured in the scene, as well as object recognition to automatically extract elements such as pipes, conduits, ductwork, structure, and walls and model them using the dimensions and geometries included in their libraries of industrial specifications. What results is a 2D or 3D derivable that is easy to export to common 3D modeling and BIM software. BIM modelers then extract the physical and functional information about each of the building systems. The multiple viewing points in the point cloud scan provides holistic visibility of the structure, ensuring the accuracy of the representation.

The deployment of 3D laser scanning can measure any complex construction environment—regardless which stage the project is at. Therefore, when integrated with BIM at a construction site, 3D laser scanning technology can greatly improve the quality inspection and acceptance levels of a project during both the design and the construction phase.

In particular, aggregating 3D laser scanning technology with BIM enables to address the following practical problems during project implementation:

- maximum fidelity of the BIM model of the site before works;
- easy earthwork volume calculations;
- easy integration during works of missing information from factory drawings;
- continuous update of BIM model as construction progresses;
- real-time identification of discrepancies between the as-built and the as-designed BIM models;
- seamless as-built data collection for client delivery.

6.1.3.3 3D reconstruction

3D reconstruction is a survey technique based on the extraction of 3D information from 2D photographs of the site. The process involves taking an appropriate number of overlapping photographs of an object, structure, or space, and converting them into 3D digital models via specific algorithms to obtain digital terrain and surface models (DTM, DSM). Pictures can be taken with a wide variety of cameras, from smartphones to highly specialized airborne or terrestrial multidirectional acquisition systems. According to the types of photo provided, either shot from the sky or from ground level, two types of 3D photogrammetry can be defined:

- close-range photogrammetry, when images are captured using a handheld camera or with a camera mounted to a tripod, with the aim of making 3D models of a smaller objects or areas;

- aerial photogrammetry, which utilizes aircrafts to produce aerial photography that can be turned into a digital 3D model of larger sites. Aerial photogrammetry has become much more accessible since the introduction of UAVs, and provides an easier way to safely capture hard-to-access or inaccessible areas where traditional surveying could be dangerous or impractical.

As with 3D laser scanning, the result of 3D photogrammetry is a point cloud consisting in millions of surface points which are measured and mapped to develop a textured, high-resolution, geometrically precise 3D model.

Software tools on the market (Pix4D, Bentley ContextCapture, Autodesk Recap Photo, 3DZephyr Photo, Agisoft Photoscan, Trimble Inphoto) are based on structure from motion, a range imaging technique that allows to extrapolate 3D points from 2D images by comparing with computer vision their photographic parameters such as focal length, sensor size, distortion, and pixels (see Fig. 6.13). Photos of the environment must have sufficient overlapping, as a point can be precisely placed in the 3D space only if it appears in at least three different images. More images translate to a more accurate model but require longer processing time. Overall, at least 3 pictures per square meter are required for a good quality reconstruction, with at least 60% overlapping between them. Multiple frames can be extracted by videos taken at ground level or even during drone flyovers as well. Images are processed by multiview stereo software such as Python Photographic Tool to determine the position of the camera within the environment and to identify points shared between different images, obtaining a dense cloud of 3D points that have inherited their original color. The 3D point cloud, commonly less dense than that obtained from LiDAR scanning, is then converted to a 3D mesh for easier optimization with any 3D modeling software. Usually, 3D models generated this way need postproduction and optimization to reduce superfluous meshes, re-triangulate them, and obtain a more manageable 3D asset. Modeling software such as Recap Photo and Rhinoceros can perform this optimization and remodel eventual portions of the 3D environment which have been incorrectly converted, such as walls which were covered by screens or objects during image taking. Final optimization consists in aligning the 3D models with the topography and between them as well as correcting scale and orientation errors. Models can be georeferenced by attaching geospatial information from ground control points or GNSS tags to specific parts of the mesh or point cloud to enable compatibility with several GIS tools and accurately measure coordinates, distances, areas, and volumes.

3D photogrammetry software also allow in-model photo navigation, that is, the ability to click on any point of the reconstructed 3D mesh to display the relative full resolutions photos, enabling in depth analysis and quality assessment of the surveyed space.

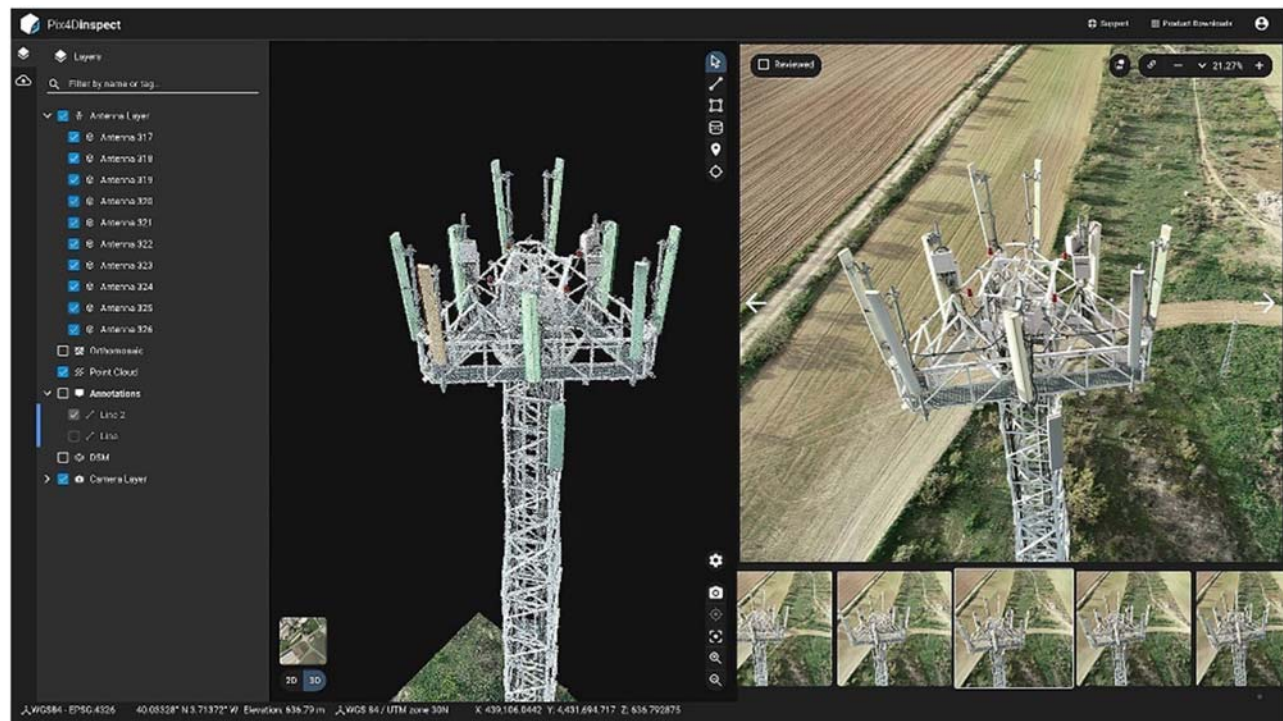


FIGURE 6.13 3D reconstruction from drone images. Courtesy of Pix4D SA.

Conventionally, 3D photogrammetry workflow entails four main steps:

- Step 1: marking at least three ground control points (GCPs) of the area of interest and ensuring they are clearly visible in the photos;
- Step 2: taking pictures from varying angles and elevations surrounding the area;
- Step 3: accurately survey the GCPs with traditional methods to scale and geo-reference the model;
- Step 4: process photos and GCPs together using the software of choice to produce the final model in a range of deliverables.

While the overall processing time varies according to number of photos and GCPs, the entire workflow, from taking the photos, surveying the GCPs, and processing, can be completed in under an hour for a medium sized survey.

Compared to 3D laser-scanning, 3D photogrammetry has the clear advantage of not needing expensive instruments, since a smartphone camera can already produce sufficient results and even camera equipped UAVs can now be acquired or rented cheaply, and saves time for data collection by eliminating the bottleneck associated with sharing the laser scanner among surveyors and needing to clear the investigated area for the minutes taken to perform the scan. Nonetheless, 3D laser scanning still has the edge in terms of millimeter level accuracy.

Nonetheless, most advanced 3D photogrammetry professional software tools are capable of aligning reconstructed data with that provided by laser scans, allowing to increase the precision of the resulting 3D model while retaining the resulting texture maps. Integrated useful functions include automated cleanup, to identify and remove unwanted points like people and moving objects that were photographed accidentally, and automatic classifications of point clouds by distinguishing between diverse objects like buildings and trees allowing to filter them.

6.2 Real-time 3D visualization

Real-time 3D rendering (RT3D) is the branch of computer graphics focused on creating and deploying in real-time interactive, realistic digital representations of physical-world assets. In real-time 3D rendering, most common in video games or interactive graphics, the final images are converted from the 3D model at a very high speed (less than 1/30th of a second—the minimum a human eye needs in order to create the illusion of movement) so that it looks like the scenes occur and reacts in real time when players interact with the digital environment. Like a video game, real-time 3D lets people move within, and interact with, an engaging, immersive digital reality in a way that traditional renderings alone cannot enable.

The spread of RT3D technologies in the last 5 years is bringing great changes and benefits to the entire construction sector. Visualizing the project and the works has always been an essential element among all stages of the building process, from design to construction, up to management and maintenance. Traditional project visualization tools include plans, elevations and sections, photo insertions, perspective views and sections, 3D models, plastic models, and prerendered images.

The new requirements posed by contemporary architecture have accentuated the need for visualization, highlighting the limits of traditional visual techniques across the building lifecycles and requiring more dynamic tools capable of allowing greater understanding of the project in all its phases.

On the one hand, in fact, the development of increasingly complex projects from a formal, structural, and engineering point of view now requires the use of visualization tools perfectly integrated into the workflow that can dynamically support the design team in identifying the best design choices (design review). On the other hand, clients have become increasingly demanding about the possibilities of actively participating in design choices from the early stages, therefore requiring more immersive, interactive, and photorealistic visualization tools for the commissioned work. Today, the customer wants to have a clear vision of what he is investing in and is no longer satisfied with simple 2D technical drawings or images that allow only a partial view of the project.

Up to the early 2010s, the high production time and cost of a single rendered image, along with the need to resort to highly specialized professionals, did not allow the use of renderings neither as a design review tool nor as a tool for presenting the projects in progress, relegating this kind of representation in architecture only to the final phase of the process, after the design is completed.

The advancement of computer graphics has radically turned this situation, now allowing to obtain images rendered in real time in a simple, fast, and economical way and therefore changing not only how to present a project but also the way of designing it. For these reasons, many firms of the AEC industry have been realizing the need for modernization in their visualization approaches across the life cycle and have been turning to RT3D techniques to create immersive digital experiences of the physical world.

Thanks to real-time rendering software, architectural rendering has become a tool for daily workflows: it is possible to instantly transform 3D models into high-quality visualizations and immersive experiences, and thus to validate project solutions at any point during the design phase, shortening the trial and feedback loop.

Through RT3D, the project team can design and make changes to the model that can be viewed in real time, allowing to reveal if a layout does not work as well as anticipated, or to detect clashes that may disrupt the construction process.

Sunlight angles and intensities can be accurately simulated in response to the addition of cloud cover, time of day, and surrounding vegetation. Model interiors appropriately reflect the lighting conditions as they would in real life, allowing architects to optimize their designs for daylight exposure, spotting when lighting is too strong (causing issues with occupant comfort and energy efficiency) or too weak.

Being able to show an array of assets such as orthographic views, animations, panoramas, or 3D architectural renderings at various stages of the design process can help to accurately communicate your design intent and ensure that everyone has a full understanding, ensuring improved collaboration, higher quality feedback, and faster decision making.

Real-time rendering gives architecture firms the ability to not only design buildings, but also experiences that will showcase the best, most important aspects of their work and present immersive real estate options. Clients and investors can get a complete view of proposed designs, enabling them to understand what the project will accomplish and how the design and specifications are justified. This helps firms winning the tenders they're submitting proposals for and also improves communication and collaboration with clients. Project stakeholders can have a clear representation of what they are getting before construction commences. Early consensus typically results in time savings and less rework during the design phase, fewer scope changes, and reduced subcontractor default down the line.

For projects that require the approval of local communities, architectural renderings can be a great tool for showing the general public how a project can enhance their neighborhood beauty and functionality. People can clearly visualize how they may interact with the place in their daily life, and see the value in their taxpayer investment.

From the operational point of view, in order to create real-time 3D rendering, it is necessary to start from a 3D model (Rhino, SketchUp, 3DsMax, Maya, etc.) or from a BIM model (Revit, ArchiCAD, Vectorworks) of the building and to export it into specific graphics engines such as Enscape, Lumion, Unity Reflect, Fuzor, or BimX that allow to view the model with photorealistic quality in real time with total freedom of movement and interaction.

RT3D software can generally be accessed from the BIM software toolbar and allow live link to the model, meaning that any modification to the model is translated and displayed in real time in the rendering or vice versa (Fuzor) for simultaneous editing and visualization, and enable capturing and communicating annotated feedback directly during the immersive navigation of the model for a collaborative workflow. The Unity Reflect 3D visualization plug-in for Revit translates BIM models into an immersive 3D model that retains BIM metadata and can be explored and altered, allowing changes to the Revit model to show up immediately in the RT3D model.

These tools allow to create real-time walk-throughs, 360° panorama views, and video paths that can be easily enjoyed with cloud-based viewers available on multiple devices, such as computers, mobile devices, and virtual reality (VR) and augmented reality (AR) headsets.

It is possible to integrate the 3D model in the context provided by a real-life photograph, recreate the actual topography surrounding the building, from small, gradual climbs to mountainous, jagged peaks, or place the model on the map by importing 2D data from the OpenStreetMap database (Lumion).

The scene can be added with atmospheric effect such as rain and snow (from light drizzles or winter flurry to full-blown downpours or whiteout blizzards) or with animated 3D vehicles and people sitting, cycling, or walking.

The benefits deriving from the use of real-time 3D techniques are not limited to the design phase but also affect the construction and management phases of the building (see [Table 6.2](#)).

Regarding the construction phase, the most interesting use cases of real-time 3D concern construction simulation, showroom or presentation to clients, job site coordination and clash detection, and interactive training. Real-time 3D is also used to overlay digitally created content and data on top of the real world in 1:1 AR.

As physical spaces are becoming increasingly connected and sensor enabled, real-time 3D digital experiences can be combined with information from data sources such as enterprise databases and internet-of-things (IoT) sensors. Known as digital twins, these representations look and behave like the real-world asset and can be placed within contextual environments and simulated scenarios (e.g., a skyscraper project shown within a city at various times of day), or used as decision making support tools through advanced data analytics (additional information on building digital twins can be found in [Section 11.4](#)).

TABLE 6.2 Relevant use cases of RT3D for the AEC value chain (Forrester Consulting, 2020).

Architecture	Engineering
1. Experienced-based design 2. Model or design review 3. Design visualization or concept validation	1. Model or design review 2. Showroom or presentation to clients 3. Training/safety for maintenance team
Construction	Manufacturing
1. Construction simulation 2. Showroom or presentation to clients 3. Interactive product configuration	1. Prototyping 2. Presentation to clients 3. Training and guidance

6.3 Extended reality in design

The terms extended reality, “X-Reality,” or XR for short, refer to the use of technology to create immersive digital experiences and encompass all various forms of computer-altered reality, including VR, AR, and mixed reality (MR). Generally speaking, XR is used as the umbrella category that refers to all real-and-virtual combined environments and human–machine interactions generated by computer technology and wearables (Khan, Sepasgozar, Liu, & Yu, 2021; Sepehr Alizadehsalehi and Huang, 2020).

XR technologies, which diffusion is on the rise - AR and VR are considered in the top 10 Gartner strategic technology trends for 2019 (Panetta, 2018) - represent one of the most interesting technological innovations within the digitalization process of the construction sector, with remarkable potential in increasing quality, efficiency, and productivity in all phases of the architecture, engineering, construction and operation (AECO) process, from design to construction, management, maintenance, and real estate.

By enhancing physical realities with digital information and making that content readily shareable, project teams can work more accurately and efficiently, make better decisions faster, and collaborate and communicate more effectively. XR allows to easily visualize, explore, and understand designs, models, and site conditions, improving workflows across the building and infrastructure lifecycle. In particular, the main applications of XR in AECO concern stakeholder engagement, design support and review, construction planning, progress monitoring, construction safety, operative support, operations and management, as well as personnel training (Delgado, Oyedele, Demian, & Beach, 2020).

Different XR technologies differ from each other according to the level of immersion in the virtual environment, the possibilities of interaction between the real and virtual world, and the devices required for fruition (see Fig. 6.14).

VR encompasses all immersive experiences and content via a VR headset or HMD (head-mounted display). The content is 100% digital and computer-generated. Current reality is replaced altogether with a new 3D digital environment in which the user is completely isolated from the real world and its surroundings.

AR instead overlays computer-generated content on top of the real world. This superimposed digital overlay can superficially interact with the environment in real-time. AR is primarily experienced via wearable goggles or through smartphone and tablet screens.

MR, also known as immersive media, spatial computing, and hybrid reality, is a digital overlay that allows virtual, 3D elements to integrate, enrich, and interact with the real-world environment. MR combines several technologies into one wearable device and is commonly viewed through transparent wearable glasses. Within the definition of MR often also falls the concept of augmented virtuality, which differs from AR because whereas in AR the context is the physical world to which digital contents are added, in augmented virtuality the scenario is a virtual world to which real contents are added, as in the case of a virtual classroom where to attend the lesson of a teacher in the flesh.

For visualization, XR employs portable devices such as smartphones or tablets, or HMDs either worn on the head or as part of a helmet (such as helmet-mounted display for aviation applications). These feature a small display optic in front of one (monocular HMD) or both eyes (binocular HMD). Display units include liquid-crystal displays, liquid crystal on silicon, organic light-emitting diodes, or multiple micro-displays to increase total resolution and field of view.

VR headsets can only display computer-generated imagery (CGI) and are combined with an electronic IMU that measures and reports a body’s specific acceleration, angular rate, and often orientation, using a combination of accelerometers, gyroscopes, and sometimes magnetometers.

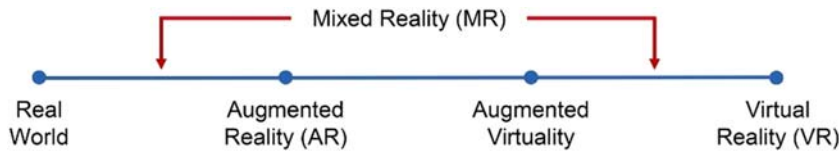


FIGURE 6.14 Extended reality and virtual continuum (Milgram and Colquhoun, 1999).

AR and MR headsets instead employ optical head-mounted displays (OHMDs) that allow CGI to be superimposed on the real-world view. OHMDs use an optical mixer which is made of partly silvered mirrors that can reflect artificial images while letting real images cross the lens, allowing the user to look through it.

In 2020 semiconductor manufacturer Qualcomm, which system-on-chips (SoC) power many VR headsets, started a collaboration with mobile operators to deliver integrated XR viewers. The objective is the convergence of smartphones, mobile VR headsets and AR glasses into a single XR wearable, with the potential to become one of the world's most ubiquitous and disruptive computing platforms of the next decade. To overcome current limitations of XR technology, namely the trade-off between desktop or portable solutions in terms of performance, fidelity and mobility, a key role will be played by the advancements in wireless connection, both in local (802.11ax or Wi-Fi 6) and mobile networks (5G). Right now, portable XR devices are limited in terms of file size and complexity that can be handled without resorting to an external computing unit such as a PC, as the specifications required for 3D visualization in terms of CPU, RAM, and storage can be too much for miniaturization and low battery consumption.

For an adequate VR experience, a prerendered 4 K 360° video requires a data rate of only 20–60 Mbps and latency below 50 ms, whereas for an optimal experience, a prerendered 12 K 360° video requires a data rate of at least 440 Mbps and a latency less than 10 ms. Connection requirements become even higher for VR interaction. For a 6 degrees of freedom (DoF) immersive interactive VR experience with a content resolution of at least 8 K, a high bandwidth of at least 1.5 Gbps, and a latency below 8 ms is required. The use of 5 G mobile network can solve the high bandwidth demands of VR and AR for cloud streaming. With cloud VR, all the content can be rendered in real time in the cloud, which minimizes the computational load on the VR kit. In addition to immersive prerendered video experience, 5 G cloud VR opens the possibility of extremely interactive VR services for construction training and practice. The increased bandwidth (up to 10 Gbit/s for 5 G and 11 Gbit/s for Wi-Fi 6) allows not only to stream the high bitrate video content required by most demanding XR applications, such as stereoscopic 4 K view at high refresh rate, but also to delegate more intensive data processing to much more powerful on-line virtual machines (cloud computing) while the XR viewer is tasked only with managing the visualization and connection aspects, with low enough ping rates to prevent motion sickness (less than 20 ms). This in turn will enable much more miniaturized and lighter headsets with improved battery life and able to operate both in the office and in the construction site with the same, high level of performance (Orlosky, Kiyokawa, & Takemura, 2017; Sukhmani, Sadeghi, Erol-Kantarci, & El Saddik, 2019; Torres Vega et al., 2020).

6.3.1 Virtual reality

VR refers to computer technologies that use software to generate realistic images, sounds, and other sensations that represent an immersive environment and simulate a user's physical presence by enabling real-time interactions via sensorimotor channels.

The concept of VR came into prominence in the 1990s, when several industries were influenced by videogames and by the first immersive human–computer interaction mockup, “Man-Machine Graphical Communication System.” After 2005, a second wave of VR emerged and was more successfully employed in different fields, including engineering, medicine, mental health, design, architecture, construction, education and training, fine arts, entertainment, business, communication, marketing, military, and travel. Now, the development of devices, components, software products, and UIs is advancing quickly and many leading players in manufacturing are adopting these technologies, including in the AECO industry. With its advanced capabilities of immersive and interactive visualization, VR has been advocated to facilitate design, engineering, construction, and management for the built environment (Zhang, Liu, Kanga, & Al-Hussein, 2020). Because VR provides a fully immersive experience, it is an especially effective tool for design teams, contractors, and owners to review and approve plans and understand sites and spaces. The VR application controls the entire environment that the user sees, creating a uniquely detailed and dynamic individual experience.

In particular, evidence suggests that VR technologies are particularly effective in construction safety training, project schedule control, and site layout optimization of construction projects. VR technologies can also provide environments for better collaboration among stakeholders; enable a better understanding of complex designs; identify design

issues; depict building geometry so that users can make sense of a project and reach a better design decision; and aid collaborative decision-making.

6.3.1.1 Virtual reality technologies

A VR system usually consists of more than one hardware device for full operation. In general, the hardware of a VR system can be classified into three types based on their use, namely, display devices, motion capture (mocap) devices, and interactive devices. A display device is the essential element of a VR system, which outputs stereoscopic images to users.

Display walls, HMDs and portable devices are three commonly used types of display equipment.

Generally, the typical VR platform can be categorized into three paradigms:

- Head-based: a head-based VR device is a helmet or head mounted display where graphic images are displayed on a screen or a pair of screens, one for each eye, while a position-tracking sensor is embedded to respond to where the user is looking (see [Fig. 6.15](#));
- Stationary: the stationary VR platform is usually fixed in place and uses projectors and/ or large display screens to display the visual information of the experience;
- Hand-based: the hand-based VR paradigm refers to the device that the participant can hold with their hands and hold up to their eyes, such as smartphones or tablets.

Motion tracking is a very crucial function for a VR system because the correctness of motion tracking and user orientation will enable an effective interaction between the user and immersive VR environment ([Kloiber et al., 2020](#)). Mocap systems are responsible for capturing and processing users' motions to provide tracking for their view and positioning for interaction. The more precise the tracking, the better the VR immersion. If there is a gap or lag between the users' actions in real-life and in VE, it may greatly hinder the user's experience. It is possible to have external or internal positional tracking:

- External (outside-in) tracking: makes use of external sensors and/or cameras to accurately track the headset's position within a delimited space (room-scaling). For full room scale, users need to install more than two sensors to avoid any occlusion;



FIGURE 6.15 HTC Vive (top) and Oculus Rift (bottom) VR headsets. Credits: Maurizio Pesce (top) and Sam Walton (bottom).

- Internal (inside-out) tracking: the VR headset uses one or more front-facing cameras to detect its position, with or without the aid of markers. This type of tracking is generally less powerful and accurate than outside-in tracking, but easier to set-up.

Common types of mocap technology are optical, inertial, mechanical, and magnetic. For “Cave Automatic Virtual Environment” and display walls, an external mocap device is required to provide a motion capture function. Portable VR devices usually embed sensors and algorithms to perform motion tracking.

Other kinds of tracking can include more complex systems such as volumetric capture (Microsoft Azure Kinect) hand tracking and haptics (Ultraleap), eye tracking and person’s entire body tracking, thanks to special suits.

In addition to lifelike visual effects, important media for enhancing the reality of VR environments are interactive controllers, through which a user can interact with objects in a VE and receive sensory feedback, such as haptic and auditory feelings. The use of an interactive controller usually requires cooperation with the mocap device to obtain accurate positions for command execution. Joysticks or wands are the most commonly used interaction devices. They enable the user to hover in the VE, move objects and execute many other interactions. Data gloves and haptic devices are other frequently used interaction devices, with which a user can perform more elaborate operations, such as grasping and picking objects. They have been widely used in industrial applications, especially in use cases that have high requirements for elaborate operations. In addition to controllers and camera-tracking, more advanced neuro-motor interfaces are under development, such as Facebook’s wrist-mounted controller that reads neural impulses as they go down the user’s arm: these promise much more intuitive and lifelike replication of intended gestures in the virtual environment, with accuracy high enough to match the operation of a virtual keyboard with a real one in terms of typing responsiveness.

With reference to the head-mounted systems, on the market there are three types of VR headsets (see [Table 6.3](#)):

- tethered VR headsets (a.k.a. PC VR, desktop VR);
- standalone VR headsets (a.k.a. all-in-one VR, wireless VR);
- smartphone VR headsets (a.k.a. mobile VR, VR viewers).

The degree of immersion that can be reached through the three types of headsets depends on various factors such as, in particular, field of view (FOV), the number of movement types that the user may experience (DoF), the tracking system, the quality of the display (pixel density, color fidelity, dynamic range, and brightness), the refresh rate (also known as frame rate), the presence of controllers, and the audio system.

In particular, a good immersive experience requires a refresh rate between 90 Hz and 120 Hz, a FoV equal to at least 100° (human eye sees about 220°), a number of degrees of freedom equal to 6 (3DoF rotational freedom: 360° head

TABLE 6.3 Advantages and disadvantages of VR categories.

VR Type	Main advantages	Main disadvantages
PC	• High-quality VR immersion • Most desktop VR headsets feature positional tracking and 6DoF controllers • Good quantity and quality of VR content available on big content platforms	• VR headsets with external sensors or cameras require a lot of space (cleared office room or dedicated room) • Desktop VR requires powerful PCs that are generally very expensive • The cabled connection may limit the user’s freedom of movement, and often needs users to set up a special cable organizer
Standalone	• Standalone VR headsets are easy to carry around (wireless) and less space is required to use them. • Standalone VR HMDs are generally more affordable than PC VR. • Plug-and-play and, therefore, easy to set-up and use.	• Less powerful VR cannot compete with most tethered PC VR headsets. • Most standalone headsets only have 3DoF, offering a less immersive VR experience. • Battery life needs to be improved if users want to use the device extensively.
Mobile	• Easy to use and ease of access to a smartphone • Affordability • Wide variety of content easily downloaded as apps	• May quickly drain the smartphone’s battery • Concerns of smartphone overheating • Limited immersion compared to PC VR and standalone VR • A number of poor-quality headsets with low-quality hardware are available, thus offering poor VR experiences

rotation; 3DoF positional freedom: up/down, left/right, forward/backward) as well as an accurate motion tracking system.

A wide FOV enables users to view their virtual environment as in real life—not only seeing what is in front of them but also perceiving objects in the periphery (see [Table 6.4](#)). High refresh rates and low latency are required to avoid cybersickness (motion sickness symptoms). 6DoF controllers allow users to benefit from a more interactive experience than with simple point-and-click controllers (3DoF).

Tethered VR headsets

Tethered VR headsets, also known as desktop VR or PC VR headsets, require a constant connection to a powerful computer and often make use of external sensors or cameras to track the user's position. The main advantages of tethered VR headsets in comparison with standalone or mobile VR are the higher-quality VR immersion and the possibility to have positional tracking and 6DoF controllers that allow users to benefit from a more interactive experience than with simple point-and-click controllers (3DoF). The main limits concern that desktop VR requires powerful PCs (Macs are not recommended due to the lower support of macOS for VR applications) that are generally very expensive, the cabled connection may limit the user's freedom of movement and often needs users to set up a special cable organizer, and that VR headsets with external sensors or cameras require a lot of space (such as a cleared office room or a dedicated room). Some VR systems manufacturers such as HP offer wearable backpack PCs to partly address the cable encumbrance and allow greater mobility. Thanks to developments in wireless technology, several manufacturers have released short-range wireless adapters for desktop VR HMDs to offer an untethered VR experience with the aim to offer both freedom in movement and high-performance VR experience. Examples include WiGig (Intel's Wireless gigabit), TPCAST Wireless Adapter (for the Oculus Rift or HTC VIVE), HTC VIVE own wireless adapter, or the DisplayLink Wireless VR adapter.

Standalone virtual reality headsets

Standalone VR headsets (a.k.a. untethered, wireless, standalone VR) do not require a PC or a smartphone to deliver a VR experience. The self-contained headsets (made popular by releases such as the Oculus Go) include built-in processors, GPU, sensors, battery, memory, and displays. In addition, as these VR goggles need no cable, users do not have to limit themselves to a restricted space. In general, they offer a more powerful VR experience than smartphone VR, but less powerful than tethered VR.

Various high-profile tech companies such as Google, Facebook, HTC, and others are focusing more resources on developing additional and more sophisticated HMD's for standalone VR.

All-in-one VR HMDs generally offer a more affordable solution compared to tethered VR for users who want to experience VR. However, the compromise in affordability is offset by having less powerful wireless VR, although newer headsets like the HTC VIVE Focus and Oculus Quest 2 are an exception in terms of performance.

Furthermore, most standalone VR headsets only offer 3DoF, hence a less immersive VR experience for the user. The inclusion of controllers has become more standard for this VR category, but not all products feature them out of

TABLE 6.4 Main VR headsets on the market and FOV values.

Tethered VR headsets		Standalone VR headsets		Smartphone VR headsets	
Brand	FOV	Brand	FOV	Brand	FOV
HTC VIVE	110°	DPVR M2 PRO	96°	BNEXT VR PRO	-
Sony PlayStation VR	100°	GenBasic Quad HD	110°	DESTEK V4	103°
HTC VIVE Pro	110°	HTC VIVE Focus	110°	Samsung Gear VR	-
Oculus Rift	110°	Lenovo Mirage Solo	110°	Merge VR Goggles	96°
Samsung Odyssey	110°	Oculus Go	-	Homido Grab	-
Dell Visor	110°	Oculus Quest	95°	Mattel View-Master	98°
Acer Windows Mr*	100°	Pico Goblin	92°	iDudu VR	120°
HP Reverb G2	114°	Pico Neo	-	Google Daydream View 2 (2017)	100°

the box and may require separate acquisition. Battery life is another key factor to consider as it will impact how long users can operate the device (and if portable battery packs are available).

Smartphone VR headsets

Smartphone VR headsets (a.k.a. mobile VR, VR viewers) are essentially a plastic or cardboard casing with a pair of lenses and cushioning for user comfort, mostly relying on the tech of the inserted smartphone to power VR apps although some products may provide additional functions such as VR controllers or custom IMUs. Mobile VR includes a number of high profile brands in the VR space and is by and large compatible with most Android smartphones and iPhones, as long as they fit inside the specific VR headset.

Ideally, for the best VR experience on a mobile device, users want to ensure a resolution that is at least full HD (1920 x 1080 pixels). Other key factors to consider for wearable mobile VR headsets are sensors:

- accelerometer: used to change the orientation of a smartphone screen from vertical (portrait) or horizontal (landscape);
- gyroscope: dictates the mobile device's orientation in 3D which is used when the phone is tilted in all directions. This is essential for rotating the user's head within VR;
- magnetic sensor: although not as mandatory, this sensor assists in detecting if the VR headset cover is opened or closed and activates the screen accordingly.

Compared to tethered and standalone VR, mobile VR is the easiest for users to set up. With tethered VR, there is greater expertise required and a longer setup time, as the VR headset is connected to a PC. Standalone VR, which is more affordable than tethered VR, cannot match mobile VR's price-point, but it does generally provide a more authentic and immersive VR experience than smartphone VR.

6.3.1.2 Virtual reality content creation

VR is a powerful tool that can offer unparalleled immersive visualization and interaction with virtual environments. However, to ensure satisfactory and productive VR experiences, care must be taken into designing and translating models and images into a workable format according to the intended final use, the VR device employed, and the degree of interaction foreseen.

In particular, the VR experience can be either static (limited to the immersive visualization of a 360° image/video from a fixed point of view) or dynamic (allowing free movement and interaction with the VR environment).

Static VR

Static VR puts the viewer at the center of a spherical image or video that is projected 360° around them, allowing to freely gaze around the view and focus on single elements of interest simply by moving their head or torso or with mouse/keyboard inputs. Static VR is the straightest form of VR to produce, as a single spherical or equirectangular image (also known as 360° image or 360 panorama) is sufficient to provide the immersive experience.

360 panoramas of real environments can be generated with dedicated multicamera tools or by stitching several photos taken from a single camera in different orientations.

Concerning multicameras devices, they range from consumer level cameras such as Ricoh Theta, equipped with two 180° fisheye lenses back-to-back, to professional set-ups with six or more image sensors in a circular or spherical rig. To use this technique for panorama generation, the positioning of cameras must be set carefully with sufficient overlapping regions between adjacent cameras. The images are then stitched together using dedicated feature-based stitching algorithms. In addition to panoramas, 360 cameras are also the only way to produce 360 videos.

Regarding multiphoto stitching, resource-constrained devices such as smartphones or low-power visual sensors use instead an embedded panoramic generation system that estimates camera motion by continuous tracking of the camera while capturing images from the surroundings then stitches the images using the projected plane of the previously taken image. Although these embedded visual sensor-based approaches are efficient and cost-effective for panorama generation, the quality of the panoramas generated using these embedded approaches usually suffers from stitching artifacts such as geometric errors (structural errors) and photometric errors (color distortion) (Ullah, Zia, Kim, Han, & Lee, 2020). Finally, it is possible to produce 360 images by taking enough photos in all directions with any digital camera then stitching them in generic image editing or panorama software such as Photoshop, PTGui, Gimp, most of which have automated tools to process panoramas. To prevent artifacts during the stitching process, it is important to ensure a sufficient overlap and a level exposure between each shot.

360 panoramas can be either monoscopic or stereoscopic, commonly called “mono” and “stereo” images, respectively. A mono panorama has the same view for both left and right eye, and therefore cannot provide depth information to the user, resulting in only a partial immersion experience. On the other hand, a stereo image consists of two images (left and right) representing a scene from two different points of view that are horizontally displaced like the human eyes. As a result, the output of both left and right image has different representations of image contents in which some objects appear closer than others, giving an illusion of depth to the user. To generate a stereo panorama of real-life locations, expensive equipment such as twin camera systems, high computational power, and long processing time are required because two panoramas need to be generated separately for both eyes.

Of course, 360 panoramas for VR fruition can be created from 3D models of the proposed environment, which can be rendered to the required degree of graphical fidelity. Contrary to photo-based panoramas, the workflow for creating virtual panoramas is much more streamlined. Most 3D rendering software such as Vray, Lumion and 3DS Max, or BIM tools such as Archicad and Revit, can produce panoramas straight from the scene with no postprocessing or stitching required, as it is only needed to set a 360° camera in the preferred viewpoint instead of a conventional 35 mm virtual camera. To ensure sufficient quality for VR fruition, it is recommended to output panorama images with horizontal resolution of at least 6000 pixels, with 8K considered optimal. Moreover, stereo panoramas are usually integrated in the panorama tool, so it is sufficient to toggle the “stereo” selector to make the software render the two views side-by-side. Rendering time is increased accordingly.

Once created, 360 panoramas are ready to be viewed with any VR device in their native image format (.jpg, .png or other extensions), using the device’s dedicated software or third-party apps. A more comprehensive static VR experience can be implemented by integrating some basic interaction in the 360 images, such as using a pointer to interrogate predetermined objects or to jump from a panorama to another to show different environments. These additional functions can be programmed in web apps using open source libraries for UIs such as ReactVR.

Dynamic VR

Differently from static VR, dynamic VR allows much greater freedom to the viewer, who can move unrestricted inside the reproduced environments, interact with objects and even modify the scene directly from the virtual dimension. For this to happen, static images are not viable and RT3D technology is required to generate content continuously according to the user’s input and movements. Rendering time must be faster than the viewer perception to ensure the virtual representation of reality approaches the authenticity of their analog experience and to provide them with precise control over their experience and vantage point. This performance is rarely achievable by conventional 3D modeling and BIM software, therefore proprietary graphic engines with VR support, often based on technology borrowed from the videogame industry, are usually employed, which can be integrated with user—environment interactions using libraries and VR platform software development kits (SDKs).

Overall, the definition of a dynamic VR experience requires the following tools:

- a 3D model of the environment to explore, obtained by BIM software, by 3D scanning or by photographic reconstruction;
- a graphic engine to perform real time 3D rendering of the model;
- a VR platform to employ in the experiences, which consist in the actual VR device and its own SDK used to control it;
- frameworks and libraries to integrate interactive functions such as physics and UIs.

Concerning the 3D model, it can be imported from the project’s BIM file or designed from the ground up using conventional modeling tools, according to the degree of geometrical detail desired. For real life locations, it is possible to reconstruct 3D models with high fidelity from picture sets or from laser scanning of the actual environment (see [Section 6.1.3](#)).

However, some amount of work is involved in transforming these models into something that is both human navigable and human interactive within the virtual environment. Graphic engines with VR support provide a useful platform with the potential of cutting down on some of the work required to make these models readily accessible (and therefore useful) to a lay audience (such as the eventual users of the building). Due to the large amount of information contained within a BIM, it is an excellent candidate to import into graphic engines to construct realistic virtual environments. Once the 3D model is imported into a graphic engine, alterations can occur to make the model more realistic (changing textures) or more believable/interactive (custom scripts and actions to support in-environment behavior and interaction) (Bille, Smith, Maund, & Brewer, 2014). Graphic engines with established support for VR visualization and interaction include Enscape, Unity Reflect, Unreal Engine, and CryEngine. These have streamlined import features which can

extract data from 3D models or BIM created in 3ds Max, Revit, SketchUp Pro, Rhino, Cinema 4D, Archicad, and others. In addition to geometry and textures, timeline information can be integrated from BIM 4D software such as Navisworks to allow animations of the construction sequence. During model import, it is paramount to enable the physics engine to calculate collisions with the objects in the scene and lay the groundwork for more immersive interaction in VR. Depending on the BIM/modeling software and file formats, the process of data import into the visualization engine can be more or less straightforward and require additional work to make BIM metadata, textures, and colors carry over; therefore, full interoperability should always be checked before choosing a graphic engine. Once the model is imported, the engine allows to populate it with a variety of assets (furniture, vehicles, vegetation, site surroundings) and to integrate additional functions such as physics simulation. Automated scripts can be programmed within the engine or retrieved from online libraries to attach animations or functionality such as doors opening, light switching, and others. Lastly, UIs can be personalized according to the functions intended.

Graphic engines currently support natively most VR devices, including Facebook Oculus, HTC Vive, Playstation VR, or Valve Index, meaning they can already process input from the headset sensors and controllers and send the correct instructions for visualization. Additionally, it is possible to program additional functions by using the SDK provided by the manufacturer of each VR.

In addition to VR visualization and interaction with specific objects, most advanced visualization engines allow real-time modification, that is, the possibility of editing the 3D model from within the engine (for instance, by moving walls, enlarging windows, adding building components). However, BIM and 3D models used for VR visualizations are not the same and are commonly not linked, which greatly hinders usability. For example, if during a VR-enabled design review meeting changes are made to the model, they remain in the VR model and do not necessarily transfer to the BIM model of the project. Conversely, any modification to the BIM model may require transferring it in the visualization engine again from scratch. This reduces the usability of the VR system and introduces additional work and possible errors. One of the main factors that make difficult bi-directional synchronization are the different data schemas used for BIM models and VR models and the lack of compatible databases systems for federated models (Delgado et al., 2020). Some commercial solutions such as IrisVR, InsiteVR, The Wild, or Enscape provide varying degrees of automated, bidirectional BIM to VR synchronization, and are able to reflect changes made in the BIM model into the VR model and vice-versa. Another challenge in using VR for actual design editing is the lack of conventional data entry and control tools that characterize desktop software, namely, mouse and keyboard, that provide much more precision and versatility compared to VR controllers.

6.3.1.3 Virtual reality design applications

Thanks to the ability to completely immerse the viewer into a simulated and interactive digital reality, VR finds numerous and interesting applications in the building design phase, allowing the actors involved to test solutions, improve understanding of the project and identify in advance potential conflicts (de Regt, Barnes, & Plangger, 2020; Delgado et al., 2020). In particular, in the design phase VR can be used as a tool to (Zhang et al., 2020):

- remotely explore and study the context where the work is to be carried out using 360° videos that combine VR technologies and 3D video cameras, or virtually experience a 3D scanned model of the location, for a faster and more involved analysis of the morphological and environmental characteristics of the site;
- support design choices through an immersive environment that is also able to encourage full collaboration between members of the work team, even remotely;
- involve future users to get useful feedback to identifying design solutions (e.g., doctors for hospitals and operating theaters);
- simulate human-building interactions in certain scenarios and situations to validate the design choices;
- show the project in real time (maquettes) to clients and general public right from the initial stages.

Virtual reality-based design review

By transforming 2D or 3D models into immersive, manipulable virtual environments, VR technology enables architects to interact with their designs to an even greater degree than what is possible with RT3D visualization. With VR, many of the most challenging aspects of architectural work become more streamlined and simplified, allowing for better designs from both a technical and an esthetic perspective.

Software such as Enscape, Unity Reflect, Resolve, or Fuzor enable the integration of VR within the design workflow, allowing to view changes made to the model in real time or to act directly in the virtual world.

Inside a virtual building, designers can change the sun's position and study how daylight affects interiors, can adjust a single or an entire array of lights causing realistic reflections and refractions on each material, can simulate the weather, the growth of trees, and the CCTV system viewpoints. From inside the VR environment, it is possible to move objects, measure distances, count steps, photograph details, and even sketch 3D notes. Water flows can be reproduced and the wind simulated, and noises can be inserted to stimulate senses while, being in a 3D space, the perception will change according to the user's location.

VR users have the possibility to navigate any environment by interacting with the scene elements: opening doors, choosing furnishing elements, turning on the television, and lighting devices. During the VR navigation, the user can associate in real-time different types of materials and colors to floors, walls, furniture elements, and freely select furnishing complements allowing a full customization of each environment.

Compared to RT3D, VR enables a visualization with a highly realistic level of spatial depth, allowing to experience a design on a 1:1 scale. While 2D renderings and digital models can impart a basic understanding of what a finished environment will look like, the experience of interacting with a physical space cannot be captured when staring at a computer screen or piece of paper. This is especially beneficial in the context of urban planning. For example, when multiple buildings must be specified in a new city development project, VR allows to gain a truly accurate sense for how a new building will fit in and interact with the surrounding structures and environment.

VR allows all stakeholders to fully understand, and accurately envision, the current design in order to make timely and well informed decisions as well as align their expectations, and allows the project team to get important feedback to stay on budget and schedule (see Fig. 6.16).

Virtual reality collaborative environment

The design activity of a building or infrastructure today involves an increasing number of highly skilled building engineers and design specialists who work within multidisciplinary teams all committed to the achievement of the highest final quality of the work, to be fulfilled on time and on budget.

For the success of the project and the achievement of the proposed objectives, it is of fundamental importance that these actors collaborate effectively with each other, with the client and with the other stakeholders from the initial stages of the design.

In this sense, numerous studies confirm that VR, in addition to being an effective design review tool, is able to encourage collaboration between team members even when they are at a great distance from each other as is increasingly the case, especially if some activities are outsourced.

VR technology makes it possible to create actual virtual design studios where members of the design team can be virtually present at the same time and the same place as 3D anthropomorphic avatars, all while being physically remote. Participants can collaboratively discuss problems and propose solutions, as though they were in a typical problem-solving meeting and can jointly manipulate and evaluate the emergence of creative solutions in a real-time manner in an immersive synchronized environment.



FIGURE 6.16 Enhanced project visualization in VR (photo by the author).

Numerous studies confirm that copresence through VR strengthens the sense of collaboration among team members, especially in terms of social aspects such as dependencies, encouragement, and mutual learning from each other, in comparison with other forms of remote collaboration.

User-centered design

As an immersive and interactive design review medium, VR allows for bi-directional communication between professionals and clients offering a promising platform to conduct user-centered design with the principle of concurrent engineering.

Thanks to its capability in facilitating effortless spatial comprehension and problem-space identification, VR technology can be used as a design review tool to involve future users since the early stage phase with a great influence on design decision-making.

VR models allow in fact participants to feel as they are physically present, giving them a sense of scale toward the design alternatives. Usually, the participant is asked to examine building design features such as spaces layout, textures, and lighting, during a VR-based walkthrough. In some cases, virtual prototypes have also been employed to assess occupation comfort of spaces or to support real-time interaction between the user and building elements to achieve a stronger sense of presence so as to acquire more precise review comments (Du, Zou, Shi, & Zhao, 2018; Kloiber et al., 2020; Zhang et al., 2020).

VR-based design review has been employed in the design phase for many types of buildings, such as residential homes, public schools, and healthcare facilities, and has proven effective in eliminating potential errors or conflicts, ultimately increasing end-user satisfaction.

Among firms specialized in the use of VR in healthcare design is American company Mortenson Construction. In particular, they use VR technology for improving the design of operating theaters by allowing medical and paramedical staff to fully visualize and interact with their instruments, work areas, and technologies to ensure optimal layout and ergonomics. Doctors, nurses, and technical personnel typically want to interact with the different elements and make decisions about room dimensions, ergonomics, esthetics, functional systems, and workflow efficiency very early in the project. VR can give them a great opportunity to spot, discuss, and correct any problems with major benefits like streamlined patient care, more efficient staff, and lower costs.

Keeping in the healthcare sector, VR technology was also used by Layton Construction company for the design of the North Alabama Medical Center, in Florence (AL), where VR HMDs were used to collect feedback from the medical staff who were able to dive in the hospital model, free to move and interact with the environment wearing the HTC VIVE system.

VR can also allow fire safety specialists, as well as firefighters themselves, to experience first-hand the designed spaces, instead of relying on 2D evacuation handbooks and paper-based documents to obtain the information which fail at effectively displaying the relationship between equipment information, personnel information and spatial information (Chen, Hou, Kevin Zhang, & Moon, 2021). In case of actual emergency, VR training can greatly improve spatial awareness and navigation within the premises.

Human behavior investigation

Another promising application of VR in the design phase is the possibility of providing a controllable, realistic, and safe testing environment to study human-building interaction in different scenarios and to explore how changes in the built environment can impact the human state of mind and corresponding reactions, in order to promote a user-centered adaptive design. Observing how people interact with a virtual environment generates valuable data that can be harnessed to guide decision-making during the design process (Niu, Pan, & Zhao, 2016). In particular, VR can be used for emergency behavior investigation and training, especially in fire emergencies or for the assessment on building energy performance with regards to human experience and behavior.

VR can also be effectively used to assess the risks and safety of workers gauging the feasibility of the existing design. If a specific aspect proves to imperil the virtual labor, it can easily and quickly be adjusted, saving money that would otherwise have to be spent on downstream rework.

VR models can also support acoustic engineering practice by simulating sonic sensory input. As most of the world's population lives in cities characterized by high noise exposure, the need for spaces that are beautiful and environmentally friendly but also quiet and soundproof has become crucial. By importing the BIM model into a VR platform such as Unity, designers can simulate the acoustics of sound waves passing through the building and bouncing off specific

materials, then users can hear through the VR visor the difference between an open or closed window or the sound reflecting on a carpet or hardwood floor.

6.3.2 Augmented and mixed reality

AR is the technology that bridges the physical and digital worlds by overlaying information, such as text, images, and interactive graphics, onto real-world objects, and is experienced through a display device that can provide both a CGI video feed and a direct view of the real world, such as HMDs, smartphones, or tablets. The overlaid sensory information can be both constructive (i.e., additive to the natural environment), or destructive (i.e., masking the natural environment). Compared to VR, AR is therefore neither immersive, since the user continues to see the real world and does not have the sensation of being elsewhere, nor exclusive, as the user can continue to interact with the people and objects present in the environment. The great usefulness of AR therefore lies in the possibility of using contextual information associated with the scenario in which users find themselves or of seeing an object inserted in the environment which is not present in reality, reducing the mental effort that is needed to transfer information from an abstract representation to the physical world. By providing relevant information in the context in which it is needed, AR promises enormous potential to facilitate manual tasks, enabling time savings, quality improvements and efficiency enhancements, as demonstrated by evaluations in numerous projects.

The CGI content can be overlaid to the physical world in different ways:

- as a static graphic overlay always fixed to the screen. This design convention is useful for permanent elements that need to be within reach at all times such as a menu or return prompt, or the dashboard of a car that allows the driver to see the vehicle speed, the speed limit, and other signals of the road on which it passes and the navigator's indications projected onto the windscreen;
- as a static graphic overlay always locked in the same position in space. The CG content can have a dynamic feature where it always faces the user. This design convention is useful for labels and materials that need to accompany an object or marker in space;
- as a dynamic and flexible graphic (content type) overlay on glass. This convention works for allowing users to position assets in custom or specific areas. This is helpful for target based or drag and drop elements;
- as a dynamic 3D content flexible in space. A great way to engage with 3D models and understanding its components, it is most commonly used for educational purposes and understanding the breakdown of an object;
- as a dynamic 3D content proportionate in space. Helpful when allowing a user to see an object in an actual environment with lighting and measurement considerations.

The positioning of the object in space is determined through systems based on geolocation (GNSS, Wi-Fi triangulation, beacons, etc.) in situations where the approximation can be large, or if a high degree of precision is required, via using tags, markers, or anchors, typically 2D printed images which are recognized by the camera and act both as a trigger for displaying the digital content and as a reference to define its position, size, and perspective.

A keynote is that in all cases mentioned above, the augmented content does not recognize the physical objects within a real-world environment. In other words, in AR the CGI content and the real-world content are not able to respond to one another. Even in the case of dynamic 3D contents placed proportionately in the space environment, these are only anchored to the camera view and are always displayed in the foreground with respect to the real objects in the environment. Thus, for example, if the viewer is seeing the digital image of a chair, which by illusion should be placed on the floor in front of them, and any real object is introduced between them and the digital content, the latter will nonetheless appear in the foreground.

Through AR, it is therefore not possible to occlude the digital object with real objects, thus not allowing a true interaction between the two worlds; therefore, users cannot interact with the information or objects being overlaid onto the real environment.

That is where MR comes into play. MR is an extension of AR that brings the virtual and real worlds together, creating a more connected experience in which the virtual and real elements can interact. The term MR was first defined in 1994 by Paul Milgram and Fumio Kishino as “anywhere between the extrema of the *virtuality continuum*,” where the virtuality continuum extends from the completely real through to the completely virtual environment (Milgram and Colquhoun, 1999).

MR removes the boundaries between real and virtual world using occlusion: the computer-generated objects can be visibly obscured by objects in the physical environment from the user's point of view and become effectively part of the real world. A CGI ball can bounce off tables, walls, or disappear under a couch. With MR, the user can play around

with virtual elements like they would in the real world, and the 3D digital content responds and reacts accordingly. For example, using gestures, you could physically turn an object around to inspect it from all angles.

MR can be achieved in two ways: by adding virtual/digital content to the real world or, by adding elements of the real world into the virtual/digital one (such as streaming video from physical spaces, like through a webcam). Thus, MR must be viewed through semi-transparent glasses or MR headsets equipped with a camera in order to film and display the user's environment. To seamlessly place digital information within a user's real world and allow users to interact with these computer-generated objects enabling MR experiences, MR devices constantly scan and update the real-world environment.

The potential applications of AR and MR in the AECO industry are numerous, especially when overlapping/interacting the virtual and physical context on a construction site, and whenever applied with other technologies and techniques they can increase the productivity and performance of construction processes at all stages from design to facility management.

6.3.2.1 Augmented and mixed reality technologies

As for VR, hardware components for AR and MR include a processor, a display as well as sensors and input devices (Roltgen and Dumitrescu, 2020).

For the best human augmentation effect, both AR and MR devices should be head mounted in order to eliminate the need for hands-on interaction and must be viewed through semi-transparent glasses or headsets equipped with optical display that allow CGI to be superimposed on real-world view and with a camera in order to constantly scan the real environment enabling MR experiences. AR glasses and MR headsets are also equipped with noise-canceling microphones and directional speakers, and some models can be controlled by virtual assistants.

Several models of AR and MR HMDs are available today on the market (Danielsson, Holm, & Syberfeldt, 2020), designed to meet different needs (see Table 6.5).

Generally speaking, there are four possible ways to implement AR in HMDs: projection based, eye multiplexed, optical see-through, and video see-through. The latter two are the most common solution currently for commercially available AR headsets. Video see-through systems use a camera to capture the real world of a user, then add virtual content to create AR, and finally present this to the user on a screen. Optical see-through creates AR by combining a view of the real world with virtual images, usually achieved through directing the light of the virtual images through half mirrors or prisms. This allows the user to continue to see the real world while seeing AR content. Regarding displays in HMD's there are three possible choices: monocular (one eye views a screen), binocular (both eyes view the same screen), or dichoptic (each eye views a different screen, enabling depth perception).

Among optical see-through products most diffused in the industry, Google Glass Enterprise Edition 2 can be used to access training videos, view images annotated with detailed instructions, manage quality assurance checklists, and can connect with each other and share expertise also livestreaming their view for real-time collaboration and troubleshooting. They can be controlled hands-free using voice commands to launch the right application.

TABLE 6.5 FOV values of main AR and MR devices on the market.

AR glasses		MR headset		
Products	FOV	Products	FOV	Category
Epson MOVERIO BT-300	23°	Avegant Lightfield	-	Tethered
EverySight Raptor	43°	Dimension NXG AjnaLens	95°	Standalone
Google Glass Enterprise Edition 2	80°	Magic Leap One	50°	Standalone
Kopin SOLOS	10.68°	Microsoft HoloLens	35°	Standalone
Toshiba dynaEdge AR100 Viewer	-	Microsoft HoloLens 2	52°	Standalone
Vuzix Blade Smart Glasses	10°	Nreal Light	52°	Smartphone/tethered
ThirdEye Gen X2	42°	Occipital Bridge	120°	Smartphone
Vuzix M300	20°	Tesseract Holoboard Enterprise Edition	82°	Smartphone



FIGURE 6.17 Epson Moverio AR glasses (credit: Marco Verch).



FIGURE 6.18 Microsoft HoloLens 2 MR headset. *Courtesy of Microsoft.*



Epson Moverio BT-300FPV AR glasses allow watching in first-person view (FPV) the video feed of a drone flying, projected on a transparent display that not only lets the user pilot the UAV, but also monitor its key flight statistics, all while keeping the UAV in sight (see [Fig. 6.17](#)).

In addition to goggles, AR can also be experienced handheld with smartphones or tablets by directing their camera at an object in the real-world environment and using an AR app to overlay content such as an image, animation, or data that the user can see. Modern mobile computing devices like smartphones and tablet computers contain, in fact, in addition to the camera, other MEMS sensors such as accelerometer, GNSS, and solid state compass, making them suitable AR platforms.

Apple, Facebook, Snapchat, Google, and other well-known tech companies already offer AR applications and SDKs, and there are also some AR headsets such as Vuzix M300 and Mira Prism that mount smartphones.

The market for MR headsets is still narrower than the AR one, and is currently dominated by Microsoft HoloLens and Magic Leap, with new products arriving for 2021.

The flagship product is certainly represented by Microsoft HoloLens, currently in their second iteration, the only ones with eye and hand movement tracking to place MR content appropriately and to allow interaction by the user without relying on external controllers (see [Fig. 6.18](#)). Eye recognition also allows to log into HoloLens instantly and securely without passwords. Plus, thanks to smart microphones and natural language speech processing, voice commands work even in noisy industrial environments.

Apart from standalone MR headsets, a new wave of smartphone MR headsets such as Zappar ZapBox, Occipital Bridge, and Tesseract Holoboard Enterprise Edition have been recently released or are in the pipeline, offering MR experiences using the phone camera and display or translucent mirrors to superimpose the virtual objects to the real world.

6.3.2.2 *Augmented and mixed reality content creation*

The creation of content to visualize with AR or MR devices shares the same basics of setting up VR experiences, namely, exporting the 3D model or BIM in a graphic engine suitable for AR/MR visualization, such as Unity 3D, then integrating the virtual environment with the chosen functionalities and interactions (see Section 6.2.1.2). Alternative workflows rely on web AR-based technologies (e.g., AR.js, A-Frame, among others) that do not require a preinstallation of the solution on the user's device, which could encourage the technology acceptance (Sidani et al., 2021).

Differently from VR, however, AR and MR are context aware technologies, with the key characteristic of the ability of blending the reality we see with our own eyes with virtual objects that are seamlessly superimposed in their expected position, whereas in VR once the user enters the virtual space they completely detach from the real world. Therefore, one of the most delicate functions of both AR and MR is the alignment between the real world and the virtual environment to ensure the display is always correctly showing the virtual assets (geolocation).

In order to determine their 3D position in the real world and align the virtual environment and objects accordingly, AR/MR devices can calculate the coordinates through the spatial relationship between themselves and multiple key points via a process called SLAM. When the device is switched on, it starts processing data from the cameras and from the gyroscope and accelerometer to build a virtual map of the environment and then locate itself within that. Once it has an understanding of the environment, it is able to place virtual 3D models that feel like a part of the real world, because they are realistically positioned, oriented, and illuminated and the viewer is able to move close to and around them just like with real objects. Two of the most used SDKs to perform AR-oriented SLAM are ARKit for iOS and ARCore for Android operating systems, which can be implemented on any decently equipped smartphone.

During SLAM processing, in particular, visually distinct features in the captured camera image (feature points) are detected, combined with inertial measurements from the device's IMU to estimate the pose (position and orientation) of the camera relative to the world over time, and used to compute its change in location. Clusters of feature points that appear to lie on common horizontal or vertical surfaces, like tables or walls, are recognized as planes and can be used to place virtual objects resting on flat surfaces. Because feature points are used to detect planes, flat surfaces without texture, such as a white walls, may not be detected properly. Data about the distance between surfaces from a given point produces depth maps that enable more immersive and realistic user experiences, such as making virtual objects accurately collide with observed surfaces, or making them appear in front of or behind real world objects. The sense of realism of the superimposed images can be further increased by detecting information about the lighting of the real world (average intensity and color correction of a given camera image) in order for the graphical engine to light the virtual objects under the same conditions as the environment around them.

To interact with objects in the environment, the AR/MR device uses hit testing to take an x, y coordinate on the phone, tablet or HMD screen and project a ray into the camera's view of the world, returning any planes or feature points that the ray intersects, along with the pose of that intersection in world space. Whenever a hit test returns a feature point, the device will look at nearby feature points and use those to attempt to estimate the angle of the surface at the given feature point, returning a pose that takes that angle into account. This way, when a virtual object must be placed, it is anchored to that specific pose (for instance, the middle of a desk) to ensure that the device can track the object's position over time when it moves around, even if it falls outside the display's field of view, and display it in the correct place at all times.

MR takes this correspondence between real and virtual world further by enabling precise and continuous reaction of virtual objects to physical ones. As the real environment is processed via SLAM, the virtual environment can be aligned by fixing three virtual points on three respective physical points to define the x, y, and z axes. Virtual objects are aligned with a two-point system: a first anchor point is placed on a position identifiable with SLAM, such as a marker or a predefined fixed object like a sign or a fire extinguisher (Koch, Neges, König, & Abramovici, 2014), and the second point is used to define scale and orientation of the virtual model. Once the virtual model is aligned with the real one, MR allows virtual objects that would be obstructed from view by real ones (such as walls, floor, and columns) to be occluded accordingly. Likewise, it is possible to toggle their visualization to show, for instance, an X-ray view of the pipes beneath a floor or wall surface, employing specific shaders of the graphical engine to regulate their transparency.

6.3.2.3 Augmented and mixed reality applications

There is no doubt that, thanks to the ability to superimpose digital images and information on the real world, both AR and MR find their maximum potential for application within the AECO industry in the construction and maintenance phases of buildings, acting as real human augmentation devices (see [Sections 9.3. and 11.3.](#)).

Nonetheless, AR, and MR in particular, are finding numerous and interesting applications also in the design phase with particular reference to building renovation interventions, infrastructure design, and urban planning ([Delgado et al., 2020](#)) and, more recently, also in digital fabrication (DF) in architecture ([Song, Koeck, & Luo, 2021](#)) (see [Fig. 6.19](#)).

One of the very first applications of AR in architecture involved the possibility of viewing, via tablet or smartphone, 1:1 scale furnishing inserted into a room, or the 3D model of the building overlaid its 2D floor plan.

Furniture retailers such as IKEA, Houzz, and Wayfair offer apps that allow consumers to preview 3D and true-to-scale models of their products in their actual rooms using their phone or tablet. The product is automatically sized to fit the space (which IKEA claims is 98% accurate) and can be moved or rotated within view.

AR mobile apps such as Augment, ARki, MAP Systems, Akular or SmartReality use the mobile device's camera to overlay a 3D model over printed construction plans, over a table or even on site at real scale, to create explorable digital 3D visualizations of projects replacing conventional architectural models, thus reducing prototyping costs and increasing customer appeal. These apps allow users to zoom, expose structural layers, move through stages of a project over time and record images and video of their experience. AR Sketchwalk app by Morpholio allows designers to use AR to dive into their sketches to give both their clients and themselves a truer sense of the space. Using an iPad, users position their sketch in the plan (or site) and can walk through it, growing the walls contextually. This makes the experience of presenting a project much more interactive and clearer to the customers.

Indeed, the possibility to combine the real environment with virtual objects makes AR particularly effective for visualizing renovations and retrofit works. Via a smartphone or tablet, AR projects a “digital window” that superimposes a detailed BIM model, be it a building or a road, onto the user's physical surroundings to help them visualize the placement of entire structures, as well as specific design features, objects, or systems. Through AR, the client can enter the building site (for example a home before the renovation works begin), as the 3D model images overlap with the real images. They will be able to walk around and view the home in an as-built simulated view.

Trimble SiteVision is an AR system that combines a field controller with a lightweight, handheld integrated positioning system (see [Fig. 6.20](#)). The system uses GNSS to pinpoint the user's location, and a rangefinder to allow measurement between remote points and the AR model. Using the built-in camera, the user is able to see the 3D model overlaid on the physical surroundings and accurately located in context, understanding precisely the interaction of the model with the environment. Sensors pick up changes in the user's motion and point of view, then the tool overlays the 3D model on the mobile device screen relative to what the user is seeing. Users can view the model on the jobsite the way it is meant to be constructed identifying issues beforehand to reduce clashes and costly errors. With the AR tool, users can also take photos, measurements, and notes onsite and can create and assign tasks to other team members to ensure productive follow-up. Updates in the field can be shared and viewed back in the office, further connecting teams, workflows, and data.



FIGURE 6.19 AR/MR design visualization with Microsoft Hololens (photo by the author).



FIGURE 6.20 Trimble SiteVision AR system. *Courtesy of Trimble.*



FIGURE 6.21 MR collaborative environment. *Courtesy of Microsoft.*

In the same way, AR is used as well to support virtual tours and in situ walkthroughs, for example, enriching cultural heritage tours by overlaying virtual objects on cultural sites (Bozzelli et al., 2019; Claudia tom Dieck and Hyungsoo Jung, 2017). AR systems can also overlay the results of building thermal or fluid dynamics simulations on the virtual model or projected on the real environment (Fukuda, Yokoi, Yabuki, & Motamedi, 2019; Lin, Cao, Zhang, van Treeck, & Frisch, 2019).

Also in the case of building renovation, numerous AR apps for mobile allow not only to quickly measure heights, lengths, and dimensions of objects (AirMeasure and MeasureKit among several others), but also to instantly create the floor plan (also in 3D) of a room by pointing smartphones or tablet cameras at the corners and taking pictures while turning around (Magic Plan, Room Scan, and Floor Plan Creator).

In addition to these possibilities, MR allows to create collaborative environments where several people, who may even be in different places, can literally walk around and at the same time interact with a virtual 3D model as with a physical one actually present in the room and show the design intent to stakeholders without using real models (see Fig. 6.21).

MR can be also used to build mockups that combine physical and digital elements by inserting the digital model over the real one. This is particularly useful in the case of interventions on an urban scale. For instance, HoloPundits City Planning application helps planners and architects to graphically visualize a plain blueprint as a completed project, allowing 3D walkthroughs, to adjust building spaces, to drag and drop props, and to replace the virtual buildings.

HoloMaps by Taqtile is a VR and AR app for navigating through a holographic geographical model while overlaying real-time data, integrating Bing 3D with over 200 cities and landmarks as a 3D model of any size. Data source integration brings contextually relevant information (live traffic, weather, and Twitter feeds) that can be shared with colleagues and clients locally or remotely, synchronously or asynchronously, along with 3D pen and voice-to-text annotations, and MR capture photos & video.

Among recent and innovative proposals for virtual design environments, particularly promising is the prototype developed by Squint/Opera, BIG and UNStudio with the Hyperform tool, a virtual cloud-based desktop that can be accessed from a computer, tablet, smartphone, or using a VR headset. As well as looking at models in a neutral space like in other AR/MR tools, Hyperform can be used to digitally view models of buildings within the environments that they are being designed for, using geolocation data to create a virtual model of a building and the landscape surrounding it to allow architects to see how the building will relate to its environment.

6.4 Computational and generative design

In the last ten years, the application of computers in the design process has undergone a profound evolution. From a mere digital design tool (computer aided drafting or computer aided design—CAD), the computer has entered the workflow as a computational tool for design tasks automation, for the generation of design solutions or for the evaluation of the performance of the building or its parts within the design process (computational design—CD). The increased computational capacity of tools and the diversity of the available CD methods have enabled architects to enhance the design process, either by making it more efficient or by expanding its conceptual boundaries. These methods empower architects to explore and evaluate other complex solutions, create and deploy advanced fabrication techniques, and control the design process at different stages.

CD is based on a parametric approach to design, which, through the use of visual programming tools, implies the use of parameters, rules, equations, and instructions for the generation of shapes or objects or for the automated execution of certain activities.

According to the type of computational activity that is carried out by the computer, CD takes different names (see Fig. 6.22), often used improperly or overlapping each other (Caetano, Santos, & Leitaño, 2020). Computational activities such as importing and exporting data, automating tasks like renaming or copying elements or views, or incorporating and propagating changes in a quick and flexible manner, commonly fall under the name of design automation.

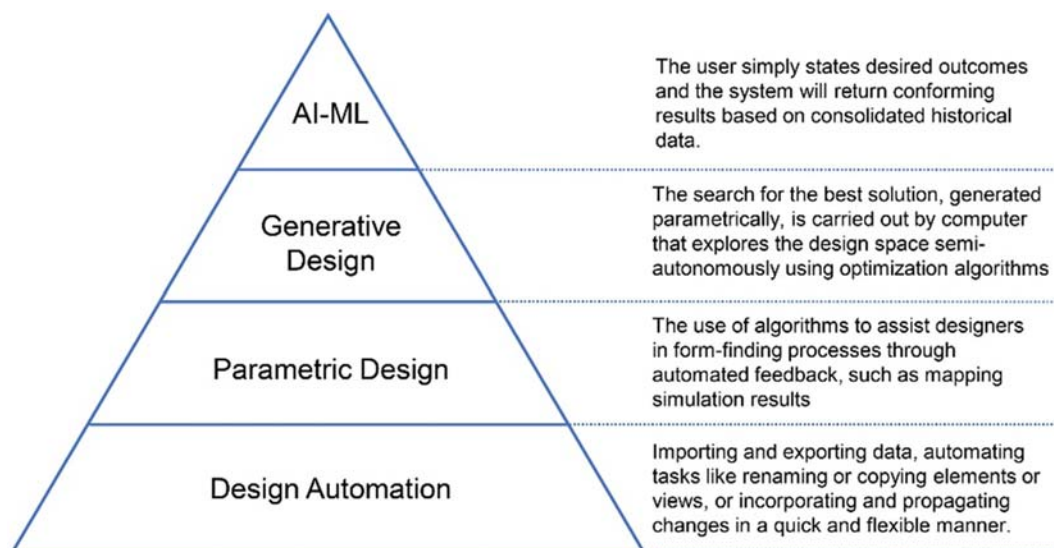


FIGURE 6.22 Computational design.

The use of algorithms to assist designers in form-finding processes through automated feedback, such as mapping simulation results, takes the name of parametric design, which often also includes the terms of algorithmic design or of computational design itself. When the search for the best solution, generated parametrically, is carried out using optimization algorithms, the ambit is instead that of generative design (GD).

GD primarily addresses the requirement by parametric approach of having to investigate and evaluate the different design options manually. This is done by tasking the computer with exploring the design space semi-autonomously and then reporting back to the designer which options it considers promising for further analysis. As a computer can process information much quicker than a human operator, this allows a much deeper exploration of complex design spaces.

For this to happen, the basic parametric model must be integrated in two ways. First, the designer must explicitly indicate the measurable metrics by which each design option shall be evaluated to determine which designs perform better than others, since the computer itself does not have any inherent intuition about design quality. Second, the model needs to be connected to a search algorithm that can control the input parameters of the model, get feedback from the metrics, and intelligently tune the parameters to find the highest performing design variations while exploring the full possibilities of the design space.

The ultimate evolution of computational design is AI and machine learning (ML) assisted design, in which the user will simply state desired outcomes and the system will return conforming results based on consolidated historical data. Instead of starting from a parametric or computational model, ML-based tools “learn” from data sets and find patterns that are inferred instead of being explicitly stated. Given a desirable set of characteristics, ML could generate a design or a set of designs that fit the description.

6.4.1 Parametric design

According to literature, parametric design can be defined as a process based on an algorithmic approach that expresses parameters and rules that, together, can define, encode, and clarify the relationship between designer’s intent and design response (Caetano et al., 2020; Touloupaki and Theodosiou, 2017). This method consists mainly in an efficient way of flexibly describing and creating geometry through scripting, linking decision variables and constraints (parameters) to geometry, establishing interdependencies between objects, and defining transformational behavior of these objects. Such an approach offers dynamic control over geometry and components, allowing the designer to seek appropriate solutions for complex problems with the assessment of multiple variants at the same time.

Parametric design aims to overcome the limitations entailed by the independent nature of the design elements in conventional computer aided drafting and is based on the definition of the relationships between elements, either single or grouped, and how these relationships are organized and controlled. The first computer tools to be widely adopted by architectural designers were computerized versions of traditional drafting and rendering tools. While they allowed designers to produce content much faster than with traditional methods, they did not fundamentally change the process of design. Conventional CAD software in fact was primarily conceived to facilitate repetitive work in design, allowing the use of basic editing functions like “copy,” “cut,” and “paste” which allow the designer to add, reposition, or remove elements of the project effortlessly. This system, however, requires each design element to be more or less independent from the others, thus when one element is moved those surrounding it remain unaffected. Such functionality, while allowing rapid development and transformation of designs, has an inherent drawback: any significant change to the model implies manually adjusting lots of elements and becomes more time-consuming as the complexity of the model increases with the integration of additional components (such as MEP systems or architectural elements) or with the pursuit of more free-form shapes. Hence, this approach may end up limiting the freedom of exploration in the early stages of the design process and constrain changes that may occur later in project development.

By establishing connectivity between elements, the parametric approach to design effectively replaces the designer’s manual interaction with the model with the development of a series of relationships by which elements automatically connect and build up the design. The designer then alters the values of the parameters or the equations that form these relationships between elements, and the effects will be reflected into the design, either visually (concerning geometrical characteristics) or only in the related databases (for instance, adjusting tags or quantities) (Dunn, 2012).

Once the relationships have been established, the designer has a much greater opportunity to explore project alternatives without time-consuming reworkings and adjustments, and the system may even run autonomously within its parameters to explore novel solutions that may not be apparent to the designer (GD). In more complex design situations, which therefore involve many different parameters, this type of design approach is extremely useful as the practitioner can integrate all the different design aspects into a single database and manipulate it accordingly. This allows multiple options to be generated within values specified by the designer, with each project alternative not requiring to make a new model or, at least, to

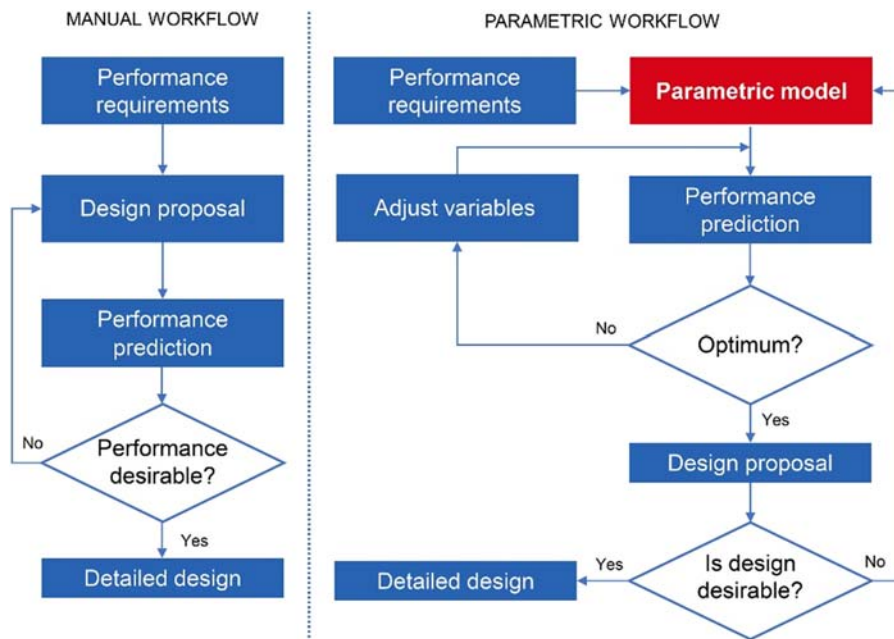


FIGURE 6.23 Manual and parametric design workflows.

reconfigure the previous one every time. Whereas, in a traditional approach, the designer crafts a single design solution, or a handful at most, after having studied the design problem and internalized all its constraints and objectives, in parametric design those inputs become the parameters and relations that are embedded into the parametric model, which can then be used to generate a variety of solutions as far as a preferred one is identified (see Fig. 6.23).

In addition to speeding up the design process, even more pivotal is the possibility offered by the parametric approach of allowing designers to think through design solutions in a deeper and more dynamic way than that possible with traditional methods: instead of designing a single solution, the designer can now think of designing a multidimensional design “space,” where each dimension represents one of the critical parameters exposed by the parametric model, and each individual design variation can be found.

It is important to note, however, that parametric design requires a higher upfront investment in terms of time and effort compared to conventional CAD, that goes into identifying and establishing the relationships within the parametric system and setting the rules to be encoded in the program. Moreover, the exploration of the design space is in any case still limited by the abilities of human designers. In this picture, ML techniques have been used to emulate the hard-coded rules and parameters, unveiling the underlying phenomena behind them (Hong, Wang, & Luo, 2020).

Parametric design can be applied to the whole project or to limited subsystems to facilitate optimization and specific problem solving. Parametric design applications include several computational performance-driven design problems at different scales, from urban planning to environmental context integration, up to structural or MEP dimensioning.

In particular, the application of parametric design principles has allowed a much more streamlined and easier control of complex and freeform 3D shapes in design and engineering development of the project, which would otherwise be cumbersome and impractical to manage with conventional CAD operations. Specifically, all modern modeling software enable the designer to produce parametrically 3D forms with unprecedented freedom and then to easily integrate them into the design and engineering activities without compromising their aesthetical or spatial characteristics. Two main methods to define 3D curved forms are non-uniform rational B-splines (NURBS) and 3D meshes, with the former more suitable for achieving smooth surfaces and curves, and the latter able to approximate the desired formal elements through subdivisions into polygons.

NURBS is a mathematical model that allows to define and generate 3D curves and shapes via a number of control points that dictate the parameters that map the surface in the 3D space. This allows easy human interaction with the curved object, as sculpting NURBS curves and surfaces is highly intuitive and predictable with control points always either connected directly to the curve/surface, or acting as if they were connected by a rubber band, and allows the user to develop complex geometrical designs parametrically. Adding more control points allows better approximation to a given curve. NURBS curves also feature a scalar weight for each control point, which allows for more control over the shape of the curve without unduly raising the number of control points. The term rational in NURBS refers to these weights.

3D meshes, on the other hand, describe the desired geometry as a polygonal or polyhedral unstructured grid, constituted by vertices, edges and faces each identifiable and with its own set of coordinates and defined characteristics. Polygons have commonly three or four sides; however, more complex polygonal elements can be used, and their number dictates the accuracy of the parametric grid compared to the original curved surface. Compared to NURBS, meshes have less intuitive interaction as there are much more points to deal with; however, they are more compatible with functions such as Boolean operations (combination, intersection or subtraction of volumes), smoothing, and simplification. Polygonal meshes are also commonly applied in digital modeling to develop physical simulations for finite element analysis (FEA) and computational fluid dynamics. Projects may typically require designs to be defined in both NURBS and 3D mesh formats, depending on the stage of the design process alongside software applications.

6.4.2 Generative design

GD is a design approach that uses algorithms to generate a host of different solutions from a given set of design goals and constraints. GD embodies many applications and techniques that use computation to augment the designer's ability to define, explore, and choose alternatives through automation, with consequent advantages in terms of design speed, quality of the result, and reduction of construction costs of the proposed solution.

GD allows the designer to identify rapidly the single design solution which, among thousands of alternatives, is able to simultaneously optimize several variables of different nature (environmental, functional, economic, performance, etc.), often antithetical to each other.

GD applications in architecture are numerous, from the urban scale for identifying, for instance, the best shape ratio and orientation of a building within the construction lot, to that of layout, structural and plant design, up to industrial design for the static optimization of the shape of a structural joint or the size of the cladding elements of a facade in order to minimize materials waste.

From the operational point of view, GD implies an iterative computational process, set up and guided by the designer (see Fig. 6.24). Starting from the initial requirements, the designer defines variables and constraints, which are then formalized in the form of algorithms that have the task of generating the solutions (generator algorithm), of connoting those through numerical quantification (evaluator algorithm), and of reaching the optimal solutions by modifying iteratively and appropriately the input variables that feed the generator algorithm (solver algorithm). It is up to the designers to analyze these final results and extract from them new information, based on which they will eventually modify one or all three algorithms of the program to obtain new and better solutions.

Generator algorithms have the task of generating, from the input data, the potential solutions to the problem on the basis of the parameters and logics set by the designer. From the shape of the stands of a stadium, to the floor layout of a hospital structure, to the routing of an HVAC system, through simple or even very complex functions based on neural networks, the generating algorithms generate potential solutions in any form the user request.

Generated solutions are then analyzed using another algorithm, the so-called evaluator algorithm, which is tasked with associating to each of them the numerical values that can allow to measure the results achieved in view of the proposed objectives, that is, level of brightness of an environment, solar radiation of a surface, aspect ratio, area of a room, safety distances, etc.

Once measurable, the proposed solutions can be optimized through a third algorithm, the so-called solver algorithm, on the basis of the objectives set by the designer: maximizing the internal lighting values, minimizing the pressure drops of a network, etc.

The solver algorithm is in fact a function capable of executing a script that iteratively carries out generating and evaluating algorithms, and of modifying the input data appropriately each time.

For this, different types of heuristic optimization algorithms (metaheuristic algorithms) can be used (Attia, Hamdy, O'Brien, & Carlucci, 2013; Back, 1996; Machairas, Tsangrassoulis, & Axarli, 2014; Nguyen, Reiter, & Rigo, 2014; Shi, Tian, Chen, Si, & Jin, 2016).

Metaheuristics algorithms are stochastic algorithms with randomization and global exploration. Metaheuristics represent an efficient way to produce by trial-and-error acceptable solutions to a complex problem in a reasonably practical time. Randomization provides a good way to extend search from a local to the global scale.

For buildings, optimization metaheuristics algorithms are preferred to direct research methods such as pattern search, linear programming, and nonlinear programming. These, in fact, work by comparing trial solutions with the best ones found so far for determining the next trial, making them efficient but susceptible to be trapped in local optima (Evins, 2013; Kolda, Lewis, & Torczon, 2003).

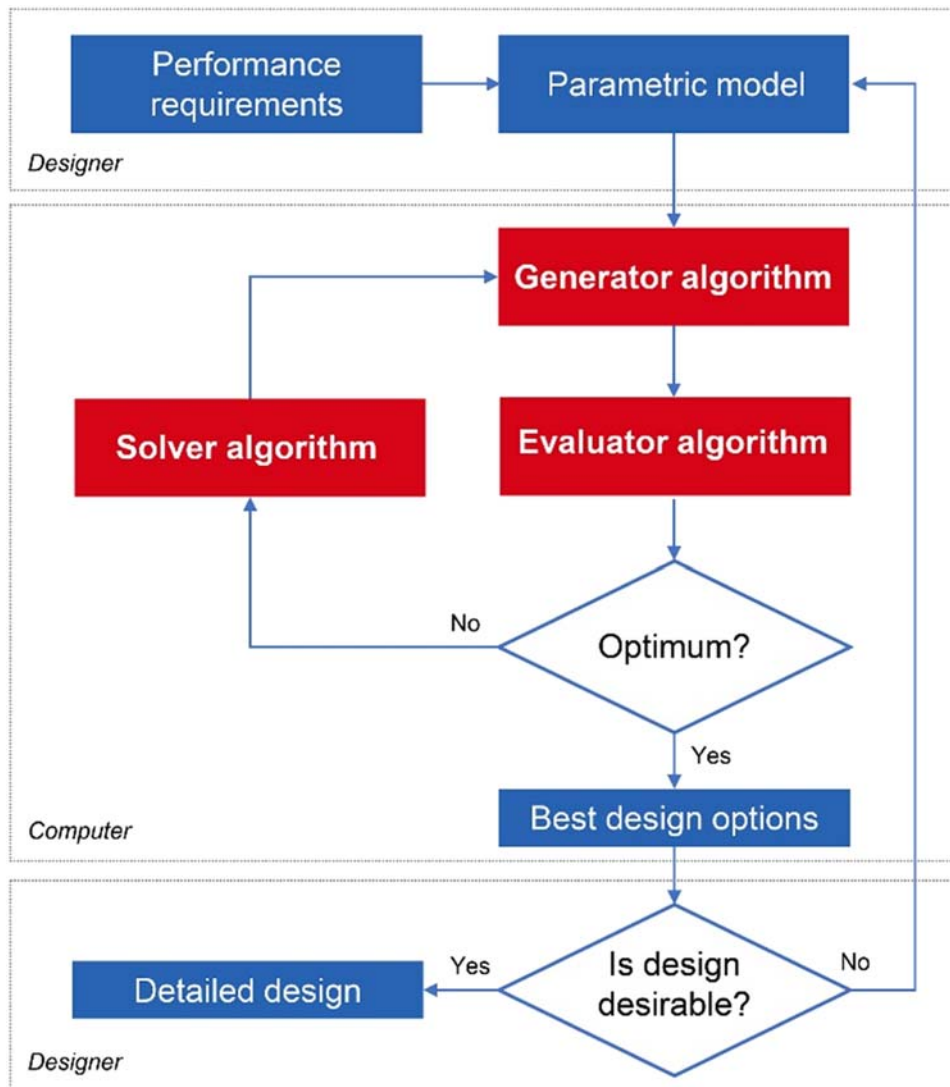


FIGURE 6.24 Generative design workflow.

Commonly used metaheuristic algorithms include the so-called nature-inspired algorithms, comprising evolutionary algorithms (EA) and algorithms that mimic other natural processes (Yang, 2010).

EAs reach an optimal solution starting from a first solution which is evolved using mechanisms inspired by biological evolution, such as reproduction, mutation, recombination, and selection. The main types of evolutionary algorithm include (Evins, 2013):

- genetic algorithms (GA): a fixed, linear data structure (i.e., a list of variable values), which is most commonly implemented for multiobjective problems as NSGA-II (Non-dominated Sorting Genetic Algorithm II);
- evolutionary programming (EP) and genetic programming (GP): tree-structures that allow hierarchical variables or representations of functions and programs. In EP, only variable values change; in GP, the structure also changes;
- covariance matrix adaptation evolutionary strategy (CMA-ES): new variable values are sampled from probability distributions, in which the dependencies are represented by a covariance matrix, updated each generation;
- differential evolution (DE): variable values are perturbed by introducing components of other good solutions;
- neuroevolution: Similar to genetic algorithms (GA), but the genomes represent artificial neural networks (ANNs) by describing structure and connection weights. Genome encoding can be direct or indirect.

In addition to evolutionary algorithms, other nature-inspired algorithms that emerged in the last decades are based on swarm intelligence (SI), and include ant colony optimization (ACO), particle swarm optimization (PSO), bat algorithm (BA), firefly algorithm (FA), cuckoo search (CS), and others (Evins, 2013; Kolda et al., 2003). These algorithms

are commonly global optimizers, and use a swarm of multiple, interacting agents to generate the search moves in the design space. They are typically simple, flexible, and yet efficient, as shown in several applications and case studies. The main nature-inspired algorithms used in building applications are (Kheiri, 2018):

- harmony search (HS): variable values are recombined to find better combinations, adding some perturbation to neighboring values. A rolling population of best solutions is maintained;
- PSO: solutions move in design space based on their own position and that of the best position in the swarm;
- ACO: mimicking the process by which ants deposit pheromones on paths to encourage other ants to follow, variable values that are much-used accumulate “pheromones,” biasing their selection in future choices;
- simulated Annealing (SA): solutions are perturbed away from their current positions, and the probability of retaining the better solution is gradually increased with time.

Metaheuristics dominate the literature on optimization in architectural design and have proven suitable for a wide range of architectural design problems. They are in fact easy to implement and are applicable to almost any kind of optimization problem, regardless of the number and type of variables (e.g., linear/nonlinear, continuous/discrete, convex/nonconvex) (Wortmann, Costa, Nannicini, & Schroepfer, 2015).

Most commonly used algorithms for building applications in case of optimization of multiobjective functions are GAs, and the elitist NSGA-II in particular (Oxman, 2008).

Neuroevolution algorithms such as ANNs are often used within the evaluating algorithms (Sia et al., 2019). Among nonevolutionary algorithms, most used is PSO, proposed by Kennedy and Eberhart in 1995, inspired from social swarm behavior in nature such as bird flocking and fish schooling (Ekici, Cubukcuoglu, Turrina, & Sariyildiza, 2019). As with other population-based optimization methods such as GAs, PSO starts with a random population of particles in the search space. However, differently than other evolutionary optimization methods, in PSO there is no direct recombination of genetic material between individuals during the search, instead the algorithm works on the social behavior of particles in the swarm and provides the global best solution by simply adjusting the trajectory of each individual toward its own best location and toward the best particle of the entire swarm at each time step (generation). PSO is becoming very popular due to its simplicity of implementation and ability to quickly converge to a reasonably good solution (Ma, Yu, & Hu, 2013).

As an alternative to the genetic process that sees the iterative optimization of gradually generated solutions when, for instance, it is necessary to carry out optimizations very quickly, it is possible to resort to a so-called surrogate model (Wortmann et al., 2015; Wortmann, 2019), that is appropriately and previously trained and is capable of evaluating the solution proposed by the designer or to generate the best solution to a problem (for example, finding the best shape of a building in a given climate). Computer models built based on real buildings are in fact usually complex, and the simulation time can vary from minutes to hours; a common optimization run usually requires hundreds or thousands of computational simulations, which makes the optimization process very time-consuming and impractical. A comprehensive survey of methods for creating surrogate models for engineering design is provided by Koziel, Ciarri, and Leifsson (2011), Simpson, Poplinski, Koch, and Allen (2001) and Wang and Shan (2006).

The surrogate model mimics the behavior of the original model with sound accuracy by learning from a given dataset, is computationally cheap to evaluate, and has been successfully applied in many building related studies for architecture design optimization or building performance optimization. Wang et al. identify three approaches to design optimization with surrogate models: construct a surrogate model and use an optimization algorithm to look for an optimum in the model; construct a surrogate model with a sampling method embedded in an (iterative) optimization algorithm; and construct a surrogate model and look for an optimum (iteratively) without employing an explicit optimization algorithm (Wang and Shan, 2006).

Compared with metaheuristics, surrogate-based optimization methods have important advantages for architectural design (Wortmann et al., 2015). Surrogate-based methods find solutions faster, allow the designer to explore quickly an approximation of the solution space, and can be refined progressively. In addition, a designer can recalculate the surrogate model essentially in real time to explore the impact of different evaluation criteria (i.e., objective functions) on the solution space.

However, surrogate-based approaches, that completely replace time-intensive simulations with surrogate models and then apply optimization methods, are inherently conditioned by the models' initial precision. Increasing the models' precision requires a larger sample size, which can negate the initial speed advantage. Contrastingly, model-based methods iteratively build and refine models during the optimization process. Model-based methods thus are particularly effective for optimizing problems with time-intensive simulations and complex relationships between variables and objectives.

6.4.2.1 Genetic algorithms

A GA is a heuristic algorithm that is used to solve optimization problems for which no other efficient algorithms are known (Miles, 2010). The adjective “genetic” is inspired by the principle of natural selection and biological evolution theorized in 1859 by Charles Darwin, and derives from the fact that, similarly to the Darwinian evolutionary model that finds explanations in the genetic branch of biology, GAs implement mechanisms conceptually similar to the biochemical processes discovered by this science.

GAs originate from the first theories of Ingo Rechenberg who in 1960 spoke for the first time of “evolutionary strategies” within computer science. The real first creation of a GA is, however, historically attributed to John Henry Holland who in 1975 published a series of theories and techniques in the book *Adaptation in Natural and Artificial Systems*, which are still of fundamental importance for the study and development of the subject.

In summary, GAs consist of algorithms that allow to evaluate different starting solutions (as if they were different biological individuals), and that by recombining them (similarly to sexual biological reproduction) and introducing elements of disorder (similarly to random genetic mutations) produce new solutions (new individuals) who are evaluated by choosing the best ones (environmental selection) in an attempt to converge towards “best” solutions (see Fig. 6.25). Each of these phases of recombination and selection can be called a generation, like those of living beings.

During its execution, a typical GA evolves solutions according to the following basic scheme:

1. random generation of the first population of solutions (chromosomes);
2. application of the fitness function to the solutions (chromosomes) belonging to the current population;
3. selection of the best solutions based on the result of the fitness function and the chosen selection logic;
4. crossover procedure to generate hybrid solutions starting from the solutions chosen in point 3;
5. mutation process to maintain genetic diversity within the population;
6. creation of a new population starting from the solutions identified in point 5;
7. re-execution of the procedure starting from point 2 and using the new population created at point 6 until the end of the iteration process.

The iteration of these steps allows the evolution towards an optimized solution of the considered problem. The end of iterations can be set according to various criteria: termination after a fixed number of generations, termination until solution meets the preset minimum requirement, or termination after reaching a plateau when no better results can be produced.

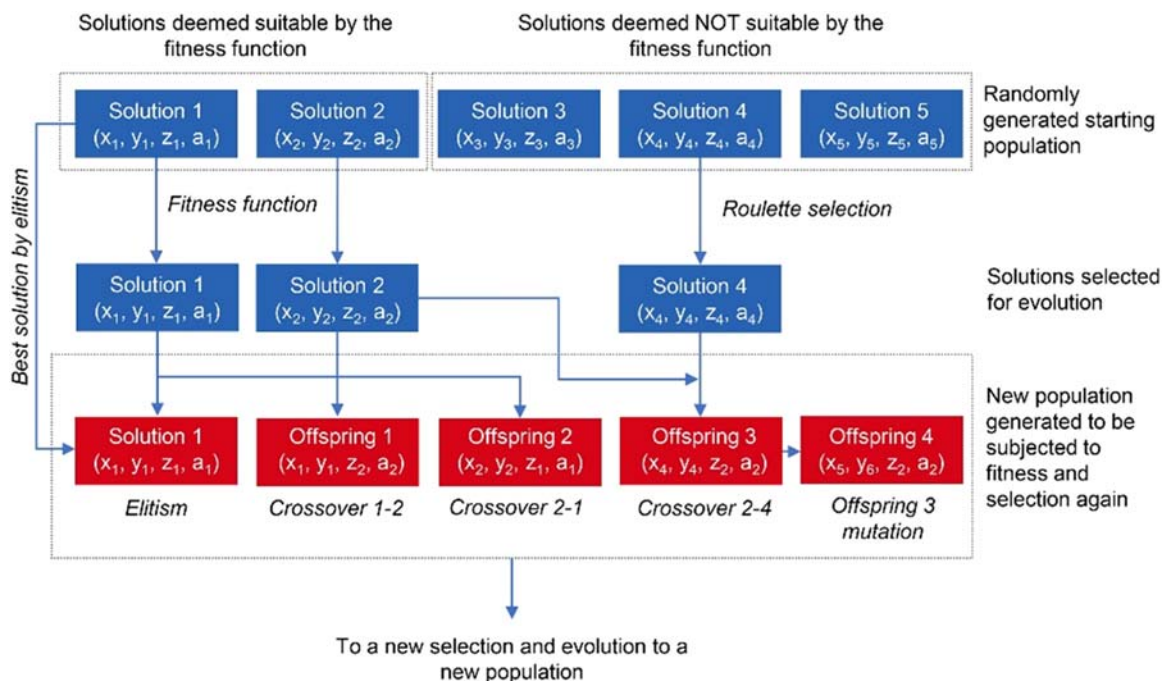


FIGURE 6.25 Genetic algorithm.

The fitness function is what allows to associate a solution with one or more parameters related to the way it solves the specific problem, and thus to determine how “good” each solution is. Basically, it is the design criterion to maximize or minimize, and any parameter that influences the execution of the design intent is eligible to become the metric of the fitness function: construction cost, structural efficiency, carbon footprint, daylighting quality, acoustic quality, programmatic compliance, view quality, etc.

Due to complex phenomena of nonlinear interaction (so-called epistaticity), it is not granted that from two promising solutions a third more promising one is born, nor that two solutions with low fitness values generate a third one with an even lower value of fitness. To overcome these problems, while sorting the candidate solutions for evolution, particular “selection” techniques are also used in addition to the parameter obtained from the fitness function. The most common are roulette selection, category selection, tournament selection, boltzmann selection.

Crossover refers to the combination or exchange of characteristics between two members of the elite group defined by selection, by which offspring is produced. There are various types of crossover, with most frequently used being one-point crossover, in which the parents’ chromosomes are cut at a specific point, and the head of the first is pasted to the tail of the second or vice versa; and two-point crossover, in which a chromosome part from one of the parents is obtained and exchanged with the part that lies in the same location of the other parent.

After the application of crossover on the population, a new generation is produced. Since basic GAs suffer from the fact that some optimal solutions could be lost during the course of evolution and from the fact that evolution could fall back and stagnate in “local optima,” they are often integrated with techniques like elitism and random mutations. The first consists of an additional step preceding point 4 in which the best individuals of the previous population are copied directly into the new populations, the second instead (point 5) introduces occasional random mutations into the solutions identified in order to allow to exit from any stagnation in local optima.

Mutation consists of the pseudorandom modification of some parts of the genes based on initially defined coefficients. These changes are sometimes used to improve the value of the fitness function for the solution in question and other times they are used to expand the research space and implement the elitist technique to avoid dropping the evolution into local optima. The frequency with which a mutation must occur is generally regulated by a specific parameter, commonly called “pm”.

Whenever there is more than one objective to optimize, as typically occurs in architectural design problems, it is possible to use a multiobjective GA such as Multi-Island GA, Real coded GA, Multi-objectives GA (MOGA), Niched Pareto GA, or NSGA-II, introduced by (Deb, Pratap, Agarwal, & Meyarivan, 2002) and employed in Autodesk Refinery software for GD.

The multiobjective NSGA-II algorithm works the same as when it pursues a single objective; hence, it always starts from a certain number of possible solutions (the population) and tries to identify, through different iterations, a certain number of optimal solutions, which will be placed on a Pareto front. The difference is that there are now two or more fitness functions to evaluate.

The Pareto front, also known as the trade-off curve, represents the set of optimal solutions, meaning it is made of all nondominated points, that is, those points for which there is no point that is better at the same time for all the objectives considered in the optimization function. A point can be part of the Pareto front even if it does not dominate anyone, since the important thing is that it is not dominated by other points. It is commonly used in engineering solutions, where a designer can evaluate a set of several optimal solutions.

Fig. 6.26 is an example of “Pareto front”: the squares represent possible choices, where small values on f1 and f2 represent the better solution; point C is not on the Pareto front because it has two dominant points, A and B. These two are instead not dominated and therefore are on the Pareto front. These solutions all have the characteristic that none of the objectives can be improved without prejudicing another.

6.4.2.2 Parametric and generative design applications

Today, computational design finds more and more applications in supporting the design process from its initial stages.

With the increased demand of the global market for more efficient and complex buildings, the number and degree of complexity of the variables to take into account in building design has grown significantly, to the point of requiring the use of innovative computational and generative tools.

Choosing the proper design solution has always been a compromise between different options. The design of the project can be summarized, in fact, as the systemization of all the environmental, technical, economic, and social aspects that emerged from the initial analysis of the needs to be met and the constraints to be respected, as well as of the characteristics of the environmental context where the intervention will take place. This phase is characterized by a

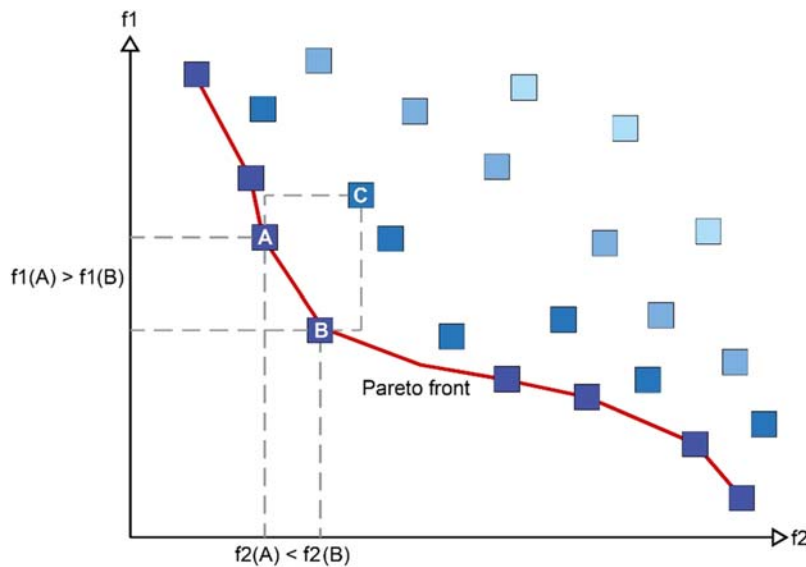


FIGURE 6.26 Solutions space with Pareto front.

continuous verification of the design choices at different scales, considering the entire life cycle of both the settlement and the building complex, in relation to the objectives set (Woodbury & Burrow, 2006). Design aspects to be considered are therefore numerous and diverse and require a collection of skills capable of interacting and cooperating toward a common goal.

In this sense, computational design can allow to obtain three important advantages. The first, of practical/operational nature, is to allow to speed up the design process, thanks to the automation of the design activities and the ability to quickly modify and update the project simply by changing the input variables.

The second advantage, of strategic nature, is directly linked to the characteristics of computational design which involve analyzing the project, identifying clear and measurable design objectives, and selecting all possible significant parameters that can influence the achievement of these targets. This allows to achieve a greater understanding of the project through a deeper awareness of the variables determining its final quality, including manufacturing issues, and therefore to make more informed and transparent choices, directing at best the creative process. Computational design involves a radical change in the design approach: from modeling an “object,” to modeling the “logic” of its design. The object of the design is no longer the building itself but rather its process. This allows design space to be explored far beyond the originally envisioned design ideas, in a way that would be impossible with traditional design and modeling approaches (Aish and Bredella, 2017; Leach, 2009).

The third advantage is, instead, of tactical nature. An optimal design of buildings has to consider multiple, and usually competitive, objectives such as energy consumption optimization, internal comfort, users’ preferences, safety, reduction of financial costs and of environmental impacts. Integrated building design is inherently a challenging multi-objective optimization problem where two or more conflicting objectives must be minimized and/or maximized concurrently.

In this picture, multiobjective optimization methods of GD provide a valid support to the design workflow, allowing to quickly identify the most promising building variants on the basis of diverse and potentially contrasting needs and objectives and to assist the project team in making better design decisions.

Typical GD objectives may concern, for example, aspects related to:

- the insertion of the building into the context, such as the optimization of its volume with respect to the ratio between the built surface and the gross floor area, or the search for the optimal shape and orientation, as well as the identification of the best position and size of the openings and screening systems in a given climate to maximize energy performance, thermal and light comfort;
- the identification and optimization of a particularly complex and unprecedented form of the envelope, or of the internal walls of an auditorium to optimize its acoustic performance;
- the internal layout distribution, such as floor plans optimization according to the shortest routes, or the best position of seats able to combine an optimal view with the greatest capacity in the case of entertainment structures such as stadiums, theaters, auditoriums;

- the optimization of the building envelope in order to reduce energy consumption and life cycle cost;
- the configuration and sizing of systems and equipment in order to ensure maximum efficiency with the lowest operating costs;
- the optimization of electrical systems routing within the building to ensure that too many cables do not end up along the same route;
- the choice of construction materials, considering cost, building energy use, and embodied energy;
- the sizing of the structural elements in order to reduce the quantities of material used and the construction costs;
- the sizing of the solar-wind-battery hybrid systems in buildings to minimize the total cost, CO₂ emissions and the load on the power grid;
- the optimization of NZEB design in different climatic zones in order to achieve the maximum reduction of the carbon footprint, of the embodied energy of materials or of the operation energy costs;
- the identification of the best energy retrofit intervention capable of minimizing the investment, minimizing the energy demand or cost, and minimizing CO₂ emissions;
- site planning, for example, to identify the best positioning of machinery based on the architectural characteristics of the building, the weight of the materials, the capacity of the equipment or the positions of the access points.

In the last two decades, a growing number of research works have investigated the theoretical framework of computational performance-driven design optimization and applied computational design and GD to solve practical architectural and engineering issues (Attia et al., 2013; Li, Liu, & Peng, 2020; Lu, Wang, & Shan, 2015; Touloupaki and Theodosiou, 2017). Following, most recent works are reported.

Suyoto et al. used the parametric and GD tools Grasshopper, Ecotect, Geco, Galapagos, and other software to solve problems during all stages of the design process (programming, site planning, building shape, structure planning, and facade planning) of a mixed use project. Specifically, computational design was used to: maximize the built area; search for the shortest pedestrian pathways; define buildings masses in line with skyline changes and regulation requirements; reduce heat gains due to solar radiation; position seating areas and public activities; optimize a diagrid structure system; verify deflections and material behavior. Finally, exterior walls of the buildings were analyzed to identify areas that needed additional shading devices, to select types of glass, suitable shading devices, and calculate overall thermal transfer value (Suyoto, Indraprastha, & Purbo, 2015).

Jin et al. conducted an optimization process for a free-form building shape to predict and optimize the heat gain and loss characteristics in the early design stages. A free-form building was modeled in Grasshopper and underwent a GA optimization process using Galapagos Evolutionary Solver to minimize passive heat gain and loss for various climate zones (Jin and Jeong, 2014).

Zhang et al. proposed an optimization method for designing free-form buildings that maximizes solar radiation gain, maximizes space efficiency, and minimizes the shape coefficient. Rhinoceros and Grasshopper were used to build the parametric model, and the shape optimization of the building was carried out with a multiobjective GA to make sure the three objectives are all achieved. Then, a Pareto frontier was generated to show the optimal solutions. Compared to a cube-shaped reference building, the total solar radiation gain of the optimized free-form shape building was 30%–53% higher, and the shape coefficient value was reduced by 15%–20%, with a decrease of less than 5% of the space efficiency values (Zhang, Zhang, & Wang, 2016).

Camporeale et al. analyzed the reduction of primary energy (PE) consumption of slab and high-rise housing typologies through the optimization of their building shapes by applying passive strategies at the concept stage of the architectural design. A quasi-steady state method provided an estimation of building PE consumption in heating and cooling. Then, a multiobjective GA optimized the building shapes with three competitive objective functions: minimization of PE consumption per m², maximization of passive volume ratio, and maximization of the sum of roofs and best oriented surfaces. The performance-driven design workflow shows the Pareto front solutions that reflect the influence of passive strategies on the building shapes (Camporeale and Mercader-Moyano, 2019).

Konis et al. applied computational design on a 5000 m² medium office building test case for four different urban settings and climates. Using Grasshopper, Honeybee, and Octopus, they optimized the building's shape, orientation, window-to-wall ratio, and shading devices to minimize energy use intensity and maximize spatial useful daylight illuminance (Konis, Gamas, & Kensek, 2016).

Qingsong et al. applied parametric and GD using Grasshopper, Ladybug, Honeybee, and Galapagos Evolutionary Solver to optimize an office building's openings for minimum energy consumption and maximum useful daylight illuminance (Qingsong and Fukuda, 2016).

Zhai et al. presented a multiobjective optimization method that combines NSGA-II with EnergyPlus for window design optimization, to minimize the building energy consumption while simultaneously improving the indoor thermal environment and visual performance. The method takes many parameters into consideration (orientation, window size, glass material, etc.) and optimizes several objectives to assess their overall performance. It is applied to an office room with various window parameters and three building design objectives. The Pareto approach is used to select optimal solutions. All Pareto-optimal solutions are shown in the Pareto frontier charts, which clearly illustrate the performance of each solution (Zhai, Wang, Huang, & Meng, 2019).

Zhao et al. presented a multiobjective design optimization method for a high-rise office building windows and shading configuration considering energy consumption and thermal comfort using the smart optimization algorithm NSGA-II in combination with DesignBuilder energy simulation software (Zhao and Du, 2020).

Pilechiha et al. proposed a multiobjective optimization tool for office window design that considers three optimization objectives: minimizing energy usage, maximizing received daylight, and maximizing quality of the view (QV). Rhinoceros was used for modeling the building, along with Grasshopper with Ladybug and Honeybee plugins to calculate the energy usage and daylight, and a Python-based plugin to evaluate the QV. The optimization algorithm (HypE), which is a hypervolume-based evolutionary algorithm, was applied using Octopus (a Grasshopper plugin) (Pilechiha, Mahdavejad, Rahimian, Carnemolla, & Seyedzadeh, 2020).

Ercan et al. produced custom design alternatives for shading devices to optimize daylight while blocking out excessive solar heat gains in an office building in Larnaca, Cyprus. They used Grasshopper, Diva, and Galapagos and achieved significantly better performance compared to the initial design. The design alternatives were generated by evolutionary algorithms in accordance with daylight performance requirements and were simulated to assess their shading and daylight efficiencies (Ercan and Elias-Ozkan, 2015).

Negendahl et al. used Grasshopper, Ladybug/Honeybee, Termite (Andy Payne, Panagiotis Michalatos, Eddy Man Kim, and Marshall Prado) (Kiss and Szalay, 2020), and Octopus to optimize a building project for energy use, daylighting, and capital cost without external shading systems (Negendahl and Nielsen, 2015).

Zania et al. proposed a method based on parametric design and GAs to develop an effective shading solution able to control radiation over the year and likewise guarantee a high performance regarding the outdoor perception and visual comfort. After the development of a geometry definition managed with a parametric modeling approach (Rhinoceros and Grasshopper), GA optimization was used to define the openings size and their angle to minimize solar radiation entrance during year, maintaining outdoor view. The possible geometric alternatives were part of a sensitivity analysis with Radiance and EnergyPlus engine to assess the shading system performance in terms of daylighting and energy use (Zania, Andaloro, Deblasio, Ruttico, & Mainini, 2017).

Santos et al. applied computational design on three prototype glass pavilions to determine the optimal fritting density of different glass panel clusters for energy efficiency and daylight for winter and especially summer conditions. They used the add-on for Grasshopper Kangaroo Physics 2.0 (Chang, Castro-Lacouture, & Yamagata, 2020) to panelize and planarize the initial NURBS models and transform them to mesh objects in order to automatically translate them to EnergyPlus (Santos, Schleicher, & Caldas, 2017).

Ebrahimi-Moghadam et al. investigated the effect of daylight distribution in interior spaces on human thermal comfort conditions and energy consumption based on light shelf design parameters (including angle, depth, and number of the light shelves), employing GA for the optimization of the two objective functions (Ebrahimi-Moghadam, Ildarabadi, Aliakbari, & Fadaee, 2020).

Zawidzki et al. proposed a framework where architectural functional layout is optimized according to functionality (defined by users), insolation (calculated according to geographical conditions), outside view attractiveness (assessed on-site), and external noise (measured on-site). A general gradient-based method for finding optimal and near-optimal solutions was applied. The output of this optimization was a set of room configurations with their locations and orientations on the site returned to the user for final selection (Zawidzki and Szklarski, 2020).

Sydora et al. demonstrated the use of a set of design rules, expressed in common language, in the automated generation of multiple code-compliant alternative model interior designs. They considered two generative-design case studies, namely, kitchen layouts using a set of real-world kitchen design rules provided by a commercial partner, and living-room layouts using rules put forward in earlier automated design research (Sydora and Stroulia, 2020).

Gossard et al. presented a method to optimize the equivalent thermophysical properties of the external walls (thermal conductivity and volumetric specific heat) of a dwelling in order to improve its thermal efficiency adopting a methodology that couples an ANN and NSGA-II and uses optimal Pareto fronts obtained from the optimization to analyze the different solutions (Gossard, Lartigue, & Thellier, 2013).

Al-Saadi et al. employed a computational approach for optimizing envelope design for housing in hot climates using a GA and a life cycle cost (LCC) analysis coupled with the EnergyPlus simulation program. Several envelope design strategies were evaluated including walls and roof insulation, thermal mass, air tightness, window's areas, types of glazing, and window's shading (Al-Saadi and Al-Jabri, 2020).

Mansour et al. used a GA to minimize the thermal loads of a parametric envelope of an office building (Mansour and Abdel-Rahman, 2021).

Bagheri-Esfah et al. presented a multiobjective optimization to achieve the minimum cooling and heating loads in a residential building integrated with phase change material (PCM). The methods applied to fulfill this objective were numerical modeling by EnergyPlus, Grouped Method of Data Handling (GMDH) type of ANN and NSGA-II. Design variables were melting temperature and thickness of PCM, thermal resistance of exterior walls, internal gain and infiltration rate, and objective functions included minimizing annual cooling and heating loads of the building. EnergyPlus software was first used to calculate the values of objective functions and to train the neural network, then the GMDH-type neural network was applied to derive polynomials computing the objective functions from input variables. Next, Pareto optimal points for objective functions were obtained through using these polynomials and NSGA-II multiobjective optimization. Finally, the optimum point was determined by a financial analysis (Bagheri-Esfah, Safikhani, & Motahar, 2020).

Naji et al. carried out multiobjective optimizations of building envelope by coupling TRNSYS (Transient System Simulation Tool) and jEPlus + EA (EnergyPlus simulation manager for parametrics + Evolutionary Algorithms). The objective functions to be minimized were thermal discomfort hours, daylight unsatisfied hours, and LCC, while conversely maintaining acceptable sound transmission levels and indoor air quality. The decision variables were envelope components of a prefabricated house to be installed in six different climate zones corresponding to eight locations in Australia. The optimal solution sets were unique for each climate zone (Naji, Aye, & Noguchi, 2021).

Lin et al. proposed a multiobjective optimal building envelope and air conditioning system energy performance decision model. This model was used to design the optimal configurations of building envelopes and air conditioning systems in order to minimize both construction cost and CO₂ emission when the envelope materials are manufactured and used to form the building envelope (Lin, Lin, Tsai, Deng, & Ishii, 2021).

Whitworth et al. investigated the relationship between embodied energy and structural forms of composite floor plates repetitively used in multistory buildings. A Matlab algorithm incorporating MathWorks global optimization toolbox GA and compliant with Eurocode 4 design processes was employed to optimize a composite beam for five separate objective functions: maximize span length, minimize beam cross section, minimize slab depth, minimize weight, and minimize deflected shape. For each of these objective functions, candidate designs were assessed for embodied energy to determine individual relationships (Whitworth and Tsavdaridis, 2020).

Combining a GA with improved penalty function and calculation method for equivalent static wind loads (ESWLs), Li et al. presented an optimal procedure for the wind-resistant design of tall buildings, which aimed to minimize the total weight of the designed building subject to the constraints of top acceleration and lateral drifts (Li, Duan, Li, Li, & Huang, 2020).

Lu et al. presented a comparison study on two design optimization methods, that is, single objective optimization using GA and multiobjective optimization using NSGA-II, for optimizing the renewable energy systems in buildings to minimize total cost, CO₂ emissions and stress on the power grid (Lu, Wang, Zhao, & Yan, 2015).

Carluccia et al. addressed the design of a detached net zero-energy house located in Southern Italy to minimize thermal and visual discomfort. The optimization problem involved four objective functions (thermal discomfort during winter and summer and visual discomfort due to glare and an inappropriate quantity of daylight) and used NSGA-II, implemented in the GenOpt optimization engine through the Java GAs package, to instruct the EnergyPlus simulation engine. The simulation outcome was a four-dimensional solution set, with the building variants of the Pareto frontier adopting diverse and nonintuitive design alternatives. To derive good design practices, 2D projections of the solution set were also analyzed (Carluccia, Cattarin, Causone, & Pagliano, 2015).

Mayer et al. provided a multiobjective design framework for household-scale hybrid renewable energy systems based on the technical modeling of several typical components. Solar photovoltaic, wind turbine, solar heat collector, heat pump, heat storage, battery, and heat insulation thickness were considered. Backup power was either drawn from the grid or produced by a diesel generator in grid-connected and off-grid scenarios, respectively. Single objective optimization using GA resulted in the least cost and the least environmental footprint options in a case study of three different locations across Europe. Then, pareto-optimal solutions between the two extremities were explored with a multiobjective GA (Mayer, Szilagy, & Gro, 2020).

Sholahudinc et al. proposed a method that use ANN and MOGA to optimize HVAC system operations in order to minimize annual energy consumption and maximize the thermal comfort. ANN performed a good correlation between decision variables and the objective function, and MOGA successfully provided several alternative possible design variables to achieve optimum solutions (Nasruddina, Satrioa, Mahliad, Giannetti, & Saitoc, 2019).

Ren et al. employed a NSGA-II algorithm to search the Pareto frontier solutions of the multiobjective optimization model that considers economy, energy, and environment performance of two different hybrid combined cooling, heat and power (CCHP) systems, one with photovoltaic panels (PV) and solar thermal (ST) collectors and the other with photovoltaic thermal solar collectors. The TOPSIS method is used as decision making tool for ideal configuration selection. The hybrid CCHP systems for three buildings (hotel, office, market) are optimized and compared under different operation strategies (Ren, Wei, & Zhai, 2021).

Salata et al. presented a procedure to evaluate the best retrofitting interventions of residential buildings for 19 European cities in different climates. Dynamic building energy simulations were conducted using EnergyPlus coupled with an Active Archive Non-dominated Sorting Genetic Algorithm (a NSGA-II type). The criteria taken into account in the optimization procedure were the reduction of annual specific energy demand, the decrease in construction and installation costs, the reduction in annual energy operating costs, and the reduction in greenhouse gas emissions. Results showed the most advantageous energy retrofitting interventions fulfilling the criteria for the different geographical sites (Salata et al., 2020).

Chang et al. introduced a procedure to support the selection of building envelope options in retrofit interventions. A multiobjective optimization model was developed considering the existing built form, uncertainties in performance predictions, and incorporating newly developed façade systems. The optimal selection aimed to satisfy indoor thermal comfort, energy balance, environmental emissions, and economic aspects. The decision-support framework was also devised to add any envelope options, enabling decision makers to accommodate new system materials and proactively evaluate their feasibility (Chang et al., 2020).

Tang et al. assessed the association of the primary features of residential buildings and the description of the best solutions of retrofitting concerning the lowest energy use toward NZEBs with the minimum thermal inconvenience or the highest economic performance. TRNSYS and the improved seagull optimizer were applied for the multiobjective optimization and simulation objectives (Tang, Chen, Li, & Rodriguez, 2020).

Kiss et al. developed and applied a modular parametric optimization framework combining advanced building modeling, LCA, energy calculation and single— and multi-objective environmental optimization to a multiapartment house in Hungary. Variables comprised geometry, envelope, systems, as well as the heating energy source, with the objective of minimizing the life cycle environmental impact expressed in terms of the six most common LCA indicators. Through the optimization, significant environmental savings of 60%–80% were achieved compared to the initial design options showing the potential for the application of such methods in architectural design (Kiss and Szalay, 2020).

Fesanghary et al. investigated a multiobjective optimization model based on HS algorithm to minimize LCC and carbon dioxide equivalent (CO₂-eq) emissions of residential buildings (Fesanghary, Asadi, & Geem, 2012).

Ilbeigi et al. proposed a method to optimize the energy consumption of buildings. After defining the most effective input parameters for energy performance of a case study building in Iran, EnergyPlus software was used to evaluate energy consumption and scrutinize the crucial factors numerically. Afterward, an ANN using multilayer perceptron simulated energy consumption in the building, and energy optimization was performed by a GA considering the critical variables, achieving a reduction of energy consumption by about 35%. Sensitivity analysis also demonstrated that the number of occupants and wall U-value have the highest influence on building's energy consumption (Ilbeigi, Ghomeishi, & Dehghanbanadaki, 2020).

Lobaccaro et al. applied parametric and GD to minimize embodied GHG emissions and operational energy in a ZEB in Oslo, Norway. An original generative workflow based on parametric design was developed to control parametrically several building features while varying the building shape, the dimensions of construction components, and the quantity of materials, and at the same time conduct energy analyses, such as solar radiation, daylighting, and environmental impact analysis. For each stage of the shape's optimization, through passive and active strategies, the embodied emissions and energy balances were estimated to evaluate how the building performance varied in terms of energy and environmental impact, and to identify the implications for the design (Lobaccaro et al., 2018).

Si et al. applied computational and generative methods to the design of a newly built complex building, optimizing the design variables to improve building energy efficiency and indoor thermal comfort. A surrogate model, developed by an ANN, was used to reduce the computing time. Four multiobjective algorithms were evaluated to select the best algorithm and parameter values for population size and number of generations, identifying NSGA-II (with a population size and number of generations of 40 and 45, respectively) as the best performer in the case study (Sia et al., 2019).

Hamdy et al. compared performance of seven commonly used multiobjective evolutionary optimization algorithms in solving the design problem of a nearly zero energy building (NZEB) where more than 1.6^{10} solutions would be possible. Evaluated algorithms include a controlled nondominated sorting GA with a passive archive (pNSGA-II), a multiobjective particle swarm optimization (MOPSO), a two-phase optimization using the GA (PR GA), an elitist nondominated sorting evolution strategy, a multiobjective evolutionary algorithm based on the concept of epsilon dominance, a multiobjective differential evolution algorithm, and a multiobjective dragonfly algorithm (Hamdy, Nguyen, & Hensen, 2016).

Sun et al. developed a heuristic multiobjective algorithm based on the glowworm swarm mechanism to refine the optimization of a grid-connected NZEB design. The Hong Kong Zero Carbon Building was examined and three design variables (area of the photovoltaic system, installation power of the wind turbine system, and capacity of the thermal energy storage system) were optimized. Results suggest that the optimized design can outperform the baseline design in terms of operating costs and grid energy consumption, and multiple local optima design solutions that represent different design strategies were identified using the proposed nonlinear model (Sun, Ma, Chen, & Xu, 2020).

Touloupaki et al. proposed a new design workflow methodology, integrating evolutionary algorithms and energy simulation through Grasshopper for Rhinoceros 3D, for a comprehensive exploration of performance-based design alternatives in the building scale (Touloupaki and Theodosiou, 2017).

Yong et al. studied a multiobjective evolutionary approach to optimize energy performance of buildings by modeling the problem as two-objective optimization functions (minimizing the energy consumption and maximizing the comfort level), then developing a new solving algorithm based on bare-bones PSO, which proposed an improved update strategy with adaptive perturbation to overcome the disadvantage of easily local convergence of the traditional algorithm. Applied into several buildings located in China, experiment result showed that the proposed algorithm can obtain good nondominated solutions (Yong, Li-juan, Qian, & Xiao-yan, 2020).

Ciardiello et al. proposed a novel approach to the multiobjective optimization of new buildings and retrofit actions that considers geometry and envelopes variables, allowing for architectural variability. The proposed multiobjective optimization approach, based on a GA, made it possible to save 60% of the annual energy demand by means of geometry optimization and, once the geometry was fixed, 23% of the annual energy cost by means of passive and active strategies, while reducing the energy simulations required from 3×10^{12} to less than 8000 (Ciardiello et al., 2020).

Ascione et al. proposed a multiobjective optimization approach to address the energy design of the building envelope. Implemented GA coupled MATLAB and EnergyPlus to minimize primary energy consumption (PEC), energy-related global cost (GC) and discomfort hours, with design variables concerning the set point temperatures, the radiative properties of plasters, the thermo-physical properties of envelope components, the window type, and the building orientation. The algorithm performed a Pareto optimization and recommended two optimal solutions: the NZEB optimal solution, which minimizes PEC, and the cost-optimal solution, which minimizes GC. Investigated in four Italian locations, these optimal solutions provided low values of PEC between 62.0 and 91.9 kWhp/m²yr and of GC between 456 and 665 €/m² depending on the location (Ascione, Bianco, Mauro, & Napolitano, 2019).

Toutou et al. investigated the potentials of parametric design and GD for the optimization of daylighting and energy performance of a five stories residential building using Grasshopper, Ladybug, Honeybee, Openstudio, Radiance, Daysim, Energy plus, and Octopus (Toutou, Fikry, & Mohamed, 2018).

Chen et al. applied a holistic design-optimization approach to a generic building with mixed-mode ventilation and lighting dimming control in hot and humid areas. Before optimization, variance-based sensitivity analyses were conducted to reduce the search space of the evolutionary algorithm by removing insignificant factors. Then, time series sensitivity indices for lighting and cooling energy outputs revealed their correlations with outdoor thermal and solar radiation conditions. Passive architectural parameters were finally explored by NSGA-II under different optimization settings and weather conditions (Chen, Yang, & Zhang, 2018).

Parallel to the scientific research activity, the use of computational design by architecture and engineering firms has grown considerably in the last twenty years, also favored by greater computing skills and the development of new and increasingly performing software that use algorithms to link geometry with data to address specific problems (Stals, Jancart, & Elsen, 2021).

Starting from Greg Lynn, Frank Gehry, Zaha Hadid Architects, UN Studio, Peter Eisenman, Morphosis, several important architects such as 3XN, Asymptote, BIG, Diller & Scofidio + Renfro, Santiago Calatrava, Coop Himmelb(l)au, Foster + Partners, Future Systems, Herzog & De Meuron, Daniel Libeskind, MAD, MVRDV, OMA, Safdie Architects, SHoP and engineering companies such as ARUP, Gensler, HOK, Aedas, NBBJ, HKS, Buro Happold, and many others embraced computational technologies for form finding and performance optimization to design increasingly iconic and smart buildings and infrastructures (see Figs. 6.27, 6.28 and 6.29).



FIGURE 6.27 Louis Vuitton Foundation by F.O. Gehry (photo by the author).



FIGURE 6.28 UAE pavilion at Expo 2020 by Santiago Calatrava. *Courtesy of Santiago Calatrava Ilc.*



FIGURE 6.29 UAE pavilion at Expo 2020 by Santiago Calatrava. *Courtesy of Santiago Calatrava Ilc.*

Parametric design allows in fact architects to make more efficient designs and to achieve simultaneously a challenging esthetic shape and a performing solution, thanks to a stronger influence on key design decisions. Furthermore, tools with increasingly user-friendly interfaces make it easier to engage clients on higher level discussions on the topic of design parameters and on the geometric logic of the shape, including fabrication issues. Information exchanged between

engineers and architects is also of higher value since it is possible to exchange not only the final design geometry but also the logic of the design.

Only ten years ago, design teams would take weeks or months to develop design ideas: brainstorming concepts, testing ideas against project requirements, and producing graphics and drawings to represent their ideas. Today, by using computational design architects can develop intelligent, flexible building models that provide instant visual feedback along with key supporting data to help to “prove” design concepts at the earliest possible stages, enabling to make decisions faster, with better information. A computational approach enables designers to explore a wider range of design variations in a shorter amount of time, providing unprecedented opportunities to design higher quality buildings, optimize efficiency and creativity, and provide a much higher level of service to clients.

Parametric design tools can be particularly useful in earthquake-prone areas, especially for high-rise buildings, where the analysis process is more complex even in early project phases. On the 528 m high CITIC Tower in Beijing (see Fig. 6.30), using computational tools, Arup reduced the time between architectural proposition and seismic analysis from weeks to mere days. Parametric approach led to a better design, with more in-depth understanding of the critical parameters of the structure, and enabled architects to study the most efficient solution amongst more than 800 design options (*The Arup Journal*, 2019).

For the Acoustic Wall of the Zuidplein Theater in Rotterdam, Arup developed a digital workflow that integrated geometrical complexity, acoustic optimization, structural logic, and fabrication in the same process. A series of design variables, optimization objectives and constraints, from the geometrical boundaries of the hall to the positioning of the sound sources, was defined to help refine the design. Through a parametric “sound-shaping” process, engineers ran a series of scenarios to evaluate the impact of the different wall designs on the hall’s acoustics and used this to inform and model the final shape of the wall, as well as the pattern and placement at different angles of the 6000 folded triangular panels made of aluminum composite. Structural rules were also combined with the digital model to customize the detailing of all the unique panels and their connections. Setting up this digital workflow allowed the team to explore numerous options in quick succession, leading to the final, optimized wall design with the desired acoustic performance.

For the renovation of the Hanwha HQ office tower in Seoul, UNStudio conceived a parametric design model that allowed to modulate key parameters with influence on the layout of the building’s façade (see Fig. 6.31). The parametric tool was also used as a communication instrument, allowing to generate key information concerning the building envelope to keep the design process transparent for all parties involved. Each facade panel unit of the model held a set of key metadata attached to the geometry including location in facade assembly, unique number, orientation, name, and basic geometric information, allowing to represent the actual facade in numerous different ways to rationalize its complexity and reduce the number of different modules used.

The parametric script employed, called Unit-Maker Tool, took basic geometric input information such as transom position, mullion dimensions, and glass properties and outputted numerous facade units, automatically generating all possible facade unit variations. Data from the 3D model were also extracted to Excel for further evaluation allowing to precisely locate problem areas and adjust the modules with precision. The base modules and all variants make up a facade-unit library which is then linked to an assembly script that builds up the overall facade of the tower (Fig. 6.32).



FIGURE 6.30 CITIC Tower, Beijing. *Courtesy of Arup.*

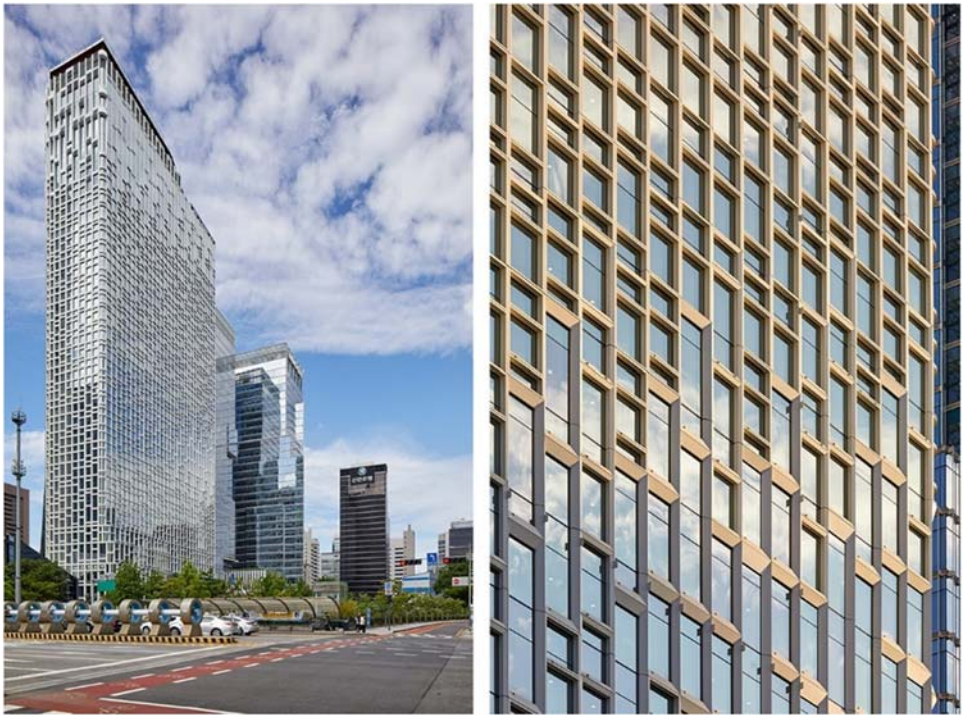


FIGURE 6.31 Hanwha HQ office tower, Seoul. *Courtesy of UNStudio, © Rohspace.*

FACADE MODULES | NORTH

Overview of base modules - 1800mm width, 3600mm height

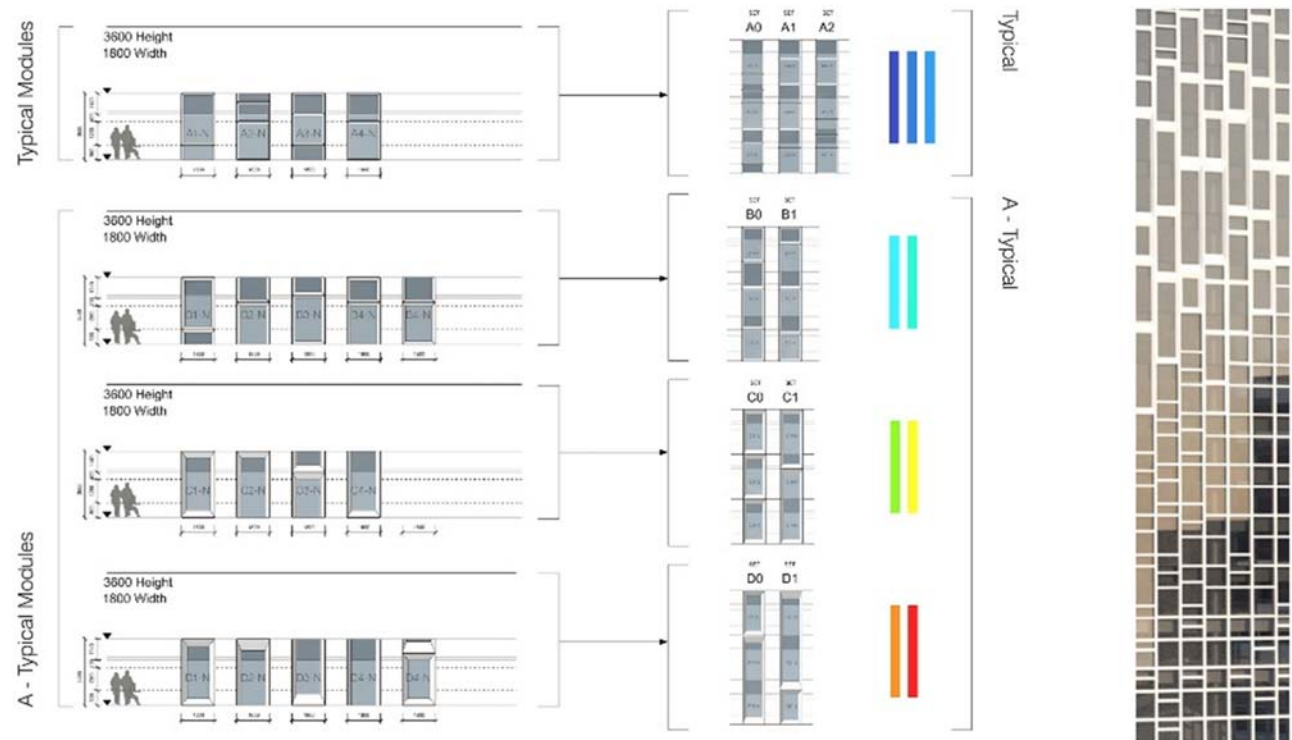


FIGURE 6.32 Parametric design of Hanwha HQ façade modules. *Courtesy of UNStudio.*

To accurately document the position of the facade units in relation to each floor, the script further allows for the generation of a basic floorplan drawing by outputting closed polylines of the geometry.

A stunning example of parametric building form is the Opus Hotel in Dubai, by Zaha Hadid Architects, designed as two separate towers that coalesce into a cube eroded in its center by free-form void, entirely clad in glass (see Figs. 6.33 and 6.34). The void's 6000 m² façade is created from 4300 individual units of flat, single-curved or double-curved glass, which were designed using digital and parametric 3D modeling that also identified specific zones which required tempered glass and where to put the mirrored dotted frit pattern to reduce solar gain and further characterize the façade.

Computational design, in addition to being a useful tool for optimizing quantitative performance and cost, can be strategic to optimize the human experience. For example, computational design can be used on a courthouse or on a stadium project to ensure that every participant has a good view of the proceedings or of the event. Also, the tool can be implemented on a corporate project to analyze walking time within and between buildings to ensure maximum connectivity between employees and amenity spaces.

NBBJ used computational design tools during development of the Hangzhou Olympic Sports Center, Hangzhou, China, to refine the competition design and explore how to improve attendees experience, use less steel, and model the energy performance. The stadium exterior is made up of a series of unique yet repetitive truss modules, or petals, that enclose the stadium bowl. Because the GD process defined loose geometric rules, multiple variations could be created and evaluated during design development. A Grasshopper script was used in conjunction with Rhino3D software to



FIGURE 6.33 Opus Hotel, Dubai, north elevation. *Courtesy of Zaha Hadid Architects, © Laurian Ghinitoiu.*



FIGURE 6.34 Opus Hotel, Dubai, south elevation. *Courtesy of Zaha Hadid Architects, © Laurian Ghinitoiu.*

generate the bowl's truss configuration. By adjusting parameters such as the number of rows, distance from the field and sightline standards, the bowl geometry took shape. After establishing the seating geometry, the exterior petal structure was linked to the bowl. As the seating parameters were changed, the petal system adapted. If the sightline standards were modified, the exterior shape would immediately adjust to conform to the new bowl. By linking the steel shell and concrete bowl together, and by providing additional structure at the top of the bowl to reduce the roof cantilever, the steel and concrete systems work in unison—thus reducing overall steel use. While the stadium may look unconventional in shape, the underlying geometric constraints create repetitive and modular components. This allows the design to be documented and constructed efficiently. By linking the two systems together, the design team was able to eliminate the build-test-discard-rebuild strategy most often used in traditional 3D modeling.

The layout of Autodesk's three-floor, 300-person office in Toronto's MaRS Discovery District was designed and planned by The Living using GD and computational workflows extensively to define and optimize the design goals and create a workspace that took into account the welfare and request of each employee. This was made possible by first defining the project constraints, which included the outline of the three floors where the office would be located, the existing column grid, the foreseen occupancy, and the programmatic requirements, that is, specific numbers and square meters of conference rooms and enclosed spaces, the diversity of different departments, project teams, and workstyles that the office needed to accommodate. Then, a parametric model of the floor layout was devised that would produce suitable geometric solutions based on 45 input parameters, and six objectives, each with its own algorithm, were defined to qualify the project response to the stakeholders requests. These were adjacency preference, work style preference, buzz, productivity, daylight, and views to outside. A MOGA method was employed to produce generations of 100 designs each, and ran the process for 100 generations, creating a design space of 10,000 solutions which were then automatically analyzed, compared against one another, ranked, and evaluated. The Living took 10 designs back to Autodesk to discuss with stakeholders on the basis of the measurable data, identifying the one solution to use as a baseline for further design development (Nagy et al., 2017).

Parametric and GD also finds beneficial applications in delicate infrastructures such as bridges, in which the aspects regarding architectural shape, structural engineering, requirements for passages and clearances, as well as fabrication, are deeply interlinked.

When designing the 120 m long Elizabeth Quay pedestrian and cyclist bridge in Perth, Australia, engineering firm Arup leveraged parametric modeling to optimize the geometry of the pedestrian pathway to overcome design constraints, including the different heights required at different sections of the walkway and boat clearance requirements (see Fig. 6.35). In particular, the digital design workflow involved both the architects using Rhino and Grasshopper parametric tools to define the architectural bridge concept, and the engineers working from the same shared parametric canvas to generate analysis models to assess the structural performance of bridge form as it developed in concept, including 1D finite element models parametrically generated directly from Grasshopper to GSA software using the firm's own Salamander plug-in.

The newest pedestrian bridge in Amsterdam, over the Oudezijds Achtedburgwal canal in the Red Light District, is a first of its kind, fully functional 3D printed stainless steel bridge, and represent a state of the art example of how GD tools and direct digital manufacturing can overlap in a single, comprehensive architectural, and engineering effort (see Fig. 6.36). Developed with Dutch start-up MX3D with engineering by Arup, the 12 m bridge was the result of extensive



FIGURE 6.35 Elizabeth Quay bridge, Perth. *Courtesy of Arup, Jacaranda Photography.*

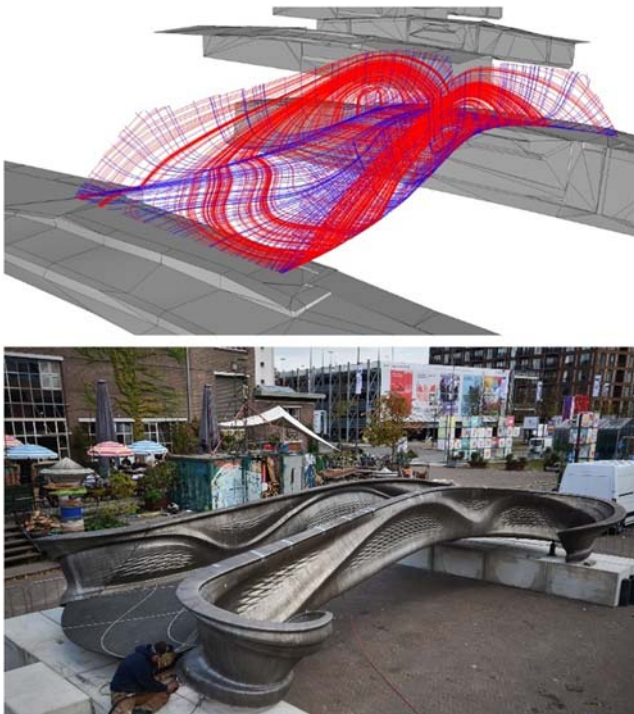


FIGURE 6.36 Parametric model and actual construction of 3D printed bridge in Amsterdam. *Courtesy of MX3D, photo by Adrian de Groot.*

iterations, allowed by advanced parametric design modeling, that had to balance esthetics, structural integrity, functionality, and ongoing research on the physical properties of the innovative building material 3D welded by six-axis industrial robotic arms.

The team worked with Grasshopper and Karamba, a generative graphical algorithm software for Rhino, to produce successive design iterations under a given set of parameters, and to assign accurate material properties to the model, enabling extensive testing from both digital simulations and full-scale physical mock-ups to allow the engineers to check the safety and serviceability of the bridge, removing for instance excess material by mixing structural calculations with geometric manipulation and teaching the algorithm to recognize which parts of the bridge are less crucial. Final model was then fed to the robotic 3D printers as fabrication code to weld the bridge sections off-site for final testing and embedding monitoring sensors that will feed its future digital twin.

6.4.3 Parametric and generative design software

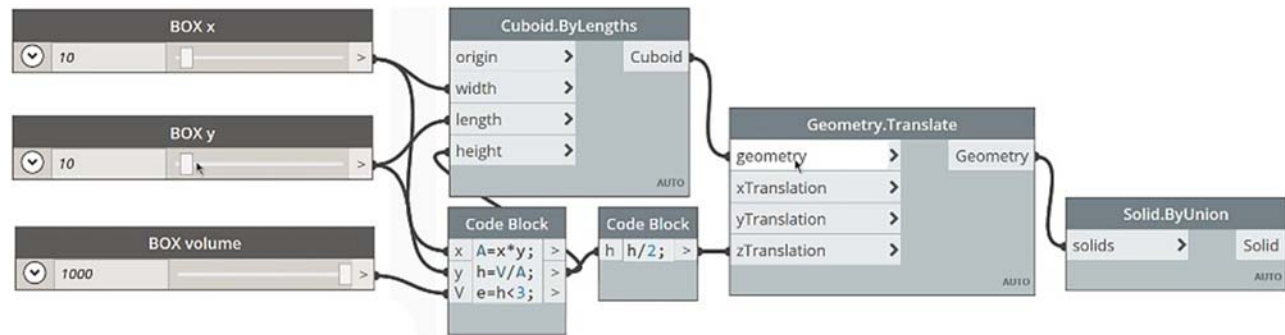
There are currently several programs for computational design and GD on the market. Some are specific for the manufacturing sector and industrial design (CATIA, Solidworks, Creo Parametric, Siemens NX, Autodesk Fusion) and are also used in direct digital manufacturing processes through 3D printing, others, more recent, are aimed more specifically to design at the urban and building scale.

As for those, some products are standalone (TestFit, HyPar or Spacemaker), while others are plugins that are often already integrated within the BIM authoring or CAD design and modeling software (see [Table 6.6](#)).

Computational design and GD software rely on visual programming language (VPL), as opposed to traditional text-based programming such as C# or Python. VPL is a form of programming which, differently from textual programming, does not require the compilation of code or knowledge of conventional programming syntax (even if it can still be integrated). In particular, VPL uses a simplified visual interface where the user connects small nodes of predefined functionality (see [Fig. 6.37](#)). Together, these nodes form a larger network of functionality that can achieve complex goals. Each node consists in a script which is assigned a task. It can be a very simple operation, such as storing a number in a list, or a more elaborate one like creating complex geometry. With some exceptions, the majority of nodes are composed of four parts: name of the node; main body, which presents options at the level of the whole node and in some software previews data results executed; IN ports where wires or arrows are connected; OUT ports where wires or arrows are connected.

TABLE 6.6 Main parametric and generative design tools on the market.

BIM authoring and CAD Software	Visual programming tools	Generative design tools
Rhino Archicad Tekla Structure	Grasshopper	Galapagos, Octopus, Optimus, Opossum, Biomorpher, Wallacei, Design Space Exploration
Revit	Dynamo	Refinery
AECOSim Building Designer	Bentley Generative Components	Optimizer
Vectorworks	Marionette	-
SketchUp	Viz Pro	-

**FIGURE 6.37** Example of VPL nodes on Autodesk Dynamo.

Connecting nodes with each other is very simple and can be done by just clicking on the out-port from a node and connecting to the in-port on another node. The input and output depend on the type of nodes and the workflow direction. This approach allows to easily set-up the generator and evaluator algorithms, whose solutions can then be explored and optimized using the solver algorithms present in the software or in the GD plugins (Refinery, Galapagos, etc.).

Although writing the generator and evaluator algorithms can be simple from a technical point of view thanks to VPL, the setting of the problem and the parameterization of the model may not be equally immediate. Before proceeding, it is essential to clearly define the objectives and decide how to review the results and measure success. Too many inputs will lead to a design space that is too big to explore, whereas too few inputs will not yield a large enough design space. First step is to turn a complex design problem into a well-defined one by identifying the parameters that dictate the shape geometry and by correctly defining the algorithm capable of generating it. The next step is to implement an algorithm capable of reading and measuring the numerical parameters that the designer believes to be significant in order to evaluate the quality of the design variants with respect to the objectives.

Usually, the parametric design graph to generate options is articulated in three sections: the inputs section which contains the input parameters that control the model, the geometry section which contains the algorithm that generates the shape, and the evaluator section that contains nodes that measure desired goals (such as surface area, volume, costs, etc.), watches the outputs, and controls the display color of the geometry.

The most popular software for computational and GD among architects are, by far, Grasshopper for Rhinoceros 3D modeler and Dynamo for Autodesk Revit BIM tool.

Both programs feature several additional tools that expand their capabilities, making them an accessible method for computational performance-driven design optimization via a VPL interface (see Figs. 6.38 and 6.39).

Concerning structural design, plugins such as Kangaroo Physics, Karamba, BullAnt, Hummingbird, Mantis for Grasshopper and DynamoSAP for Dynamo allow interactive real-time load simulation, form generation, optimization, and analysis of structural components and constraint introspection. These plugins make it extremely simple to combine parametrized complex geometric forms, load calculations, FEA, etc., and enable accurate analysis of spatial trusses,

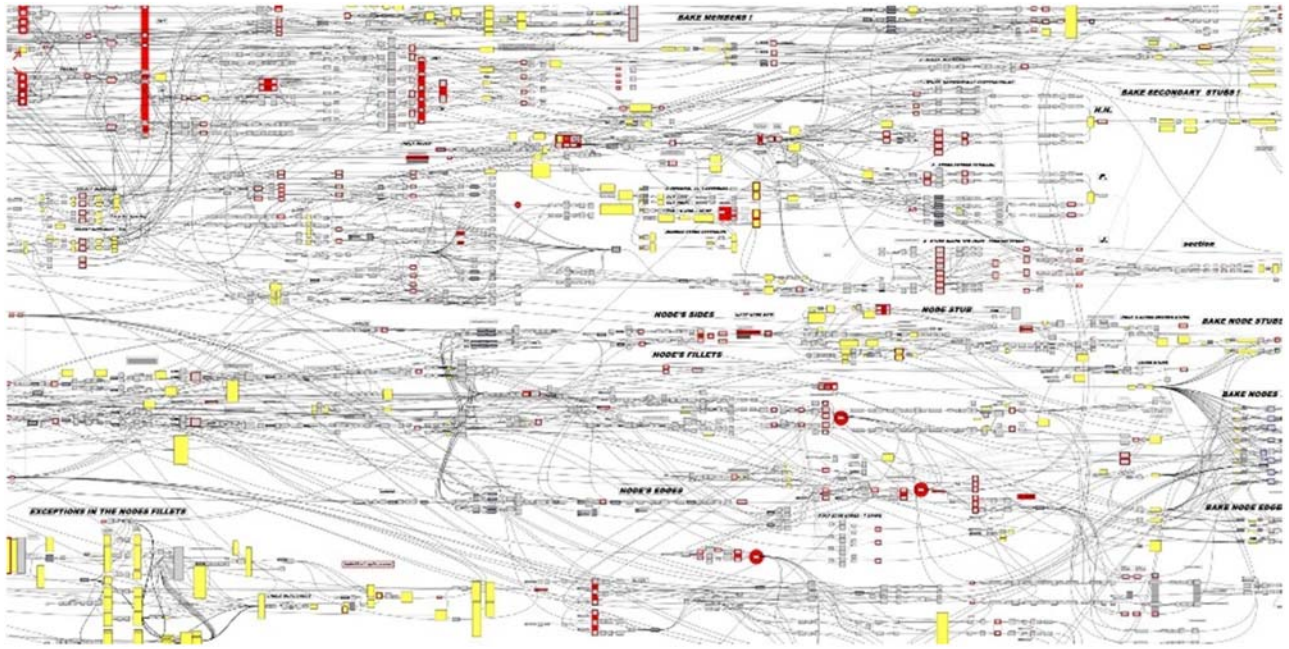


FIGURE 6.38 Grasshopper definition of the exoskeleton cladding of Morpheus Hotel, Macau. *Courtesy of Zaha Hadid Architects.*

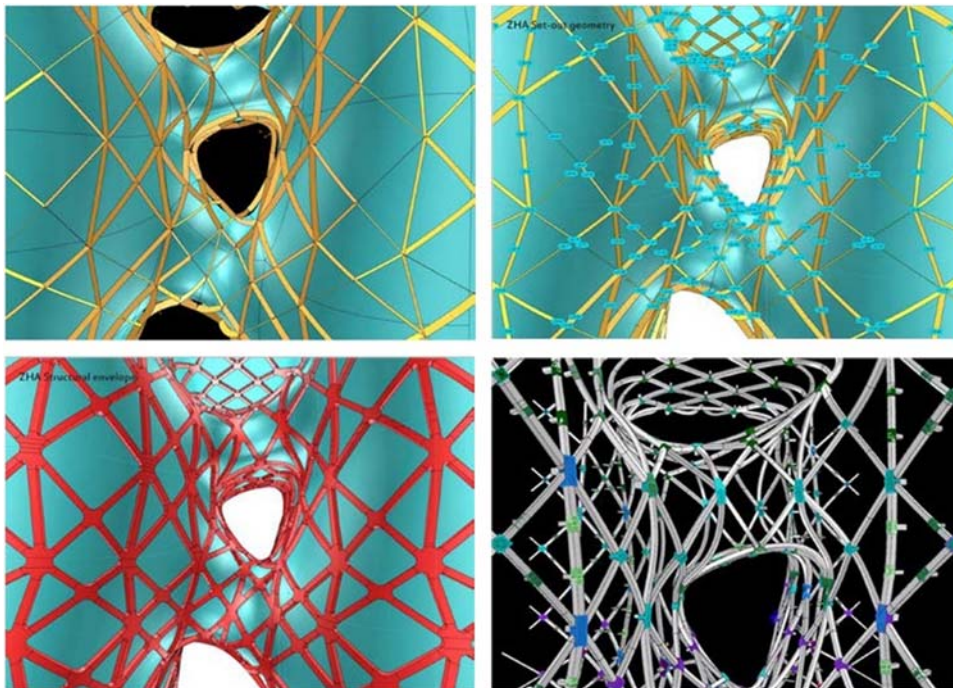


FIGURE 6.39 Parametric models of the exoskeleton cladding of Morpheus Hotel, Macau. *Courtesy of Zaha Hadid Architects.*

frames, and shells since the early stages of design. The user is able to create basic “pin-jointed” planar systems, from which graphic statics are generated and analyzed, to understand the available degrees of freedom in these systems, in order to leverage them structurally.

As regards the integration of the building in its context, environmental analysis plugins such as Energy Analysis for Dynamo, ClimateStudio for Grasshopper, and Ladybug Tools for both, allow to optimize parametrically aspects such as shape, orientation, openings, and shading systems of buildings to achieve maximum comfort and maximum energy efficiency.

GD tools such as Refinery for Dynamo and Galapagos Evolutionary Solver (by Robert McNeel & Associates) (Rutten, 2013), Octopus (by the University of Applied Arts Vienna and Bollinger + Grohmann Engineers), and Optimo (Rahmani Asl, Stoupine, Zarrinmehr, & Yan, 2015) for Grasshopper allow to seamlessly generate and evaluate alternative solutions through methods such as randomize, cross-product e like-this or to obtain a set of optimized options for specific design goals (Optimization method).

Specifically, the randomize method generates a specified number (population) of design options, randomly assigning a value to each of the input parameters. In this method, the design options are not driven by results as they are created and can be used to quickly explore the possibilities given by the parameters of the algorithm being used.

The cross product method allows, on the contrary, to explore the entire design space of the solutions, combining each values of each parameter with the remaining parameters.

The like-this method, instead, applies slight variations to the predefined input configuration. This method allows to explore different variations of a design that might already be fine or to further refine the results of an optimization process.

Lastly, the optimization method produces the best design options identified with respect to the objectives set in the number previously indicated by the user. The optimization process works by running multiple generations of a design, each using the input configuration from previous generations and from that optimizing the new design options.

There are several parameters that effect the optimization: output goals (maximized or minimized), population size (i.e., how many designs are tested in each generation), generation size (i.e., how many generations are tested), and seed (initialization value).

The optimization algorithm is designed to drive the model to higher and higher fitness, so defining a fitness function precisely and accurately is crucial. Examples of fitness functions that could be used in a GD context include: maximize hours of daylight for each desk in an office; maximize circulation in common areas; minimize number of distinct types of parts needed to assemble an object; minimize number of total parts needed to assemble an object; maximize the structural strength of a critical component in a product; minimize the weight of a design, and many others.

For each design option, the geometric and numerical results can be organized and displayed in different ways: in the form of a list, in a four-dimensional scatterplot, in a parallel coordinate plot in which the values of all variables are represented simultaneously, or as a graphic preview of how the design variant develops from a geometric point of view.

The kind of visualization chosen for the project may vary depending on what kind of process is running. If the designer is running an optioneering process, it can be beneficial to visualize it using a parallel coordinates chart as it will be easier to filter options, while visualizing a multiobjective optimization using a scatterplot chart will make it easier to find the best trade-off between two objectives.

The graphic preview is particularly useful in cases where the morphology of the elements is highly variable or it is important for the designer to evaluate it qualitatively, beyond its mere numerical values. Each graphic solution can be individually rotated, zoomed, and panned to explore the design in more detail.

After a first observation of the data, it is possible to filter some values from the scatter or parallel coordinate graphs, choosing a reduced range of alternatives from which it will therefore be easier to read the results and choose the best option to continue developing the project. If no option is satisfactory yet, it may be necessary to rethink data, refine the generating and evaluating algorithms and re-launch the optimization algorithm to obtain results more in line with the design needs.

Finally, for GD support, several plugins are available for both Grasshopper and Dynamo containing ML tools for the exploitation of ML in the context of computational design. The most common are

- Crow—ANN in Grasshopper;
- Owl—Library written for ML-oriented data processing;
- LunchBoxML—Components for regression, clustering and neural networks;
- Dodo—Collection of tools for ML, optimization and geometry manipulation.

In particular, LunchBoxML is commonly used in clustering processes, for example, in the optimization of the size and shape of the cladding panels of complex surfaces in order to reduce the number of typologies, thus minimizing construction times and costs.

Using Lunchbox, after subdividing with a grid the surface to optimize, it is possible, thanks to the recognition capabilities of the ML software, to group the panels into different clusters based on geometry attributes, eventually weighed in advance, such as perimeter, area, and orientation of the panels. With a subsequent solver algorithm, it will then be possible to optimize the configuration of the panels based on the objectives to be achieved (see Fig. 6.40).

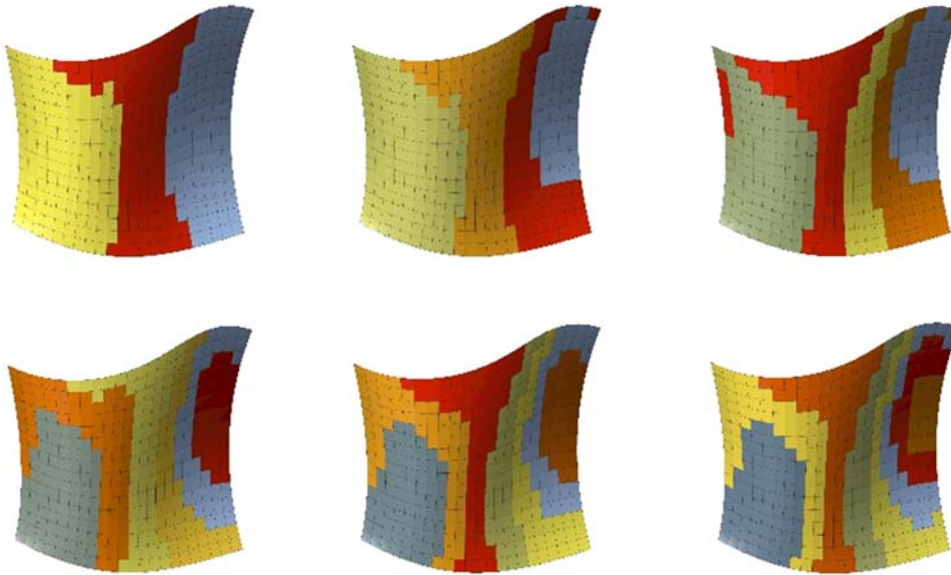


FIGURE 6.40 Example of panel clustering by LunchBoxML and Grasshopper.

6.5 Design for digital fabrication

Nowadays, the whole AEC sector is experiencing a profound evolution in both architecture/engineering design activities, via the advent of advanced design tools and methods, and in construction, with several innovative processes, once relegated to the manufacturing or rapid prototyping industries, that are now available for building and infrastructure construction with huge benefits in terms of speed, freedom of shapes, customization, logistics, cost control, and sustainability. These new highly automated construction methods include 3D printers, computer numerically controlled (CNC) routers, multi-axis industrial robotic arms, laser-cutters, plasma cutters, water-jet cutters, and hot-wire foam cutters, as well as cable robots, unmanned aerial systems along with a wide array of customized tools, robotic end-effectors and other machinery (see [Chapter 8](#)). These tools, which are greatly widening the field of achievable possibilities in construction, are mostly digitally controlled, that is, act based on informatic fabrication code converted from design and engineered data and are therefore known collectively as digital fabrication (DF). DF techniques are evaluated in three main categories: additive, subtractive, and formative methods. Additive techniques such as 3D printing are driven by layering materials on top of each other. Subtractive milling and cutting instead remove material pieces from the whole to build the intended shape, as with CNC milling and laser or water-jet cutting, also employing robotic arms for greater freedom (see [Fig. 6.41](#)). Finally, formative methods apply force to give the material a specific shape, such as robotic cold metal forming or CNC press braking. Essentially, DF can be intended as a subcategory of Computer-Aided Design and Computer-Aided Manufacturing (CAD/CAM) since it utilizes computer-controlled machines as tools with which to cut or make parts. While still relatively novel in architecture, CAD/CAM processes have been used in engineering and industrial design for more than 50 years in the development and fabrication of cars, airplanes, and smaller consumer goods ([Dunn, 2012](#)).

In particular, examples of DF processes in construction include robotic fabrication and assembly, large-scale additive manufacturing, and the use of specialized automation systems for material processing in areas ranging from advanced fabrication of metal or timber assemblies, to various forms of concrete processing, to the fabrication of multi-material composites. This digital approach to construction has the potential to achieve higher geometrical complexity, precise material processing, and improved time and cost control, leading to new architectural possibilities by allowing, for instance, economical serial fabrication of customized unique parts that would otherwise prove impossible to produce with standard fabrication methods, as well as reduced use of materials, structurally effective shapes and graded assemblies (see [Fig. 6.42](#)), and functional integration such as thermal activation, acoustics, electrical, or HVAC systems ([Kaseman and Graser, 2020](#)).

However, harnessing at best these new possibilities provided by DF methods demands a sea-change in how designers think and implement their projects: an updated approach to architecture and engineering is required, focusing on new ways of designing that maximize the potential of the whole workflow from the latest digital design software tools to computer-controlled manufacturing processes.



FIGURE 6.41 Multiaxis robotic milling. *Courtesy of ODICO.*

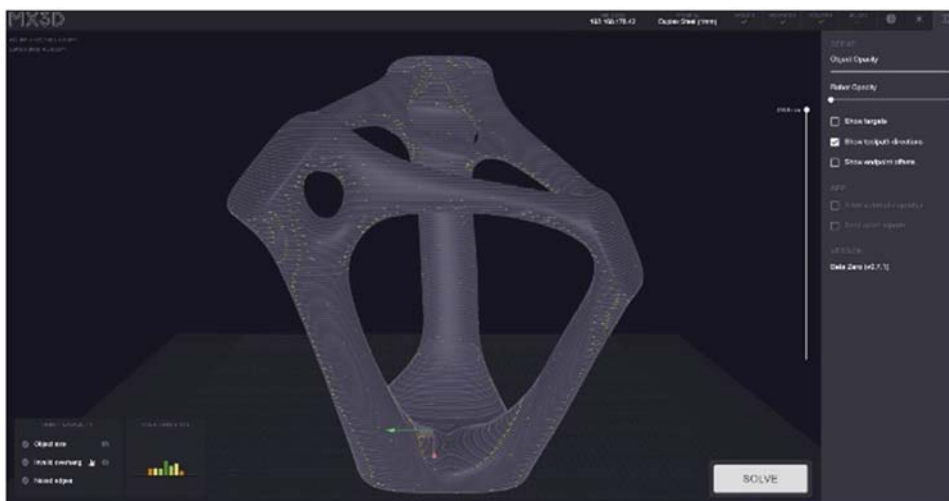


FIGURE 6.42 3D printing design to fabrication. *Courtesy of MX3D.*



In fact, design tools such as BIM and parametric, algorithmic, and generative modeling allow today to close the process chain that links a construction idea to its fabrication. Detailed 3D models can be created already in fabrication quality, enabling the spatial coordination of different trades, and generating a reliable basis for the execution of complex, multifunctional, and freeform architecture. This approach, known as design for DF, has applications that can be geared toward the rationalization and digitally driven production of complex geometry, or, better yet, can expand its scope into the realm of project logistics, making the digital models serve as the direct source of fabrication data, production processes, assembly orchestrations, and construction sequences. In the past ten years, research in design to DF has significantly advanced the instruments that enable a fluid connection between design environments and production machines, with current research enquiring how these technological advances can be deployed to a wide range of material processes (Raspall, 2015).

The objective is for the design process to shift to production-oriented data modeling to ensure a seamless transition of the design data into the DF process, effectively balancing creativity, costs, and quality over the entire design and construction workflow and bridging the knowledge gap between design and engineering, materials and applications, attachment points and installations.

It is therefore essential for the whole project team to take materials, DF and construction methods into account in order first to establish fabrication-aware design approaches already in early project development phases, then to develop and coordinate advanced design and fabrication workflows and schedules.

In particular, projects shall prioritize performance by exploring the capabilities and limitations of the materials related to their form, construction, analysis, and optimization in view of the machinery foreseen in their DF. These in fact dictate construction constraints that include the predefined working area, the payloads and support materials used in CNC milling, laser cutting, water-jet cutting, and 3D printing or robotic fabrication, as coded for specialized tasks (Yazici and Tanacan, 2020). In this picture, collaboration with specialty fabricators and digitally advanced contractors has proven particularly profitable to extract insight on the design to fabrication workflows and on producing fabrication data from design documents and models, allowing the project team to expand design, engineering, and fabrication capabilities simultaneously over the span of multiple projects. Furthermore, the design to DF approach allows late changes—which may always happen, for example, due to difficulties with regard to logistics or procurement, special wishes by the client, etc.—to be addressed with a reasonable effort (Burry, Sabin, Sheil, & Skavara, 2020).

Many iconic projects worldwide took advantage of a fully accomplished design to DF approach, often by allowing striking building envelopes and claddings, by enabling freeform and sculptural architectural shapes or by achieving successful integration of form and function. These projects have commonly involved fabricators and consulting firms such as Branch Technology, Zahner, Kreysler and Associates, CW Keller, Design-to-Production, all specialized in DF via custom milling, CNC machining or 3D printing of metal work, timber, and composites for architecture.

Parametric modeling is a common mean to delineate a safe and efficient route from concept to machine, therefore from design to production. It can provide 3D construction documentation and process the data required for digitally controlled fabrication, ensuring that all the components fit together perfectly.

This workflow is based on a single starting source of input to provide the efficiency and the flexibility needed and to overcome the lack of interdisciplinary communication between specialized software, like for example between BIM, Finite Elements Analysis (FEA), and CAD/CAM software used for fabrication instructions. This “Central Data Model” containing all the important information (dimensions, material, etc.) of each component is based on software such as Rhinoceros, within which almost all the elements can be defined by scripting (C++, C# and Grasshopper) using specific interfaces (often developed in-house by the project team, consultants or fabricators involved). This unique source can then be employed to share information with other software programs (FEA, BIM, CAD, etc.) and to develop sub-models, including structural models (SOFiSTik, Tekla Structures), BIM coordination models (Revit, Rhinoceros, Navisworks, etc.), BIM models for production (Tekla, Rhinoceros, Allplan, etc.), and sometimes 2D CAD drawings (which may still be required for authorization purposes or manual interventions) (Burry et al., 2020).

A remarkable example of this approach is the Kilden Performing Arts Center in Kristiansand, Norway, designed by ALA Architects. Its waterfront façade features a 3500 m² undulating oak surface constituted by 14309 individual timber components. A single source fabrication-detailed parametric CAD model was used to generate the actual fabrication code for CNC manufacturing of each element, which included milling the connection points and even engraving the unique code for installation. The precise identification of each component and the production of detailed instructions ensured a quick and error-free installation, with an overall cost much lower than that of an equivalent work conducted with traditional design and fabrication techniques.

Similarly, the EPFL Learning Center in Lausanne, designed by SANAA, stands on an 80-cm-thick concrete slab characterized by freeform hills and slopes up to 7 meters high, which required the project team to automate the process

of planning and CNC fabricating each one of the 1458 sections of formwork, as well as of almost 10,000 individual timber supports.

The Morpheus Hotel in Macau by Zaha Hadid Architects, characterized by an elaborate load bearing exoskeleton, is another exemplar case of parametric engineering techniques which allowed to design approximately 1200 complex nodes weighing up to 18 tons each, and 2500 steelwork connections (see Figs. 6.43 and 6.44). BuroHappold Engineering was tasked to design these connections and negotiated with architects and contractors to develop the scope, processes and program for this effort. Their intricate and irregular geometry required extensive FEA to model the complex stress states. Moreover, since the load bearing exoskeleton would be clad in aluminum, all connections and associated plates had to fit within the cladding zone defined by the architects, further constraining options for the connections' geometry and entailing nonplanar solutions.

Engineers solved this by employing a bespoke computational approach involving application programming interfacing, allowing efficient processing of the huge number of FEA models required and, crucially, the corresponding 3D visualization of every connection. Rhinoceros and Grasshopper were chosen as parametric design tools to enable the geometry of numerous complex 3D forms to be created quickly, flexibly, and accurately using visual programming and changing parameters (see Fig. 6.45). Rhinoceros was also used to model the outer surface geometry, using clash detection to confirm connections fit within the cladding zone. To identify unique connection types, a Grasshopper script was



FIGURE 6.43 Morpheus hotel, Macau. *Courtesy of Zaha Hadid Architects, photo by Ivan Dupont.*



FIGURE 6.44 Morpheus hotel, Macau. *Courtesy of Zaha Hadid Architects, photo by Ivan Dupont.*



FIGURE 6.45 Parametric model and construction of Morpheus hotel. *Courtesy of Zaha Hadid Architects.*



FIGURE 6.46 Freeform structure and cladding of Morpheus hotel. *Courtesy of Zaha Hadid Architects.*

written to interrogate the Rhinoceros geometry file allowing similar connection information to be verified more easily. The 2,500 connections were thus reduced to 400 unique types.

Parametric modeling of the load bearing exoskeleton allowed to provide the contractor with construction information in 2D formats for the connections where geometry could be readily defined using conventional drawing software, and as 3D digital models for the freeform areas to help fabricators understanding the connection geometry and to directly transfer into their own 3D construction model. This transparency helped to minimize fabrication errors. The aluminum cladding itself was the result of extensive digital modeling and rationalization to reduce and simplify the manufacturing of the panels, through the creation of a parametrically complex network of the structure, with each node defining the size of neighboring members, and vice versa (see [Fig. 6.46](#)).

Architectural detailing such as fillets and chamfering was defined in families associated with the model. These rationalized data automatically generated all the relevant sets of information needed to clearly visualize each detail, with every bolt numbered, positioned in space, and viewable in tabular specifications.

The four funicular stations of Cable Park Railway in Innsbruck, also designed by Zaha Hadid, feature a curvaceous glazed roof-cladding which is connected by over 2500 unique polyethylene (PE) profiles to the steel ribs of the supporting structure below (Fig. 6.47). Again, the detailing and fabrication planning for these profiles was automated from the CAD model, delivering the processed fabrication data directly to the five axis CNC router that cut and milled the profiles allowing for an error and rework free installation. This solution, along with the digital thermoforming of the glazed shell elements, guaranteed a very precise and automatic translation of the computer-generated design into the built structure.

Sofi Stadium in Los Angeles, designed by HKS, is characterized by an overarching canopy consisting of a translucent ethylene tetrafluoroethylene membrane at the top and surrounded by 34,789 perforated anodized aluminum exterior panels. Each triangular panel was perforated with a specific pattern that took into account climate control, façade decoration, and fabrication constraints. To do this, a strategy using Grasshopper, Rhino, C++ and Visual Studio was conceived which let the designers determine perforation density and mapping, positioning a total of 20 million uniquely placed holes in eight different sizes to allow perforations to fall neatly in line with the panel's edge, respect the required minimum distance of 1.3 mm between each one as well as enhance the facade's pattern. According to the project team and metal fabricator Zahner, this system enabled to see every bit of information about every tile and translate it into text-based code allowing to digitally fabricate 512 panels per week over 67 weeks.

Another prime example of design to DF is Barclays Center in New York City by Shop Architects, which façade is built from 12,000 uniquely shaped panels in weathered steel that recall the color and scale of adjacent brownstone blocks (see Fig. 6.48). To align the architects' vision to the capabilities of the automated machinery used in component manufacturing, designers developed a parametric model-based process that integrated all of the information necessary to streamline the design and delivery of each facade panel with the direct output of digital instructions for their fabrication and assembly. Accordingly, the laser cut steel components were accurately bent with a CNC press brake and then



FIGURE 6.47 Hungerburg station of Cable Park Railway, Innsbruck. Courtesy of Zaha Hadid Architects, photo by Werner Hutmacher.



FIGURE 6.48 Barclays Center, NY. Credit: Ryan McGrady (left) and Jules Antonio (right).

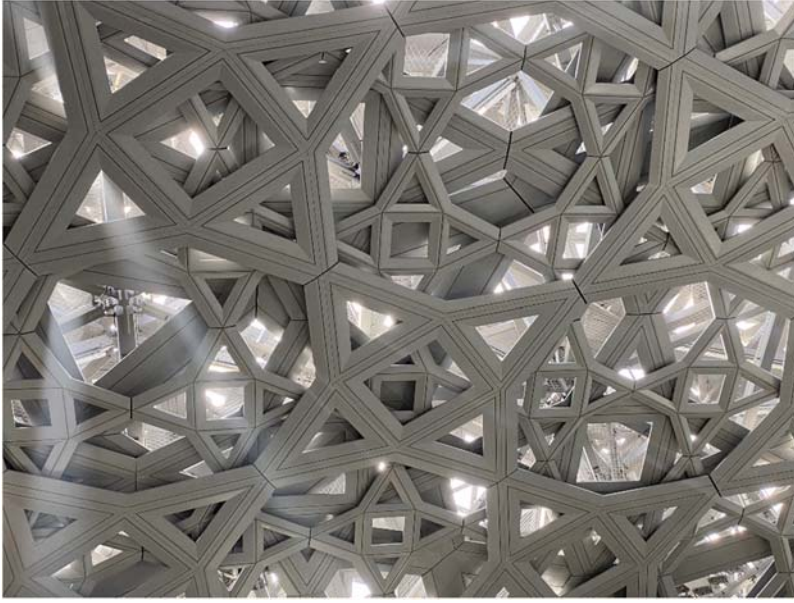


FIGURE 6.49 Louvre Abu Dhabi detail of the roof. *Photo by the author.*



FIGURE 6.50 Louvre Abu Dhabi museum. *Photo by the author.*

fabricated into larger assemblies. The whole manufacturing and delivery chain was managed by a purposed digital platform to control all aspects of design and delivery, from automating printed production tickets from parametric design models, to itemizing and tracking the production, delivery and installation of every assembly, also allowing the client to receive real-time graphic updates on progress via a live virtual model.

A world-renowned application of design to DF is the Louvre Abu Dhabi museum by Ateliers Jean Nouvel, namely, its overarching dome spanning 165 m over the exhibition buildings and circulation spaces. The dome itself is constructed as a 5 m thick steel spaceframe clad on both sides with 8750 aluminum facade elements distributed on eight layers forming a Mashrabiya pattern, which modulates incoming sunlight into a “rain of light” that is brighter on the roofs of the exhibition buildings and darker on the circulation areas and pools (see Figs. 6.49 and 6.50). Using a parametric design approach, daylight requirements were translated into a perforation ratio which defined the width of individual stars. Design options were validated with forward daylight simulation. The parametric model was

implemented in a functional programming style using F#, Visual Studio, and Rhinoceros and was flexible enough to express the geometry of the elements and to produce in few minutes enough geometric information to define the CNC cut patterns for the 459,260 aluminum profiles, and to represent details such as the actual profiles, drill holes, slots and supporting pins, providing spread sheets with construction specifications and assembly documents for use in the factory and on site (Wortmann and Tuncer, 2017).

Design to DF was also employed in the completion of the La Sagrada Familia church in Barcelona by Antoni Gaudí: the six remaining towers of the church, if built in traditional masonry or earthquake resistant reinforced concrete with stone cladding, would have been too heavy for the foundations and crypt below. Therefore, Arup developed a design that used prestressed stone masonry panels as the primary structural element, providing greater strength and allowing them to be accurately fabricated remotely, transported to site and easily assembled on site by crane. This solution also allowed the panels to resist stresses imposed by wind and earthquakes, while halving the weight of the tower. Each component was modeled parametrically in 3D to a construction level of detail (including nuts, bar threads, couplers, fillets, and chamfers), with carefully designed connections to ensure that panels craned into place would fit together like play blocks, without any further adjustment. These digital models were then used to automatically cut the individual blocks of stone, that were accurately fabricated into 5 m tall by 4 m wide panels using laser cut plywood templates, prestressed with machined stainless-steel bars, and finally assembled on site in only 30 minutes each.

The design to DF approach lends itself well for achieving free-form timber structures such as the new Swatch HQ in Biel, Switzerland by Shigeru Ban Architects, which consists of CNC-manufactured, continuously curved glue-laminated timber beams (see Fig. 6.51). As fabrication data for gluing and CNC-machining are directly derived from the 3D model, a precise and continuous reference surface is a mandatory basis for all subsequent design to fabrication activities. In this case, each of the 4500 timber beam segments of the grid shell was affected by a multitude of required detailing, ranging from structural cross- and butt-joints to shear connectors, installation cut-outs, and support (see Fig. 6.52). Hence, the detailed 3D model featured more than 140,000 screws, bolts, and connectors in order to include them in order lists, fabrication data, and collision control, in addition to 2800 curved façade-elements, bent sprinkler pipes, bespoke cooling panels, etc. Such a model was therefore implemented parametrically, that is, by defining rules for detail families and applying them to the model algorithmically, automatically adapting to each individual geometric



FIGURE 6.51 Swatch HQ, Biel. *Courtesy of Shigeru Ban Architects, photo by Didier Boy De La Tour.*



FIGURE 6.52 Construction of Swatch HQ, Biel. Courtesy of Shigeru Ban Architects, photo by Philip Zinniker.

situation. The sheer size and complexity of the model, however, did not allow to use a generative approach in which the entire model would be recomputed after each variation or permutation. In order to reduce computation time and allow the necessary flexibility in the system to handle exceptions, a “step-by-step” approach was established, allowing to run tasks only on parts of the model or to intervene with manual modeling in exceptional situations and still be able to feed the result back into the following parametric process steps, including automatic quality control of the manually modeled parts (Burry et al., 2020).

Finally, the design to DF approach is a keystone of the DFAB House at ETH Zurich, a technological demonstrator of the possibilities offered by merging several on-site and off-site highly automated construction methods. Being a research project, its design concept was based on exploring the architectural and technical implications of selected novel digital building processes, which included: high-resolution 3D printed formwork for concrete slab elements integrating different functions such as building technology, lighting, and acoustics (Smart Slab); automated assembly of rebar steel mesh and subsequent formwork-free concrete pouring (Mesh Mold) by an autonomous construction robot (In Situ Fabricator); 3D robotic prefabrication of highly integrated, building scale timber structures (Spatial Timber Assembly). The latter, in particular, implied the parametric design of 487 timber beams with unique geometries in a constructive system informed by the robotic fabrication constraints and the required assembly sequence of the structure (see Fig. 6.53). The cutting planes for the beams at each end were generated algorithmically and processed automatically by the robot in cooperation with the CNC saw, and concurrently the algorithm generated the milling and drilling vectors for the screws or the tension rods. Actual assembly was performed collaboratively by two gantry mounted robotic arms controlled by path planning algorithms to generate trajectories according what is already built, the timber currently being held by the robot, and the position of the other robot as to avoid collisions (Thoma et al., 2018).

6.6 Conclusions and future trends

In the last ten years, the introduction of different, interconnected digital technologies on data acquisition, building modeling and DF, and data analytics, along with the increased computational capacity of workstations and the introduction of several computational design methods, have started to dramatically transform the conventional design activity, no longer able to cope with the new requirements posed by the architecture of the new millennium. These new tools have allowed at the same time the improvement of the design process, of the construction process and of the final performance of the constructed building.

The integration of these new advanced digital design tools and methods allows in fact an augmented digital design approach based on:

- More accurate and streamlined acquisition and virtual migration of physical structures thanks to advanced survey systems (LiDAR, GIS, GNSS);

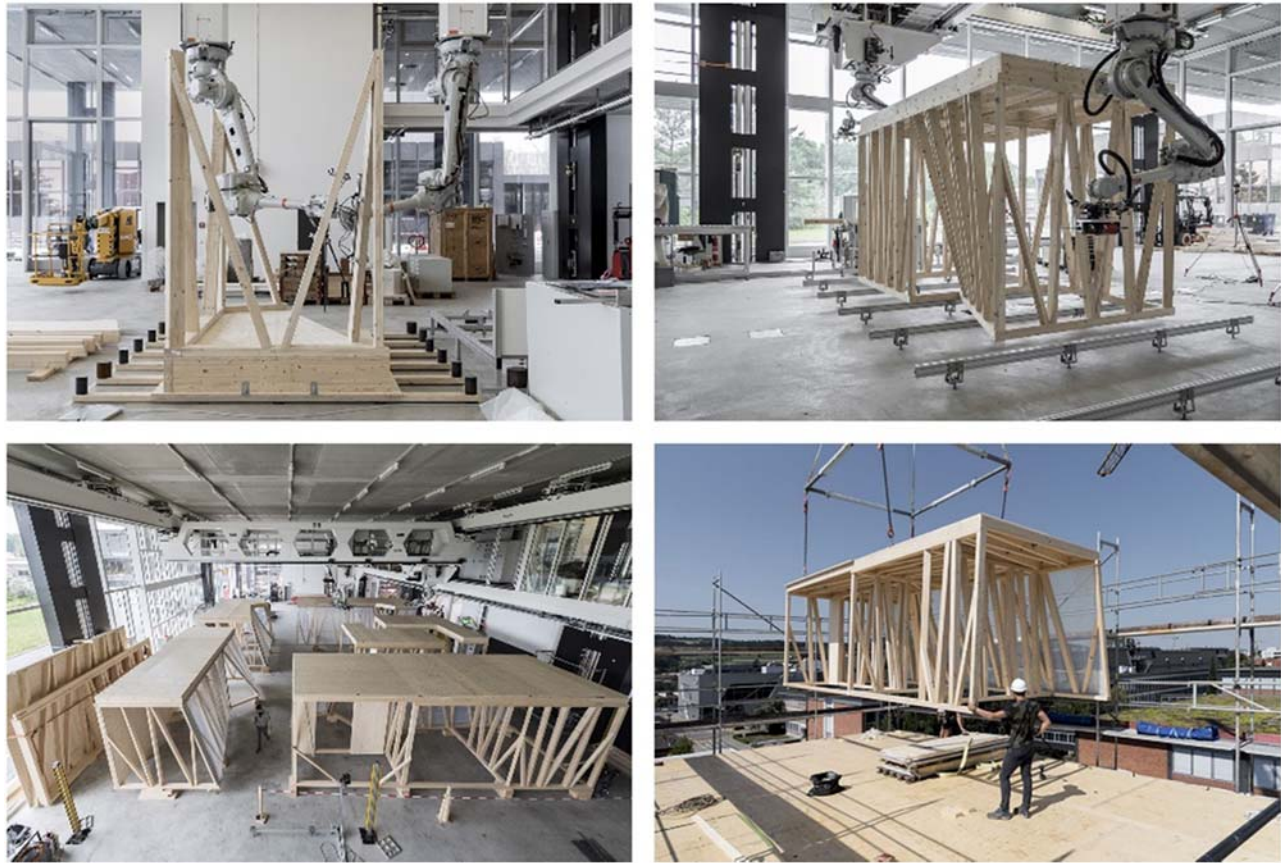


FIGURE 6.53 Digital fabrication process of Spatial Timber Assembly. *Courtesy of Gramazio Kohler Research, ETH Zurich.*

- Enhanced exploration and visualization of the design space through real time 3D rendering, extended reality (VR/AR/MR) and rapid prototyping;
- Optimization of design solutions through parametric and generative tools;
- Higher geometrical complexity, precise material processing, and improved time and cost control through DF.

Augmented with these innovative tools and methods, the digital design process now allows to anticipate the physical construction of the building with a perfect digital replica, starting from a millimeter representation of reality, that contains both geometric data and technical parameters and information (BIM). With this model, designers can simulate and optimize performance, environmental impacts and construction costs, plan the sequence of construction and give direct input to the manufacturing of components or to the automation of on-site activities.

By virtually building, simulating, and analyzing projects during the design and preconstruction phase, costly mistakes can be avoided and the overall performance of different design options can be compared, analyzed, cost-engineered, and optimized. For instance, several alternatives can be assessed during design for how they affect the built space in terms of acoustics, indoor comfort, usability, and safety, to identify the optimal solution to the project requirement brief. Moreover, the wider application of BIM and parametric/GD methods can foster the transition of the construction industry toward the more digitalized and productive manufacturing practices already established in more advanced industry sectors such as automotive, electronics, and consumer goods manufacturing. In fact, recent digital and automated construction methods, including additive manufacturing, CNC routers and cutters, or multiaxis industrial robotic arms, are allowing a more effective integration of DF aspects well within the BIM design workflow. Ideally, this will allow to close the process chain that links design to construction, greatly reducing the loss of quality and performance usually involved in the transition between construction drawings and the actual fabrication process.

Future trends on digital and computational design regards big data and advanced analytics, which the construction industry is beginning to use beneficially. Data mining methods based on AI and ML methods allow to process the huge amount of heterogeneous data generated by construction projects and their environments as taken in by digital survey

systems, and to exploit that data to enhance building design, facilitate real-time decision making, increase the accuracy of predictions, and support systematic improvement. ML-based tools will learn from these expansive data sets and find replicable patterns, allowing AI and ML assisted design to be able to return effective solutions to stated desired outcomes entirely based on consolidated historical data. Instead of starting from a parametric or computational model, AI could generate a design or a set of designs that fit the desired project brief, on which designers can orient the subsequent project development.

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Part III

Advanced materials, technologies, and building construction methods

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Advanced construction materials

7.1 Advanced materials for construction 4.0

Advanced materials are defined as those (both new and deriving from the modification of existing materials) specifically designed to possess new or improved technical properties (structural or functional) or environmental features compared to materials traditionally used to perform the same functions (Featherston & O'Sullivan, 2014; Pacheco-Torgal, Jalali, Labrincha, & John, 2013b).

The introduction of advanced materials in the construction industry is contributing substantially to increase the productivity of the sector, to ensure more safe and comfortable buildings, and to improve energy and environmental efficiency of the built environment, leading to profound changes in the whole construction process, from design to maintenance.

Advanced materials are in fact a key platform technology for many others and have a main role in enabling advanced/high-value manufacturing as well as in addressing society's key socioeconomic grand challenges like climate change, urban air pollution, and improved efficiency in using resources, supporting the development of new products through radically different and unique functionality, including low carbon technologies.

Advanced materials can introduce new functionalities and improved properties, while adding value to existing products and processes, in an optimized approach oriented to resource conservation, low-impact raw materials, cleaner production, efficient distribution, green use and maintenance, reuse, re-manufacture, disassembly, recycling, and safe disposal. This is particularly advisable with the building sector, characterized by high environmental impacts in terms of resources consumption and waste production and traditionally reluctant to innovation and slow in adopting new technologies.

Advanced materials in architecture can be characterized by a fixed, high-performance response or by a dynamic behavior in response to external stimuli; the latter characterizes the so-called smart materials that are finding application in a high number of products and systems, especially in building envelope components which can most take advantage of their properties of adaptation to different use conditions (Addington & Schodek, 2005).

These new or improved properties are the result of an engineering process at the nanoscale (nanomaterials) or at larger scale levels (micromaterials or macromaterials) (see Table 7.1).

In particular, the nanometric scale offers today higher potential in developing innovative materials and products and in improving performance of existing ones (Pacheco-Torgal, Diamanti, Nazari, Granqvist, & Pruna, 2019; Smith & Granqvist, 2011). In fact, fundamental properties of matter at the nanoscale level can be significantly different from the same material in its bulk state. These property variations at the nanoscale level can be exploited by embedding these materials with others either at the micro- or macroscale level, improving the performance of the bulk material to the desired extent in real-life applications. Advanced materials may be applied by themselves as end products or be integrated in other products or devices, both during the manufacturing process and in the final unit to enter the market.

Along with the development of nanomaterials and smart materials, research in the field of advanced building materials, in an ever more circular approach to economy, has been paying increasing attention in recent years to the use and engineering of natural materials of vegetable or animal origin or materials manufactured from living matter (namely, bio-based materials), characterized by a lower environmental impact of the whole life cycle and capable of ensuring the closure of the circle of materials.

Research in the sector of advanced construction materials is now focusing on the development of these main building products:

- advanced concrete for enhanced mechanical properties, self-healing, 3D printing of buildings and a more sustainable life cycle;

TABLE 7.1 Advanced materials for architecture: enhanced and new properties (Casini, 2016b).

Enhanced properties	
• Corrosion and oxidation resistance	• Quick compacting and curing time
• Durability	• Rheology
• Electrical conductivity	• Shock resistance
• Energy storage	• Surface energy
• Fire behavior	• Thermal conductivity
• Hardness	• Thermal radiation reflectance
• Insulation properties	• UV resistance and control
• Light transmission or reflectance	• Water-protection
• Mechanical resistance	• Weldability
• Photoelectric effect	• Workability
New properties	
• Air purifying	• Electromagnetic radiation block
• Antigraffiti and antistain	• Light emission
• Antiicing and fogging	• Real-time structural health monitoring
• Antireflection	• Scratch-resistance
• Biocidal activity	• Self-healing
• Chromogenism	• Shape memory
• Easy to clean	• Thermotropism

- engineered massive timber for more sustainable building structures and for more modularized and prefabricated components;
- high-performance insulators and latent heat storage products to improve energy efficiency and thermal comfort of new and existing buildings;
- dynamic windows for optimized light and solar radiation control and full integration of building envelope with energy management systems;
- smart coatings for new and enhanced properties of building surfaces, including self-cleaning, air purifying, and antibacterial;
- highly efficient colored and textured PV modules to enable the maximum integration of renewable energies in the building envelope;
- embedded sensors and actuators to monitor and control environment conditions and materials/structure performance

Regarding the latter, the design of more intelligent buildings is leading to the digitization of building components through the integration of micro- and nano-sensors within them, capable of collecting stimuli and information from the surrounding environment, including their thermo-physical state, and of communicating them in real time to the building management system both for the regulation of material and energy flows (adaptive envelope) and for their maintenance or replacement through building digital twin systems.

On the wave of the new digital era and automatic construction trends, material science is now focusing also on printability of construction materials in additive manufacturing (AM) processes, in order to broaden the potential applications of 3D and 4D printing and improve the productivity of the whole building sector. Currently, in fact, the materials applicable for AM of construction components are still limited and require further development to overcome the shortcomings especially with respect to structural strength and stiffness, as well as the constraints imposed by the extrudability of the material vs its rapid strength gain.

7.2 Nanomaterials

The term “nanomaterials” includes all materials having at least one of the three dimensions confined to the nanoscale range <100 nm (nano-objects), as well as those with an internal or surface structure at the nanoscale (nanostructured materials or bulk nanomaterials) even if they have none of the three dimensions at the nanoscale (zero-dimensional or 0D nanomaterials) (see Table 7.2) (ISO/TS 80004–1:2015, n.d.). Nanomaterials are not restricted to newly discovered materials but include nanoscale forms of well-known materials such as gold, silver, platinum, iron, and others.

Nanotechnology is certainly offering essential innovations for the development and formulation of innovative building products with increased mechanical, physical, and chemical properties, with application potential in all technical elements, from structures, to opaque and transparent closures, internal partitions, up to systems and appliances.

By operating at the molecular level, nanotechnology opens up new possibilities in building material design. In a world where quantum physics rule, objects may change color, shape, and phase much more easily than when in the macroscale. Bulk properties of materials, such as strength, electrical, chemical, and optical characteristics, may indeed change dramatically when miniaturized to nanoscale dimensions and can be designed to create different materials: at this scale (<100 nm) they do not depend anymore on chemical composition only but also on size and form.

For instance, normally opaque substances become transparent (copper); inert materials become catalysts (platinum); stable materials turn combustible (aluminum); solids turn into liquids at room temperature (gold); insulators become conductors (silicon).

Composites made from ceramic or metal nanoparticles can suddenly become much stronger than predicted by existing macroscale materials science models: metals with a grain size of around 10 nanometers can be as much as seven times harder and tougher than their ordinary counterparts with grain sizes in the hundreds of nanometers.

Properties gained by materials at the nanoscale may be static (*high-performance fixed response*) or dynamic (*dynamic performance or smart behavior*). In the latter case, nanomaterials become part of the category of so called smart materials, able to vary their own characteristics according to external stimuli (chromogenics, thermotropics, etc.).

Within construction materials, elements, and systems, nanomaterials can be integrated in the form of solid nanocomposite materials, solid materials enhanced with nano-coatings or characterized by nanostructured surfaces, nanoporous materials (such as aerogel) and fluid nanodispersions as nanopaints, nanoadhesives, or nanolubricants. Table 7.3 reports an example of new and enhanced concrete properties obtained through nanotechnology.

TABLE 7.2 Nanoproducts classification.

Nanomaterials	
ISO/TS 80004–1:2015	
Nano-object	Nano-structured material
Material with one, two or three external dimensions in the nanoscale (1–100 nm)	Material having internal nanostructure or surface nanostructure
<i>3D: Nanoparticle</i> Nano-object with all external dimensions in the nanoscale where the lengths of the longest and the shortest axes of the nano-object do not differ significantly. (e.g., quantum dots, nano spheres, buckyballs) <i>2D: Nanofiber</i> Nano-object with two external dimensions in the nanoscale and the third dimension significantly larger. (e.g., nano rods, nanowires, single or multiwalled carbon nanotubes) <i>1D: Nano-plate</i> Nano-object with one external dimension in the nanoscale and the other two external dimensions significantly larger. (e.g., graphene, monolayers, thin films)	<i>Nanostructured powder</i> Powder comprising nanostructured agglomerates, nanostructured aggregates, or other particles of nanostructured material. <i>Nano-composite</i> Solid comprising a mixture of two or more phase-separated materials, one or more being nanophase. <i>Solid nanofoam</i> Solid matrix filled with a second, gaseous phase, typically resulting in a material of much lower density, with a nanostructured matrix, for example, having nanoscale struts and walls, or gaseous nanophase consisting of nanoscale, or both. <i>Nanoporous material</i> Solid material with nanopores. <i>Fluid nanodispersion</i> Heterogeneous material in which nano-objects or a nanophase are dispersed in a continuous fluid phase of a different composition.

TABLE 7.3 Main concrete enhanced and new properties through nanotechnology.

Concrete properties	Nanotechnology
Air purifying	TiO ₂ particles
Antigraffiti and antistain	TiO ₂ , SiO ₂ coating
Curing time	TiO ₂ , CaCO ₃ particles, calcium-silicate-hydrate (CSH) nanocrystals
Durability	Al ₂ O ₃ , SiO ₂ , ZnO particles
Fire behavior	TiO ₂ particles
Formability	Nanopolymers
Hardness (abrasion-resistant)	Carbon nanotubes (CNT), FeO particles
Mechanical resistance and crack prevention	Polymers, SiO ₂ , FeO, and CaCO ₃ particles, CNT
Moisture resistance	C ₆ H ₁₀ O ₅ particles
Quick compacting	TiO ₂ , particles, CSH nanocrystals
Real-time structural health monitoring	CNT
Self-healing	Nanopolymers
Shock resistance	Al ₂ O ₃ particles
Water-protection	SiO ₂ particles

In particular, the use of nanomaterials in architecture allows important improvements in:

- performance of load bearing structures, with the realization of lightweight nanocomposite construction materials (CNT, metal-matrix composites, nanocoated light materials, ultra high-performance concrete, polymer composites, etc.);
- thermal and lighting control, with the realization of high-performance nanoporous insulating materials [aerogels, vacuum insulation panels (VIP), transparent insulation materials (TIM)], high reflective coatings (cool roofs), along with low-e, antireflective (AR), passive and dynamic solar control, and self-cleaning nano-coatings for glazing;
- surface characteristics of building elements, with the application of specific nanocoatings or nanopaints (self-healing, air purifying, self-cleaning, antibacterial, antigraffiti and antistain, photo luminous, scratch-resistant, antireflection, antiicing antifogging, fouling-resistant, oxidation and corrosion resistant, UV resistant, fire resistant, etc.);
- energy efficiency in lighting (LED/QLED, OLED);
- more efficient and integrated renewable energy systems (polymeric, dye sensitized, quantum dots, thin-film and multijunction PV solar cells, fuel cells, etc.);
- building and environmental monitoring and control, with the realization of nano embedded sensor, actuation, and control systems (NEMS).

Finally, nanotechnology can lead the way for new and innovative applications for 3D printing technology, helping to ease the manufacturing process and enhance the properties of products, especially in the fabrication of intricate structure and complex shapes. In the past few years, there have been a lot of advancements in the integration of nanomaterials in AM for various applications. The usage of nanocomposite materials (such as Nylon 6, SiO₂ and Ag nanoparticles, carbon nanotubes, nanoclays, among others) is a fast-growing market for allowing generating lightweight products with many improved characteristics such as mechanical, thermal, and electrical properties, fire resistance, and biocompatibility.

7.3 Smart materials

“Smart materials” are a new class of highly innovative materials able to perceive stimuli from the external environment and to react immediately to them, adapting to the changed environmental conditions (Addington & Schodek, 2005; Ritter, 2007; Schwartz, 2002; Schwartz, 2009; Shahinpoor & Schneider, 2007).

This reaction is usually caused by a change in the values of the surrounding energy field (change in potential, electrical, thermal, mechanical, chemical, nuclear, or kinetic energy) that triggers in the material a chemical reaction, a change in the molecular or crystallographic structure, an alteration of the voltage ranges, the absorption of a proton, and other phenomena.

Smart materials may come in the micrometer, millimeter, or nanometer scale (smart nanomaterials). The effects may show in phenomena such as a change in color, a change in volume, a change in the distribution of stress and deformation, or a change of the refractive index. The ability of smart materials to produce a useful effect in response to external stimuli makes them greatly interesting for their application in the fields of design and of architecture in particular, both characterized by ever changing and dynamic needs.

Depending on the type of reaction to the external energy field, smart materials are generally divided into property-changing materials and energy-exchanging materials (see [Table 7.4](#)).

The first category includes materials that autonomously and reversibly change one of their mechanical, chemical, optical, electrical, magnetic, or thermal properties in response to a stimulus. They include different types of materials such as chromogenic or color change materials, phase change materials (PCMs), photocatalytic materials, electrorheological, and magnetorheological materials, as well as shape memory alloys (SMAs).

To date, these materials already found application in architecture in a high number of products and systems, especially in building envelope components that can most take advantage of their properties of adaptation to different use conditions.

In particular, property changing materials can be used in:

- transparent closures for dynamic control of solar radiation (chromogenic materials);
- closures and in internal partitions to increase their thermal inertia (PCMs);
- mortars, paints or coatings of external and internal surfaces of the building in order to achieve a self-cleaning and at the same time air purifying effect (photocatalytic materials);
- integrated smart building sensors for structural health monitoring (SHM) and vibration control (electrorheological and magnetorheological materials).

The second category of smart materials includes those materials capable of converting more or less reversibly an input energy into another form of energy in accordance with the first law of thermodynamics. They include photoelectric, electroluminescent (LED, OLED), photoluminescent, piezoelectric, thermal and pyroelectric, electrostrictive and magnetostrictive materials.

In particular, energy exchanging materials can be used in:

- lighting appliances to improve energy efficiency and visual comfort (electroluminescent materials);
- photovoltaics for the production of electric energy from sun radiation (photoelectric materials);
- paints and coatings to obtain photoluminescent surfaces (photoluminescent materials);
- integrated smart sensors for building structure, safety, and comfort monitoring (piezoelectric, thermal, and pyroelectric materials).

Among smart materials, shape memory materials (SMMs) and smart sensors are the most promising in the perspective of a construction 4.0 model, as the open new interesting scenarios on both AM (4D printing) and on intelligent objects fully integrated into the building management system.

7.3.1 Shape memory materials

SMMs are among the most promising smart materials for buildings, due to their capability to vary their geometric configuration according to external stimuli (heat or electricity) in an autonomous and controlled way.

SMMs can be categorized in SMAs and shape-memory polymers (SMPs) and can have interesting applications in the construction of building, mechanical, and architectural elements able to self-adapt to ambient temperature or to assemble with the only supply of electricity or heat.

When a SMA or SMP object is deformed from an initial shape to a new one, it will keep this last configuration. However, if heated to a certain temperature, either directly or by electric current, it will revert to its initial shape without any mechanical aid, as if it remembered its base configuration.

Concerning SMAs, most used is nickel titanium (Ni-Ti or Nitinol), due to its high recoverable strain and corrosion resistance, but copper- and iron-based alloys also exist ([Fiorito et al., 2016](#)). The shape memory effect is caused by the internal solid–solid phase changes that the alloy undergoes during the deformation and shape return processes: upon

TABLE 7.4 Smart materials classification and main building application.

Type of smart material	Environmental stimulus	Reaction/effect	Building application
Property-changing materials			
Thermochromics	Temperature difference	Color change	Thermochromic glazing
Photochromics	UV radiation	Color change	Photochromic glazing
Mechanochromics	Deformation	Color change	-
Chemochromics	Chemical concentration	Color change	Gasochromic glazing
Eletcrochromics	Electrical tension	Color change	Eletcrochromic glazing
Liquid Crystals	Electrical tension	Color change	LCD glazing
Suspended particles	Electrical tension	Color change	SPD glazing
Photocatalytics	UV radiation	Chemical reaction	Self-cleaning and air purifying coating
Thermotropics	Temperature difference	Phase change	Latent heat storage products (PCMs)
Electrorheological	Electrical tension	Viscosity change	Sensors and actuators
Magnetorheological	Magnetic field	Viscosity change	Sensors and actuators
Shape memory	Temperature difference	Crystalline phase change	Sensors and actuators, materials for 4D printing
Energy-exchanging materials			
Electroluminescents	Electrical tension	Visible light emission	LED, OLED lighting
Photoluminescents	Radiation	Visible light emission	Fluorescent lighting, Photoluminous paints, Luminous solar collectors
Chemiluminescents	Chemical concentration	Visible light emission	-
Thermoluminescent	Temperature difference	Visible light emission	-
Photovoltaics	Solar radiation	Electrical tension	PV cells
Bidirectional energy-exchanging materials			
Piezoelectric	Deformation	Electrical tension	Sensors and actuators, harvesting energy systems for pavements
Thermoelectric	Temperature difference	Electrical tension	Sensors and actuators
Pyroelectric	Temperature difference	Electrical tension	Sensors and actuators
Electrochemical	Chemical concentration	Electrical tension	-
Electrostrictive	Electrical tension	Deformation	-
Magnetostrictive	Magnetic field	Deformation	-
Optical fibers	Light ingress	Light egress	Sensors and lighting

heating, it goes from the martensite phase, stable at lower temperatures, to the austenite phase, stable at higher temperatures, and vice versa upon cooling. During the martensitic phase transformation, the molecular structure is twinned, allowing to carry size and shape to the austenitic phase. When external loads deform the structure, this induces a detwinning phenomenon that can be regained by heating above the finishing temperature of austenite (see Fig. 7.1).

This process is generally reversible, although some shape deterioration over time may occur if the bending and heating are not carefully controlled.

SMPs have instead been developed in the form of rigid plastics or relatively porous foams, with a wide application scope, including self-unrolling surfaces, knots that tie themselves for medical applications or consumer customizable furniture (Safranski & Griffis, 2017).

Characterized by low density and high biocompatibility, they are constituted by chemically bonded molecular chains of monomers and, like SMAs, owe their capability to a phase transition trigger within their matrix. According to their chemical composition, they can be distinguished in two main categories: SMPs based on a glass transition (chemically cross-linked glassy thermosets and physically cross-linked amorphous thermoplastics), and SMPs based on a melting transition (chemically cross-linked semicrystalline rubbers, and physically cross-linked semicrystalline block copolymers) (Fabiani, Pisello, & Paksoy, 2018).

Once heated to its specific transition temperature, the softened SMP can be easily modeled in a temporary desired shape. By keeping the material in this shape upon cooling, this configuration will be preserved until the specimen is heated above its transformation temperature again. As a further evolution, triple shape memory polymers (TSMPs) are SMPs that have the capacity to form and remember multiple shapes when exposed to stimuli, acquiring an additional tertiary stage comprising of covalent cross-links. Compared to SMAs, SMPs can also recover a larger magnitude of strain and consume considerably less energy during the shape memory programming (Wang et al., 2011). SMMs containing magnetic nanoparticles such as iron oxide (Fe_3O_4) can also display shape shifting effect when subjected to magnetic fields (Wei et al., 2017).

As regards industrial applications, SMMs, and SMAs in particular, are currently applied in several sectors, including biomedical, aerospace, and automotive, and are mostly used in actuators, release mechanisms, or articulated components to reduce the need for moving parts and make them smaller, cheaper, and more reliable. Concerning structural building applications, SMAs are employed in the civil engineering sector for repair and reinforcement of metal structures, where their superelasticity allows metals to undergo extreme deformation (up to 8%) without consequences (Casini, 2016b). Current applications of SMMs are limited mostly to the aerospace and medical industries.

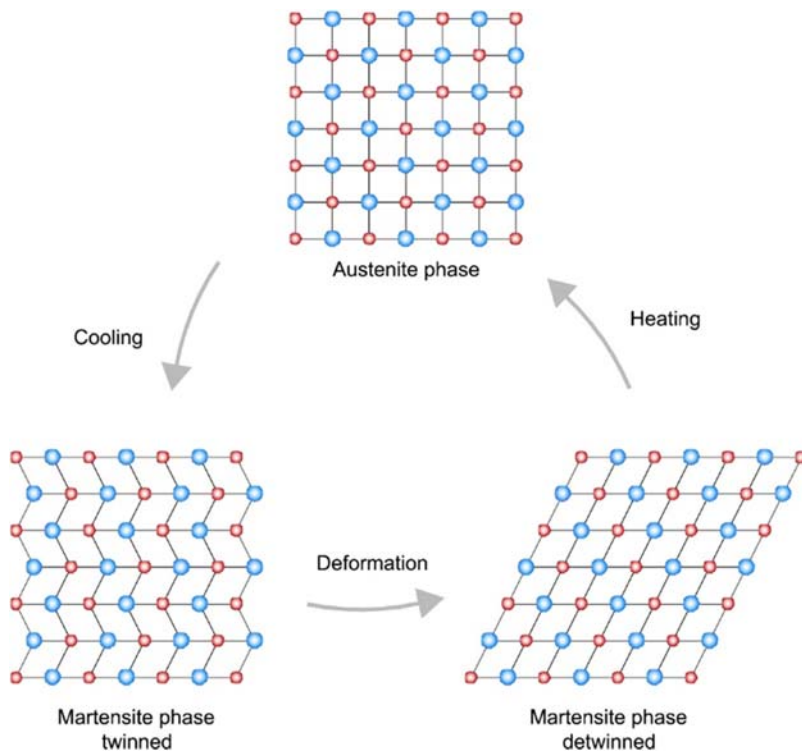


FIGURE 7.1 Memory shape alloy operation.

Most recently, SMMs have gained much attention for their perspective integration in AM processes. 3D printing is already leaving a mark in multiple industrial sectors, including construction, for its ability to print complicated shapes layer by layer, the wide variety of materials that can be employed, and the unparalleled freedom offered during the design stage to produce unique shapes and configurations (Gao et al., 2015). The next generation of 3D printing techniques will use SMMs to print structures that could change their shape with time after being manufactured, effectively adding a fourth dimension of time to the printing process leading to the evolution of 4D (four-dimensional) printing. 4D printing allows the base material to transform into predetermined shapes over time in response to external stimuli such as heat or electricity, which translates to countless new possibilities as well as to several advantages over traditional AM including the reduction of assembly time, net cost, number of components, or failure rates (Joshi et al., 2020).

7.3.2 Smart sensors

Due to their inherent ability to detect external stimuli and react accordingly in a measurable manner, several smart materials have gained much attention for their potential application as or within miniaturized sensors, allowing to easily monitor a range of parameters in both bulk materials and finishes without needing external power or wiring, and with a great degree of precision. The systematic application of these smart sensors has the potential to interface more and more building elements with their respective management and control systems, implementing for instance self-sustainable wireless sensor networks, self-tuned vibration energy harvesting devices, seismic applications, thus enabling buildings that are even more intelligent.

Smart sensors employ one or more smart materials belonging to both energy exchanging and energy generating categories, mainly piezoelectric and pyroelectric materials, electrorheological and magnetorheological fluids (MRFs), optical fibers, and SMAs.

Concerning piezoelectric materials, their effect consists in the property of some crystalline structures to polarize when subjected to a mechanical deformation (direct piezoelectric effect), generating a potential difference, and at the same time to deform in an elastic manner when traversed by electrical current (inverse piezoelectric effect) (Chen, Qiu, Han, & Lau, 2019). The piezoelectric effect occurs only along one direction and deformations associated with it are the order of nanometers. Many common devices, including doorbells, speakers and microphones, or quartz watches, are based on piezoelectric technologies. Piezoelectric elements are also the key of recent proposals for harvesting energy from pavements and roads by exploiting kinetic stress. More interesting is the ability of piezoelectric materials to convert strain or vibrations into electrical current to allow, for instance, to impart self-monitoring capability to civil structures simply by embedding piezoelectric fillers during the construction phase and, once operational, measuring the overall electrical properties of the single building elements to track strain or vibrations (Song et al., 2017).

Similarly, pyroelectric materials are based on crystals that are given a permanent polarization due to aligned molecules with fixed dipole moment. When the temperature changes, the polarization varies accordingly, triggering surface electric charges or, if the surfaces are connected, a pyroelectric current. The pyroelectric effect is commonly used in intruder detection systems and in thermal imaging. Pyroelectric materials constitute an inexpensive, diminutive and resilient alternative to thermometers and permit the diffused monitoring of large parts of the building envelope as well as smaller components of the building systems.

Concerning MRF and magneto-rheological elastomers (MRE), as well as electrorheological fluids (ERF), their applications are mostly related to high tech industry sectors, where their property of being able to alter their stiffness and viscosity as a function of an electrical or magnetic stimulus has long been exploited in active suspension systems for cars or in prosthetics. In particular, MRE are a rubber-like material composed by an elastic nonmagnetic matrix and magnetic particles, allowing to alter their shape or mechanical characteristics. ERFs are suspensions of very small particles in electrical insulating fluids, that upon electrical stimulus rapidly form a solid-like structure in the direction of field, turning a the liquid into a gel and viceversa. Both MREs and ERFs are used in buildings together with piezoelectric smart sensors for vibration absorbers and tuned mass dampers (Bahl, Nagar, Singh, & Sehgal, 2020).

As regards optical fibers, they are made by drawing glass or plastic to a diameter slightly thicker than a human hair, allowing a degree of flexibility and the ability to transfer light from one end to the other with minimal signal loss. Widely used in fiber-optic communications, in recent years, they have found their way in buildings as microsensors for SHM. Employed mostly in the form of fiber Bragg grating (FBG) and fiber-optic polarimetric sensor (FOPS), they allow local strain measurements in both mechanical and structural components (Bahl et al., 2020). The diminutive diameter of few microns of optical fiber sensors allows to embed them in concrete or composite structures during the construction phase, and to instantly detect cracks or deformations tracking the light path variations within the fiber. In

conjunction with hydrogel, optical fibers are also employed as distributed humidity sensors, in which water presence induces swelling of the hydrogel component that can be picked up by measuring light attenuation in the optical fiber (Bremer et al., 2016).

Finally, SMMs, thanks to their ability to shift between predetermined shapes according to external stimuli, are fitting candidates for the production of actuators and sensors. In fact, their configuration may be used for tracking temperature, electricity or, in case Ni Mn based SMAs or iron oxide SMPs, even magnetic fields.

7.4 Bio-based materials

In the concept of sustainable construction, building materials play a key role throughout the entire life cycle of the building and in several respects. In fact, the overall life of a building begins with the extraction of raw materials needed for production of construction elements, which are then transported to the site and used for its fabrication, continues with the use and maintenance of the building, and ends with the management of demolition waste coming from its decommission.

The extraction and processing of raw materials in building products imply the consumption of resources and energy and the release into the environment of pollutants and waste related to manufacture, transportation from production factories to the construction site, and installation methods.

The materials and products chosen will dictate the performance of the building during its operational life in terms of release of polluting substances in indoor environments, acoustic and thermal well-being, safety, energy consumption, durability, and maintainability.

Conversely, the same design choices will affect the environmental impact of the building at the end of its life, linked to the possibility of recovering the materials used and disposing of them safely by reducing the production of wastes.

In this picture, looking at a more sustainable and green building sector, designers and researchers have increasingly focused on promoting the use of materials and products of vegetable or animal origin, so-called bio-based materials, able to guarantee performance on par with conventional materials, although with a lower environmental impact throughout their entire life cycle (see Table 7.5).

The aim is to increase the usage in the building sector of high-performance materials that are highly renewable, with a lower amount of incorporated energy, easily recyclable or in turn composed of recycled natural material, free of hazardous substances, whose resources supply methods, manufacturing, and disposal cycles have low environmental impact (Khatib, 2016).

Indeed, in addition to reducing the need for mining and extractive processes of raw minerals, bio-based materials offer an alternative construction product which is typically biodegradable at the end-of-life, further helping to regenerate natural systems. Moreover, bio-based materials often sequester CO₂ emissions while growing, acting as a carbon storage and helping to regenerate soils in between cultures. Nonetheless, the adoption of bio-based construction materials also requires to ensure sustainable land use in the sourcing of “raw biomaterials,” preventing the exploitation of land for biomaterial resources and avoiding subtraction of land already used for agricultural food production. This can be achieved by incentivizing small to medium scale localized production of biomaterials, as well as by using agricultural by-products (e.g., rice, straw, corn, and coconut husk) and by growing plants which help fertilize fields for agriculture (e.g., hemp). Another concern for agricultural practices used to produce bio-based feedstocks regards the fuel essential for manufacture, transport, harvesting, plowing and the use of pesticides and herbicides, which can have ecological effects as high as those of the conventional building materials they would replace (Yadav & Agarwal, 2021).

Furthermore, by transforming postagricultural waste streams into resources in the production of new construction products, bio-based materials represent a circular economy solution to the need for immediately available building materials. Biomaterials are also fully compatible with the new advanced construction methods of off-site prefabrication, modular construction, robotic assembly, and 3-D printing (see Chapter 8). Sustainability benefits of bio-based materials are best exploited when used locally, as climate specific renewable materials can offer effective performance characteristics in climate responsive design and improve income and employment to local economies. Moreover, the use of local materials reduces both embodied energy and carbon costs associated with transportation and can ultimately support the resilience of the construction industry against price inflations due to scarcity of globally sourced construction minerals.

Bio-based materials and building products can also improve indoor comfort and health conditions in terms of air quality, temperature control, and humidity regulation. For instance, bio-resins such as mycelium, used in biomaterials manufacturing, can replace synthetic glues and resins and other potentially toxic chemicals which may release volatile organic compounds (VOCs) and other harmful substances. However, the widespread adoption of bio-based materials in the construction sector is still hampered by various factors, including social acceptance. In addition to concerns about

TABLE 7.5 Life cycle sustainability features of building materials (Casini, 2020b).

Life cycle stage/environmental risk factors	Sustainable features of building materials
Raw materials supply • Consumption of nonrenewable natural resources • Land deterioration • Pollution from transport	Designed for resource and environment conservation • Renewable or vastly available raw materials • Recycled or recovered raw materials • Environment and biodiversity protection • Use of natural techniques • Certified cultivation and extraction systems
Manufacturing process and distribution • Energy consumption due to manufacturing process, transport and distribution • Air, water, and soil pollution • Health risks for production workers	Designed for cleaner production and for efficient distribution • Absence of hazardous raw materials • Certified environmental management system (EMAS, ISO 14001, ISO 50001) • Low energy consumption in the manufacturing phase • Low pollutant emissions • Absence of risks for production workers • Low distance from the construction site to the manufacturing plant (zero km)
On-site works and installation • Harmful emissions during handling • Production of process scraps and waste	Designed for easier and cleaner installation • Absence of harmful emissions hazards • Ease of installation and workability on site • Instructions for on-site operations and installation
Building operation • Short and long term hazardous emissions • Low durability of performance • Low resistance to atmospheric and biological agents	Designed for green use and maintenance • Absence of harmful emissions hazards • High durability • High resistance
Decommissioning • Partial or total loss of natural resources following the impossibility to reuse, recover, recycle, or reintroduce materials to the environment. • Air, water, and soil pollution for disposal	Designed for reuse, re-manufacture, disassembly, recycling, safe disposal • Use of recyclable materials • Ease of disassembly • Absence of additives or substances that impede recycling • Ease of treatment and disposal

durability and resistance to chemical and biological attacks (from insects, rodents or mold), local biomaterials and vernacular design are often associated with undesirable or “old-fashioned” esthetics, rather than with modern or contemporary lifestyles which are more linked to concrete, steel, and glass (United Nations Environment Programme, 2020).

Parallel to bio-based materials grown or harvested naturally or coming from industrial byproducts and waste streams, advancements in biotechnology, synthetic biology, and genetic engineering have also lead to entirely new manufacturing approaches to materials, consisting in living materials produced by a variety of wild-type and engineered microorganisms hierarchically replicated in controlled conditions to obtain engineered living materials (ELMs) with the specified characteristics. ELMs are composed of living cells that form or assemble the material itself and may be inactivated after manufacturing to set the performance at the desired level or can keep on “living” to modulate the functional performance of the material postproduction. The predominant application of living materials to construction concerns inert, deactivated bulk products such as bricks grown from mycelium, and active living materials such as self-healing and biologically cemented concrete. Further development of organisms as electrochemical biosensors could lead to advanced applications as living wallpaper (e.g., bacterial pigments, electrically conductive bacterial displays), sensors and indicators of indoor environmental quality (e.g., humidity, temperature, CO₂, CO, and harmful VOCs), and active bioelectronics for SHM.

The most interesting bio-based materials in construction sector, in addition to wood, are bamboo, cork, cardboard, cellulose fibers, hemp, flax, straw, corn starch, wheat stalks, sheep wool, seaweed, mushrooms, and feathers poultry.

Their use in construction concerns all building elements, from structures to masonry, up to insulating or finishing products (plasters and paints).

In particular, main bio-based building products include:

- engineered massive timber products (CLT, LVL, Glulam, etc.) and engineered bamboo products (LBL, Glubam) for structural use in substitution of steel and concrete, even for tall buildings;
- eco-friendly masonry bricks or blocks made of straw, hemp, wood fiber, in substitution of cement or clay or as their additives;
- bio-bricks made through microbial activity or directly manufactured from fungi mycelium (engineered living building materials, ELBMs)
- bio-based panels for dry-wall construction such as fiber boards or particleboards made of bamboo fibers and power (Nguyen, Grillet, Bui, Diep, & Woloszyn, 2018), wood strands, coconut coir, lavender stalks, sunflower pith, rice chaff, all bound with eco-friendly adhesives (bone glue, nerve glue, lignin);
- bio-based insulating materials and PCMs in substitution of synthetic or mineral products;
- bio-based materials for AM in construction such as bioplastics components or bio-concrete materials for 3D printed buildings.

While selecting bio-based building elements in view of the sustainability, a distinction must then be made between materials and building products. The latter are generally made up of multiple materials whose assembly can reduce the overall environmental performance. For example, the presence of joints, binders, coatings, or treatments may compromise the recyclability of the product or determine the emission of substances harmful to health or the environment.

Furthermore, it is important to stress that there are no ecological materials in an absolute term, as the life of a building component is inextricably linked to the life of the building itself, influencing and in turn being influenced by it. The overall sustainability of the life cycle of building materials is therefore dependent on the distance between the place of manufacture and that of installation (therefore privileging where possible the so-called zero-km materials), on the characteristics of the context in which the intervention will be carried out, on the application methods of the product into the building, on the use conditions, and on the method of disposal. For instance, the real possibility of recovering building materials is linked not only to the recyclability of the single products, but also to the construction techniques used and to the method of demolition at the end of the building life. All these variables are not known to the scale of the product and are definable only from time to time on the basis of the context and building characteristics and of the project requirements. In this context, for the correct assessment of the environmental sustainability of a bio-based building material or product, the following areas of interest have to be investigated: the life cycle of the product off-site (*from cradle to gate*); the transport of the product (*from gate to site*); the life cycle of the building (*from construction to cradle*).

In addition to final building products, another important field of application of bio-based materials is that oriented to the production of biopolymers, replacing synthetic polymers normally used as additives in the production of cement in order to improve its workability, strength, and durability (melamine, naphthalene condensates, or polycarboxylate copolymers), or in the production of polyurethane (isocyanates) used in thermal insulation, as sealant, adhesives, in concrete jointing, and as protective coating.

Regarding concrete, new and biodegradable polymers based on renewable feedstocks such as lignosulfonate, starch, chitosan, pine root extract, protein hydrolysates, or even vegetable oils are now being researched for the production of bio-based admixtures, and bio-enhancing concrete additives. Concerning polyurethane, in the last five years, many investigators have dedicated to the development of bio-based polyurethanes foams through the acid liquefaction of biomass resources, like starch, soybean, alginic acid, palm, sugar-cane bagasse, lignin, cork, or coffee grounds (Pacheco-Torgal, Ivanov, and Tsang (2020)). Polystyrene can be fabricated by exogenously adding crosslinkers to biogenic styrene produced by genetically engineered *Escherichia coli* (Srubar, 2020).

Moreover, an important contribution to the development of new and improved biopolymer-based materials is coming from the recent advancements of nanotechnology with the investigations on cellulose nanocrystals (cellulose elements having at least one dimension in the 1–100 nm range). Renewable, biodegradable and carbon neutral, cellulose has the potential to be processed at industrial-scale quantities at low cost, enabling the development of eco-efficient high-performance materials. Effective applications of cellulose regard its use in cement industry in nanocrystalline form and in building insulations as cellulose aerogel.

Concerning 3D printed buildings, recently the use of vegetable fibers has been tested by mixing a compound of 25% of soil taken from the site (30% clay, 40% silt, and 30% sand), 40% from straw chopped rice, 25% rice husk, and 10% hydraulic lime to 3D print an entire habitation unit with zero environmental impact and low costs (Gaia 3D printed house by Wasp, 2018).

7.4.1 Bio-based insulation and phase change materials

Along with the development of high-tech insulation products, the proposal of bio-based materials has been growing over time. These materials are expected to be rapidly renewable, of vegetable or animal origin, possibly recycled or recovered and reused (Casini, 2020b). This trend addresses the scope of using environmentally friendly building materials and products that ensure the reuse or recyclability of the construction works, of their materials and of their parts after demolition. The use of bio-based insulation is also encouraged by the main environmental buildings certification systems (LEED, BREEAM, Living Building Challenge, etc.), that in fact award points to the project in case of use of renewable, recyclable, recycled materials, or materials with recycled content. Using these products aims to reduce the environmental impact of the whole life cycle through greater resource conservation and a reduction of energy consumption and pollutant emissions during production and disposal.

Compared to insulation materials of synthetic and of mineral origin and to fiber reinforced aerogel blankets (FRABs), bio-based insulation materials have, with a comparable performance, lower environmental impact at every stage of their life cycle and a lower embodied energy value (Table 7.6).

Some materials of vegetable origin such as hemp, kenaf, flax, corn, reed, coir, jute, and cereal chaff derive from easily renewable raw materials, others from recycled raw materials and processing waste (cellulose and wood). Cork is a

TABLE 7.6 Comparative analysis of main environmental risk factors of insulation materials (Casini, 2020b).

Life cycle stage/environmental risk factors	Insulating materials			
	Organic synthetic	Inorganic	Bio-based	FRABs
Raw materials supply				
• Consumption of fossil resources	■ ■ ■	□	□	■
• Land deterioration	■ ■	■ ■ ■	□	■ ■ ■
Manufacturing process				
• Energy consumption	■ ■ ■	■ ■	■	■ ■ ■
• Greenhouse effect	■ ■ ■	■ ■	■	■ ■ ■
• Ozone depletion	■ ■	□	□	□
• Acid rain	■ ■	■	□	■
• Photochemical smog	■ ■	■	□	■
• Health risks for production workers	■ ■ ■	■	□	■
On-site works and installation				
• Harmful emissions during handling	■	■ ■	□	■ ■
Building operation				
• Short-term hazardous emissions	■ ■	■ ■	□	■
• Low durability of performance	■ ■ ■	■	■ ■	□
• Low resistance to atmospheric and biological agents	■ ■	■	■ ■ ■	□
Decommissioning				
• Partial or total loss of natural resources following the impossibility to reuse, recover, recycle, or reintroduce materials to the environment.	■ ■ ■	■ ■	□	■ ■ ■
• Air, water, and soil pollution for disposal	■ ■	□	□	■
Legend: □ None; ■ Low; ■ ■ Medium; ■ ■ ■ High.				

renewable raw material but of limited availability (the plant can be decorticated only every 8–10 years). For the production of some particular products (hemp, kenaf, cellulose, flax, sheep wool), a percentage of synthetic fiber, generally polyester may be added to the main fiber in a measure of 10%–15% up to 50% for support or reinforcement. Overall, fast-growing bio-based materials, such as straw and hemp, provide the most promising opportunity to radically decrease the carbon footprint of buildings. Unlike forest products, they do not require long rotation periods, and their capacity for storing carbon increases when they are used as thick insulation for exterior walls due to the rapid CO₂ uptake in plantations (Pittau, Krause, Lumia, & Habert, 2018).

In addition to the more traditional renewable insulation materials, innovative products made with fungi roots, wood foam, seagrass, or the fibers of recycled jeans have been developed (see Table 7.7). Mushroom roots (mycelium) insulation materials are grown from agricultural and food waste, obtaining a material with good thermal performance, inherently flame retardant and stable over time that does not need chemical additives, thus containing VOC emissions (see Fig. 7.2). Wood foam is intended as a replacement of conventional petroleum-oil-based foams for thermal insulation and is manufactured by finely grinding wood with high water content, foaming the resulting fiber suspension with CO₂, and then hardening it in a drying chamber. The result is a porous insulation material with weight, compressive strength and thermal resistance values comparable to polystyrene foams, 100% renewable and held together by wood's own bond without adhesives. Seagrass insulating products are derived from naturally shored piles of *Posidonia oceanica*, which, instead of being disposed of in landfills or composted, are separated from sand and shred into fibers for insulating panels or cavity filling, obtaining a material with excellent characteristics of incombustibility, mold resistance, thermal capacity, and vapor retention (see Fig. 7.3).

TABLE 7.7 Thermal properties of unconventional bio-based insulation materials (Asdrubali, D'Alessandro, & Schiavoni, 2015).

Insulation materials	Volume mass	Thermal conductivity
	kg m ⁻³	W m ⁻¹ K ⁻¹
Bagasse	70–350	0.046–0.055
Cattail	200–400	0.043–0.060
Cellulose (recycled)	28–60	0.037–0.038
Cotton (recycled denim)	n.d.	0.036–0.038
Cotton (stalks)	150–450	0.059–0.082
Cotton (recycled)	25–45	0.039–0.044
Date palm	187–389	0.072–0.085
Durian	357–907	0.064–0.185
Mushrooms	120	0.039
Oil palm	20–120	0.055–0.091
Posidonia seaweed	65–75	0.041–0.044
Pineapple leaves	178–232	0.035–0.042
Reeds	130–190	0.045–0.056
Recycled textile (commercial)	30–80	0.036–0.042
Recycled textile fibers (polyester and polyurethane)	440	0.044
Recycled textile fibers (synthetic)	200–500	0.041–0.053
Rice	154–168	0.046–0.566
Sunflower (pitch)	36–152	0.039–0.050
Straw bale	50–150	0.038–0.067
Wood foam	40–280	0.040

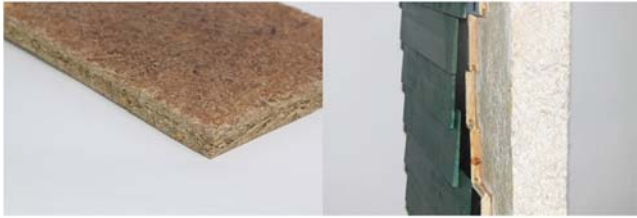


FIGURE 7.2 Mycelium insulating materials. *Courtesy of Ecovative.*



FIGURE 7.3 Algae-based insulation. *Courtesy of Neptutherm GmbH.*

Among the insulators of vegetal origin deriving from recycled raw materials or processing wastes, in addition to wood, particularly interesting are those that use textile fibers or recycled cellulose. Recycled cellulose comes from waste and by-products of paper processing as well as returned newspapers and is mainly applied in the form of flakes or wadding via blowing inside cavity walls, roofs, and attics. Cellulose is commonly added with 15% lime or verdigris to protect it from molds, rodents, and insects and improve fire behavior. Recycled textile insulation materials are also gaining interest, in particular referring to fibers of jeans recycled preconsumer (waste from the production) or post-consumer (denim insulation) (see Fig. 7.4). Regarding sheep wool, the one used in building applications comes from flocks bred for meat and milk production, not for the textile industry, and would otherwise be wasted.

The production process generally has a low or almost zero environmental impact, with the exception of those insulators requiring a heat treatment such as mineralized wood fiber and expanded cork. In particular, mineralized wood fiber panels have a significant consumption determined by the production of the Portland cement binder used to manufacture the panels that account around 50% weight (the production process requires the mixing of fir wood fibers with cement followed by a drying phase).

As far as the operating phase is concerned, possible health risks may derive from the emission of powders and fibers, or from the release of any toxic substances used for adhesives (cork, wood fiber). Furthermore, for some materials, the presence of residual insecticide or pesticide used in intensive cultivation and farming (flax, hemp, sheep's wool) or preserving treatments to protect the material during long-distance transport (coconut, jute) may be an issue. Substances contained in sheep wool fibers are instead able to absorb indoor pollutants such as formaldehyde, VOCs, nitrogen oxides (NO_x), and sulfur oxides (SO_x). This is due to the presence of keratin, a base component of the albumin protein that constitutes the wool: molecules from lateral groups of its amino acids can bond with polluting agents and degrade them into harmless substances.

Regarding the recovery or recycling of materials after the phase of disposal, this can be made problematic, if not impossible, by the presence of binders (mineralized wood fiber), additives (addition of synthetic fibers), fireproofing or antiparasitic treatments (sheep wool), or glues or adhesives used for installation (cork and wood fiber).

The search for more environmentally friendly insulation solutions also concerns PCMs, a category of innovative smart materials with the ability to store large amounts of thermal energy without increasing their own temperature due to the solid-liquid reversible phase change that takes place within them (latent heat). PCMs are finding use in thermal



FIGURE 7.4 Recycled jeans insulation. *Photo by the author.*

energy storage (TES) solutions in both building systems and, most interestingly, in the building envelope, in which they allow to greatly increase thermal inertia with low mass and thickness preventing summer overheating phenomena even in lightweight construction systems. Most used PCM in commercial products are inorganic salt hydrates, organic paraffin waxes, and organic fatty acids. Fatty acids have been recently gaining interest due to their potential lower environmental impact, higher biodegradability, recyclability, and nontoxicity. In fact, fatty acids and their derivatives (alcohols, amines, and esters) or compounds can be extracted from renewable cultures or byproducts of agriculture and livestock industries (bio-based PCMs), whereas paraffin waxes come from fossil sources and hydrated salts manufacturing requires excavated minerals and salt (Naresh, Parameshwaran, & Vinayaka Ram, 2020). In particular, bio-based PCMs can be sourced from plants (coconut oil and fat, palm oil and wax, soy oil, and wax), animals (beeswax, animal fats), sugar (polyols). Polyethylene glycol, one of the best performing PCMs (Liu et al., 2020), can also be considered Bio-based when sourced from corn starch instead of fossils.

7.4.2 Bio-bricks

Despite their consolidated and wide use in construction, traditional clay bricks have an high environmental impact throughout their life cycle, due to the nonrenewable raw materials consumption and large quantities of energy and CO₂ emissions required in manufacturing process. Following the trends of developing more sustainable building materials, alternative bricks have been devised by employing bio-based materials in substitution of clay or as additive (Harries & Sharma, 2016; Pacheco-Torgal, Lourenço, Labrincha, Kumar, & Chindaprasirt, 2015). The main applications include:

- fired clay bricks manufactured with different percentages of recycled biomass (paper pulp or agricultural wastes);
- bricks of hemp and cement;
- bio-bricks made with the cementation of sand through microbial activity, or directly manufactured from fungi mycelium (ELBMs).

Hemp core has a naturally high silica content, allowing it to perfectly bind with water and lime to manufacture non-load bearing blocks that are enjoying good diffusion on the market (see Fig. 7.5). Hemp plant is quick and easy to grow, alternates well with other cultivation species such as barley or rye, advances the quality of the soil, and does not need herbicides or pesticides. While hemp outer fibers are used in the textile industry, its inner core lends in fact itself well as an additive to lime binders to achieve building materials with good mechanical and insulation characteristics. Compared to concrete, so-called Hempcrete has about 1/20 of compressive resistance and 15% of density, with a much better thermal transmittance of 0.08 W/mk, enough to reach good thermal resistance values without requiring additional insulation layers. Its light-weight nature can also cut back the embodied energy of a building by reducing emissions related to transport and installation (Yadav & Agarwal, 2021). Finally, hempcrete is inherently fire resistant and does not need flame retardant substances, does not attract pests, and has excellent hygroscopic behavior, by combining the vapor permeability of lime with the vapor storage capacity of hemp shiv. Environmental impact is obviously extremely reduced, with each ton of grown hemp absorbing 1.7–1.9 tons of CO₂, and each ton of hempcrete absorbing an additional 249 kg of CO₂ along its 100 years life cycle.

Equally interesting is the ELBM innovative approach, which combines engineering progress with in the most advanced bio-technologies. Special biological bricks have been manufactured from a combination of corn husk and fungi mycelium, by applying the constructive process invented by New York start-up Ecovative and demonstrated with the Hi-Fi building in New York (see Fig. 7.6). Each brick organic was “grown” starting right from the living raw material supplied from the



FIGURE 7.5 Hempcrete blocks wall assembly. *Photo by the author.*



FIGURE 7.6 Hy-Fi, The Living, New York. *Courtesy of Ecovative.*

fungi mycelium and then dried with corn husks. This combination produces a material with excellent thermal performance, perfect for green architecture, VOC-free, flame-resistant, and 100% ecological (see [Fig. 7.7](#)).

Furthermore, great potential has the manufacture of blocks and bricks using a natural microbial process, due to its simplicity, low embodied energy in materials, and scalability. These ELBMs exploit microbially induced calcite



FIGURE 7.7 Mycelium brick preparation. *Courtesy of Ecovative.*

precipitation (MICP), a bio-brick manufacturing technique that effectively grows precast materials by mixing aggregates and bacteria, molding the compound into shape, and feeding it with an aqueous solution containing nutrients. Bacteria feed on the nutrients and transform them into calcium carbonate, bonding the aggregates, and hardening the brick to specification. The whole curing process is carried out at ambient temperature and is considered as a sustainable and environmentally friendly method since it does not deplete natural resources, is pollution free, and does not emit any greenhouse gases. Various MICP forms are available using different bacteria and nutrients.

A common approach uses natural soil bacteria to metabolize urea, promoting mineral precipitation. Urea is naturally present in various soils and can be even extracted from urine (Randall & Naidoo, 2018). In particular, highly urease positive bacteria *Sporosarcinapasteurii* have the ability to precipitate calcite efficiently in the presence of an urea-calcium medium, that can consist of urea, calcium chloride, as well as nutrient broth containing beef extract and peptone to enable bacteria reproduction within the brick mold (Bernardi et al., 2014). Sand bricks obtained with this method evidenced a compressive strengths that exceed 2.0 MPa (more than adobe and rammed earth bricks) making then suitable for nonload-bearing walls. Longer growth time translates to improved mechanical properties as more cement is precipitated in the compound.

However, ureolytic bacteria have only limited life in the harsh, high-pH environment of cementitious materials, whereas long-term survival opens the potential to impart sustained self-healing characteristics to bio-concrete. These alternative ELBMs can be created by inoculating sand with dissolved gelatin media and *Synechococcus*—a robust photosynthetic cyanobacterium capable of MICP—obtaining a living hydrogel that acts as a scaffolding to be strengthened through physical crosslinking during dehydration. *Synechococcus* utilizes the enzyme rubisco to convert CO_2 to sugars via photosynthesis. In low- CO_2 media, O_2 competitively binds to the enzyme active site and diminishes CO_2 carboxylation efficiency. *Synechococcus* surmounts this limitation by concentrating HCO_3^- from media to CO_2 within its cell and exporting OH^- outside of the cell, thereby increasing local pH and promoting CaCO_3 precipitation (Heveran et al., 2019). ELBM bricks obtained with this method achieved 3.60 MPa compressive strength. Structural applications can go beyond building bricks and blocks, by preparing columns and beams with inert scaffolds of sand and gelatin that bacteria can mineralize and toughen, and can be subsequently regenerated with the right environmental conditions.

Bacteria-grown cement is also employed to manufacture masonry tiles for various applications. Such is the case of bioMason, a United States-based supplier of concrete tiles for interior and exterior floor and wall installation. Produced with 85% waste aggregates and 15% bio-cement, these claim 99% less carbon footprint than other cement products on the market and comply with living building challenge standards.

7.5 Advanced building products

7.5.1 Advanced concrete

With a consumption of about $10 \text{ km}^3/\text{yr}$, concrete is the largest volume material used on earth (for comparison, the amount of fired clay, timber, and steel used in construction represent, respectively, about 2, 1.3 and 0.1 km^3) (Flatt, Roussel, & Cheeseman, 2012; Pacheco-Torgal et al., 2019).

As a result of the large volumes of concrete used, the production of portland cement, the main binder of concrete, contributes 5%–8% of global CO_2 emissions. Producing a tonne of cement today generates around 0.6 tonnes CO_2 on

average, two-thirds of which are process emissions generated from carbon released from the raw materials used. Fossil fuels—mostly coal plus some petroleum coke—account for 90% of thermal energy needs (IEA, 2021). Concrete also accounts for more than two-thirds of construction and demolition waste with only 5% currently recycled (ECORYS, 2014; UNEP United Nations Environment Programme, 2012).

To a lesser extent, the use of aggregates of natural origin and water consumption also negatively affects concrete sustainability.

Accordingly, in the last two decades, several strategies to achieve environmentally friendly concrete have been researched that can be summarized as follows (De Brito & Agrela, 2019; Nazari & Sanjayan, 2017; Pacheco-Torgal, Jalali, Labrincha, & John, 2013a; Siddique & Cachim, 2018):

- reduction of the content of portland cement in favor of blended cements, through the use of supplementary cementing materials (SCMs) that include by-products of industrial processes, such as fly ash and ground granulated blast-furnace slag (GGBFS) (de Carvalho et al., 2019), as well as bricks and concrete powder (Silva, Kim, Aguilar, & Nakamatsu, 2020);
- use of recycled materials in place of natural resources: as aggregate constitutes about 70% of concrete volume, an effective strategy is to substitute virgin materials with aggregates from demolition and excavation waste, waste glass (Stefaniuk & Sadowski, 2020), tires, and plastics, favoring those characterized by the shortest delivery distance to limit transportation emissions and those able to improve mechanical characteristics to reduce material use (Dixit, Du, & Pang, 2021);
- reuse of wash water and reduction of water withdrawals (the recycling of wash water is readily achieved in practice and is already required by law in some countries);
- improvement of concrete properties such as mechanical strength and durability, that can lead to a reduction of materials needed both in construction and in maintenance/ replacement, extending its service life (Pellegrino, Faleschini, & Meyer, 2019).

7.5.1.1 Nanocomposite concrete

Nanotechnology application to the concrete industry allows to obtain products with unprecedented performance regarding both mechanical properties and durability over time, along with improvements in the construction process (ease of mixing, rate of setting, workability etc.) and a reduction of carbon emissions of cement manufacturing (reduced kiln temperatures and durations that occur during processing) (Kaizar & Shaik, 2015; Leone, 2011; Liew, Nguyen-Tri, Nguyen, & Kakooei, 2020).

Nano-enhanced concrete products belong to the nanocomposite category, as the cement blend is directly added with various nanoparticles to enhance its properties.

Nanomaterials suitable for addition to concrete mixture include silica, titania, carbon nano tubes, graphene/graphene oxide, calcium carbonate, clay/kaolin, and nano metallic oxides like alumina, zirconia, magnesia, iron oxide, and chromium III oxide (Hanif, 2019).

Nanocomposite concrete can become impermeable through the addition of inorganic solutions that, during curing, fill its capillary voids with nanocrystals, and can cure much faster due to silicate hydrates nanoparticles that accelerate hydration process without requiring energy intensive treatments such as hot steam or hazardous additives. The inclusion of inexpensive nano-clays (montmorillonite, bentonite, kaolinite, hectorite, and halloysite) improves compressive/flexural strength and accelerates curing, with the added benefit of increased electrical resistivity and therefore decreased permeability of concrete (Jamshidi, Kurumisawa, White, Jize, & Nawa, 2019). Addition of TiO_2 nanoparticles makes concrete photocatalytic, allowing for improved durability, self-cleaning action, and even an air purifying effect, with the added benefit of improved fire behavior. Nano- TiO_2 addition was also proven effective in improving cement's capacity to absorb CO_2 from the atmosphere over time (Moro, Francioso, & Velay-Lizancos, 2021).

Regarding mechanical performance improvement, currently available ultra high-performance concrete (UHPC), added with metal and silicon oxide nanoparticles, require much less material to achieve the same structural strength compared to traditional products thus allowing for a much reduced environmental impact with 6 times reduction in raw materials, 50% reduction in GHG emission, and 40% reduction in manufacturing energy. The inclusion in the cement mix of relatively inexpensive graphene oxide results in enhanced compressive, tensile, and flexural strength as well as improved strain hardening behavior and toughness (Hanif, 2019), at the same time CNT addition is being researched and will allow a 90% reduction in material use. As a pilot project, graphene-enhanced concrete—"Concretene"—was used to pour a concrete floor slab for the new Southern Quarter gym near Stonehenge in England: scientists at the University of Manchester and construction firm Nationwide Engineering added tiny amounts of graphene to water and

cement, where it both acted as a mechanical support and offered an extra catalyst surface for the chemical reactions that turn the mix into the concrete paste, resulting in improved bonding at a microscopic scale and overall 30% increase in mechanical resistance ([Greener AND cheaper: Graphene@Manchester solves concrete's big problem](#)).

Lastly, the incorporation into the cement mix of nanocarbon black in proportion as low as 4% can impart remarkable electric conductivity to concrete, therefore the possibility to exploit building and infrastructure mass for joule heating. A voltage as small as five volts was enough to boost the surface temperature of the concrete samples to about 41°C, with potential application both outdoors, for de-icing surfaces such as airport runways, and indoors for radiative heating ([Soliman, Chanut, Deman, Lallas, & Ulm](#)).

7.5.1.2 Fiber-reinforced concrete

Concrete strength and durability performance can also be improved by mixing it with fibrous additives, with the primary aim to bridge across the matrix cracks that inherently develop as concrete is stressed, and thus to provide post-cracking ductility and improve resilience, as well as improving durability over time as cracks constitute a main ingress for water or other corrosion agents.

Most used fibers used in concrete reinforcement are made of steel, glass, polypropylene-polyethylene, carbon, or a combination of two or more, with dimensions of several centimeters in length and a fraction of millimeter in diameter (microfibers). With the scope of a more sustainable concrete industry, vegetable fibers such as cellulose from wood, wheat, rice husks, or bagasse, have recently gained attention as cement additives ([Benaïmeche, Seghir, Sadowski, & Mellas, 2020](#); [Rodier, Correia, & Savastano, 2020](#)). In fact, cellulose allows an effective hybrid reinforcement of cement in both the nano and micrometric scales, combining the mechanical anchoring of the nanofibrillated cellulose with the matrix and the higher length of the cellulosic pulp ([Correia, Santos, Tonoli, & Savastano, 2020](#)). Environmental concerns are also fostering recycled fibers from waste processing that include PET plastic and glass from packaging, rubber and steel from scrap tires, pre- and post-consumer textiles ([Merli, Preziosi, & Acampora, 2020](#)).

Fibers are added to the cement mix in volume fractions commonly below 1% and require some attention as they tend to decrease concrete workability and to clump nonhomogeneously. Compared to plain concrete mixes, fiber-reinforced concrete evidences improved toughness, that is, the ability to maintain its load capability even when cracks develop in its matrix, better impact resistance and reduced cracking phenomena due both to drying and plastic shrinkage.

In the last years, more sophisticated applications of fiber reinforcement have been developed, with mixes that carefully combine larger fibrous content (up to 2.5% Vol), smaller or absent coarse aggregates, and low water to binder ratios. These high-performance materials are characterized by very high strength values (over 180 MPa compressive strength, more than 60 MPa flexural) and excellent impermeability and durability over time. In view of their high cost and tight quality control in production, placement, and curing, these products are mainly used in niche applications such as structural rehabilitation of bridges, beams, or columns or specialized precast elements like tunnel sections ([Plizzari & Mindess, 2019](#)).

7.5.1.3 Self-healing concrete

As previously noted, the improvement of concrete durability is a key to reducing its environmental impact, ensuring longer lasting concrete structures which require fewer maintenance interventions. This is particularly relevant for concrete infrastructures such as bridges, viaducts, and tunnels, especially in demanding environments such as those characterized by high saline or acid concentrations, as their maintenance is costly in terms of manpower and materials and can lead to dramatic consequences if overlooked. In particular, concrete inherently tends to develop little cracks over time, which hinder its resistance to water, freeze-thaw cycles and allow moisture and oxygen to reach the steel reinforcement inside.

In this picture, concrete mixes that are able to cope with cracking autonomously without any external intervention have been the subject of vast research and development ([Jawaid, Shiju, Raveendran, & Asiri, 2019](#); [Pacheco-Torgal et al., 2018](#); [Wypych, 2017](#)).

These self-healing concretes are entering the market as additives or mixes, with the involvement of manufacturers such as Sika, Buzzi Unicem, BASF, and Basilisk AG.

The main method to impart self-healing capacity to concrete is the mix integration of chemical reagents, either mineral or synthetic, or bacteria, with the aim to precipitate or produce substances able to fill the cracks that develop upon loads, commonly calcium carbonate ([Wang et al., 2019](#)).

Concerning mineral reagents, suitable substances include silicon oxides such as sodium silicate, colloidal silica and ethyl silicate, which react with the portlandite present in cement based matrices to form a surplus of calcium silicate hydrates, the main constituent of the cement matrix itself. In liquid form, these can be encapsulated in glass vials that rupture upon cement cracking freeing the healing agent (Kanellopoulos, Qureshi, & Al-Tabbaa, 2015). Another solution is magnesium oxide, a powder that hydrates in contact with water to produce brucite, an expansive crystalline phase, which further reacts with water and carbon dioxide and precipitates magnesium carbonate to fill the cement crack. Magnesium oxide, however, requires separate capsules with water to break in order to trigger the chemical reaction, a drawback that tends to jeopardize the good dispersion of the healing agent within the crack.

Bio-based self-healing concrete exploits biological functions instead of chemistry, embedding in the cement mixture bacteria spores able to activate when needed and repair cracks and holes that may develop over time (see Fig. 7.8). These bacteria eat nutrients provided in the concrete mixture, commonly calcium lactate, combining it with oxygen and carbon dioxide to form calcium carbonate (Jonkers, Mors, Sierra-Beltran, & Wiktor, 2016). Suitable bacteria strains should be able to resist in the extremely basic concrete environment and to lay dormant for years, and include bacillus subtilis, bacillus pasteurii, bacillus pseudofirmus, bacillus sphaericus. An additional benefit is their ability to consume oxygen and therefore minimize steel-reinforcing bars corrosion. Bacteria spores are introduced in the concrete matrix via a carrier compound to increase their survivability over time, and thus the reliability of the healing process that is directly proportional to the bacterial concentration (Rong et al., 2020). Viable carriers include lightweight aggregates, hydrogel, polyurethane foam, microcapsules or graphene nano-platelets, with varying effects on concrete strength (Khaliq and Ehsan, 2016). Spores lay inactive until concrete cracks expose them to penetrating water. Bacteria colonies rapidly develop and transform water and calcium lactate in calcium carbonate, usually repairing the concrete matrix within two weeks (Souradeep et al., 2017).

Another approach to self-healing provides for the inclusion in concrete of bars of SMA or tendons of SMP, able to close tensile cracks by contracting the concrete when stimulated by external heat or electricity (Nassiri-monfared, Baghani, Zakerzadeh, & Fahimi, 2018; Teall et al., 2018).

7.5.1.4 Sensors integrated concrete

Sensors and actuators are more and more used in buildings to monitor and control the environment conditions and the materials/structure performance. In the last years, advantages in the fields of nanotechnologies and smart materials have reduced their dimension down to the nanoscale, allowing to embed them into any structure and building element during the construction process itself.

One of the most promising applications is their integration within structural building materials such as steel and concrete in particular, where they can perform multiple functions (Atwa et al., 2015). The integration of sensors at the stage of concrete casting allows to accurately monitor hydration and curing steps of the cement mixture from inside the material, enabling their correction with additives where necessary or the accurate prediction of the future performance, as well as the achievement of needed strength thresholds to better plan the subsequent processing and thus minimize downtime on site. Once full maturity is reached, sensors can be further used for the continuous monitoring of the structural elements, registering shocks, impacts, and loads and allowing the scheduling of targeted maintenance and the safe prediction of eventual collapse hazards.



FIGURE 7.8 Bio-based self-healing concrete. Credit: Hendrik Jonkers.

Most used structural sensors consist of optical fibers, for instance, FBG and FOPS, embedded in concrete to instantly detect cracks or deformations tracking the light path variations within the fiber itself.

Nano-electrical and mechanical systems (NEMS) promise even smaller size and better integration with the concrete mix. These sensors usually take advantage of smart nanomaterials that display properties such as piezoelectricity, that is, the ability to convert strain in electrical signals, or improved electrical conductivity. As nanocomposite concrete is subjected to force and deformation, the contact between the fillers and the matrix is affected, thereby affecting the electrical resistivity of the concrete structural element. This way, nanocomposites can be used to sense such structural parameters and environmental parameters as stress (or force), strain (or deformation), crack, damage, temperature, and humidity (Zheng et al., 2019).

Although plain cement paste already exhibits piezoelectric behavior, its capacity is not enough for energy harvesting for self-powered sensing, making it necessary to optimize the piezoelectricity. Additives to enhance the potential of cement paste include carbon fibers (above 1% of the mass of cement), steel fibers, and lead zirconate titanate with polyvinylidene fluoride (PVDF) (Chen et al., 2019). Particularly interesting is the inclusion in the concrete paste of multi-walled CNT, which allows to turn the whole concrete mass into a conductive, piezoelectric sensor which electrical signals can be picked during vibrational testing to assess its structural integrity (Rao and Sasmal, 2020).

7.5.1.5 3D printable concrete

The rise of AM techniques, which in the last years have revolutionized the rapid prototyping processes and have found several industrial applications, has opened up the possibility of obtaining objects of unprecedented geometrical complexity and mechanical properties in a cost- and time-effective way. Recently, 3D printing has been extended to the building sector, with more and more examples of off-site prefabrication of building elements and, more interestingly, on site fabrication of entire buildings or infrastructures, with numerous benefits (WinSun China, Dubai 2016; Cobod Copenhagen, 2017; Wasp Italy, 2018; Apis Core Dubai, 2019; Cy Be Construction Saudi Arabia, 2019). In addition to allowing production of structures without the formwork (that alone accounts to 35%–54% of total costs of raising concrete structures), 3D printing also reduces total production time, costs, and labor. The technology also increases the safety of workers on the construction site, produces less waste, and uses raw materials with low embodied energy (Hoffmann et al., 2020; Ma, Wang, & Ju, 2018).

3D printing is compatible with several materials, from polymers and plastics to metals, but for building applications the most common printing material by far is concrete, due to its workability in the fresh state, its mechanical resistance once set, and its affordable price (Sanjayan et al., 2019).

Adapting concrete to 3D printing fabrication, however, requires a deep rethinking of all its characteristics, both in the fresh and set stages.

In conventional concrete construction, the fresh material is poured into a formwork under the sole effect of gravity, with the rigidity of the formwork equilibrating gravity-induced stresses. The formwork therefore fully dictates the shape of the final concrete element and also plays an early-age protecting role against drying before it is stripped or removed, commonly 24 h after casting and/or once the material has set (Roussel, 2018).

Conversely, in 3D printed concrete structures, most essential steps are conveying mixed materials to the nozzle via a delivery system, then depositing this paste to build the solid object in a layer-by-layer manner, without any formwork (see Figs. 7.9 and 7.10). In the conveying step, the materials are required to have good pumpability, which indicates



FIGURE 7.9 3D printed concrete nozzle. *Courtesy of ICON, photo by Regan Morton Photography.*



FIGURE 7.10 3D printed concrete walls. *Courtesy of COBOD.*



FIGURE 7.11 GAIA 3D printed house with soil, limestone, and agricultural waste. *Courtesy of WASP.*

how easily material can be conveyed; whereas in the deposition step, the materials are required to have good buildability, which in turn indicates how stably the materials can be stacked. Both pumpability and buildability are closely related to the rheology performance of materials, namely, static/dynamic yield stress and plastic viscosity. In particular, good pumpability requires low plastic viscosity, and buildability needs high yield stresses (Weng et al., 2018).

While designing concrete mixtures for 3D printing, therefore, care should be taken that the mortar meets the performance assumptions in both fresh and hardened stages, considering the necessity of extrusion, the influence on workability, and open time before concrete sets, as well as the compressive and bending strength of hardened cement. In particular, main properties to consider for 3D printed concrete are extrudability, pumpability, workability, printed shape maintenance, early robustness, proper binding time, possibility to build another layer, finished element durability (Pacewicz et al., 2018).

All these properties are determined by the mix design of cementitious material, that is, tuning the type and volume fraction, respectively, of the binder (mainly portland cement or limestone), aggregates (sand in various gradation, industrial byproducts such as fly ash, recycled debris, soil taken from the site, up to recovered agricultural waste) and additives that compose the concrete mixture (see Fig. 7.11).

In particular, it has been observed that a higher cement fraction increases the concrete static yield stress, but conversely a lower sand fraction has a negative effect on dynamic yield stress (Liu et al., 2019). Concerning additives, they can be used to provide required open time and to obtain a constant workability of the material during production. Polycarboxylate-based superplasticizers can be used to increase the workability and material strength by reducing water content, along with hydroxypropyl methyl cellulose. In order to increase open time, retarders based on amino-tris (methylene phosphonic acid), citric acid, and formaldehyde can be added. Concrete setting can be hastened with accelerators based on sulfones, aluminum salts, and diethanolamine. Lithium carbonate can also be adopted to promote the cement hydration and shorten the setting time (Chen et al., 2018).

Experimental concretes for 3D printing also contained polypropylene microfibers with a length of 12 mm and a diameter of 0.18 mm, which were designed to reduce shrinkage and deformation in the plastic state (Le et al., 2012).

As explained above, a most delicate aspect of 3D concrete printing is balancing workability before and during the extrusion stage with a rapid setting once deposited so that each layer can support those above it and allow self-sustainability for higher construction. With this aim, a novel solution is to control rheology and stiffening of the fresh

cementitious material actively, as currently studied in the ERC Advanced Grant “SmartCast” project by adding magnetic particles in the concrete paste and controlling those with magnetic fields. These responsive ingredients contribute to the paste stiffness by aligning themselves with the magnetic field lines, forming a more rigid or entangled structure. In case of magnetic particles, a rigid network structure is expected to contribute to the shear resistance of the paste, making this particle-field combination a prime method to arrest paste flow as desired (De Schutter et al., 2018).

7.5.2 Engineered mass timber structures

The objective of reducing energy consumption and carbon dioxide emissions associated with the production and installation phases of building components, steel and cement in particular, has led in the last twenty years to important advancements in the development of engineered massive timber products suitable for structural applications.

The new types of engineered wood products (EWP), obtained through industrial processes aimed at improving their performance in terms of mechanical strength, durability, and environmental sustainability, allow today to use wood without dimensional limitations and with good quality uniformity and performance, helping to increase the competitiveness of timber structures and to open new perspectives to designers by providing a valid alternative both to steel and to concrete, even for multistory buildings. Between 2008 and 2020, the maximum height of modern buildings using engineered timber increased from the nine-story, 29 m high Stadhaus building in London to the 18 story, 85.4-meter-high Mjøstårnet building by Voll Arkitekter in Brumunddal, Norway, verified as the world’s tallest timber building by the Council on Tall Buildings and Urban Habitat. Over the same period, in Europe cross-laminated timber (CLT), laminated veneer lumber (LVL), glued laminated wood (glulam), and wood fiber insulation boards experienced annual growth rates between 2.5% and 15% (Winchester and Reilly, 2020).

Rising use of EWPs is driven by the adoption of new regulations and by their technical capabilities (including fire and seismic performances), cost-competitiveness, and lower environmental impact compared to mineral-based building materials. Regarding the latter, according to the Canadian Wood Council, “compared to wood design, the steel and concrete designs embody 26% and 57% more energy, emit 34% and 81% more greenhouse gases, release 24% and 47% more pollutants into the air, discharge 400% and 350% more water pollution, produce 8% and 23% more solid waste, and use 11% and 81% more resources (from a weighted resource use perspective)” (Canadian Wood Council, 2013).

Furthermore, wood resources supply methods, following the principles of sustainable management of forests of programs such as Forest Stewardship Council—FSC, Program for the Endorsement of Forest Certification schemes—PEFC, or the Sustainable Forest Initiative—SFI, ensure the full renewability of wood as raw material. Moreover, wood provides a good indoor climate, perfect acoustics, helps regulating the inside temperature, and can be exposed without being covered with plaster or other costly finishing materials.

In addition to these advantages, EWPs are also at the forefront of the innovative construction techniques of industry 4.0, perfectly adapting to the new possibilities offered by the digitalization and prefabrication of the components, thus increasing the efficiency of the construction process, with a greater return on investment and reducing waste both on- and off-site. Engineered wood structures are made on the basis of precise executive drawings and each component is cut to size with numerical control machines, thus ensuring maximum precision, and at the same time it is possible to make changes on site in a very short time compared to traditional materials (cuts, adaptations, bevels).

The elements arrive on site ready for installation and are dry assembled; given their lightness, it is possible to preassemble entire frames or partitions on the ground before lifting them in place. This aspect has direct effects on production times and costs: to install wooden components, machines with a lower capacity are sufficient, or elements preassembled to an higher degree can be installed, thus ensuring considerable time savings. Prefabrication allows total control over the dimensional characteristics of the elements, therefore ensuring greater control over their quality. This implies the reduction of waste produced by work on-site, with savings in terms of both raw materials and disposal costs. In addition, at the end of the building’s life cycle, the wooden structural elements can be reused as such, or as fuel to produce electricity in cogeneration plants.

EWPs are typically fabricated from the adhesive bonding of wood chips, flakes, veneer or sawn timber sections, and/or the mechanical fastening of timber sections to form larger sections, beams, panels, or other structural elements. Families of these materials include CLT made from solid wood layers set at 90° orientations, laminated strand lumber (LSL) made from a matrix of thin chips, and LVL made from thin laminations of wood, similar to plywood but much larger in scale. Beam and column products come as structural I-beams, parallel strand lumber (PSL), and glued laminated timber (glulam) (see Table 7.8).

TABLE 7.8 Engineered wood product for structural uses.

Engineered wood product	Composition	Resistance	Uses
Cross laminated timber (CLT)	Boards	Bidirectional	Slabs, walls
Glue laminated timber (Glulam)	Boards	Monodirectional	Beams, columns
Laminated veneer lumber (LVL)	Veneers	Monodirectional	Beams, columns
Laminated strand lumber (LSL)	Strands	Monodirectional / Bidirectional	Beams, columns / panels
Parallel strand lumber (PSL)	Veneers	Monodirectional	Beams, columns

The benefits of these wood composites include higher strength-to-weight ratios, enhanced dimensional stability, reduced effect of natural defects (e.g., knots), more homogenous mechanical properties, greater durability, and therefore the possibility to form larger and more complex structural sections.

Compared to sawn timber, EWP's exhibit an ability to be reinforced by other materials (limited quantities of steel and exotic fibers including carbon, aramid and glass) to gain even higher efficiency, along with the capacity to use also low-grade wood fiber where lower stress levels will exist in service.

7.5.2.1 Cross-laminated timber

Among the different engineered timber structural systems on the market, particular interest and worldwide diffusion has had since the 2000s the construction system with load-bearing panels in cross-laminated wood, called CLT system, by virtue of the numerous advantages that this system offers in terms of resistance, flexibility, energy efficiency, economy, durability, comfort, and environmental sustainability (Harte, 2017).

CLT is increasingly being used by architects globally, with CF Møller Architects recently completing Sweden's tallest timber building, Voll Arkitekter building the world's tallest timber tower in Norway and 3XN designing the "tallest timber office building" in North America.

CLT panels are made by assembling finger jointed solid wood boards which form single-layer flat elements, crossed and tied together with glues. The number of overlapping layers that make up the single panel varies from 3 to 9 (see Fig. 7.12).

The panels' density varies between 450 and 500 kg/m³, and they can be up to 24 meters long, up to 4 meters wide and 6 to 37 cm thick depending on the number of crossed layers that make up the panel. For needs related essentially to transport, the panels normally do not exceed the dimensions of 4x16 meters. Most used arboreal essences are fir, pine, douglas fir, and larch.

CLT panels have a thermal conductivity λ equal to 0.13 W/mK which allows to obtain low values of thermal transmittance U between 1.3 (thickness of the panel 10 cm) and 0.35 (thickness of the panel 37 cm) W/m²K.

The CLT system allows the construction of structures extremely solid and effective against earthquakes, while providing a building envelope with good energy and acoustic performance. Its flexibility of use also guarantees a great possibility of modularity and, thanks to the reduced structural thicknesses, a strong benefit in terms of net usable surface. The CLT panel is also excellent as a wall, attic, and roofing element in residential buildings, including multistorey buildings, in public buildings, including schools, and in commercial, office, and logistics buildings with high modularity (see Fig. 7.13)

The panels are joined together by means of connections to protect overturning and sliding. In particular, there are wall-foundation, wall-floor, floor-floor, and wall-wall connections. The connection systems between the panels are entirely made of steel and include wood screws, retractable brackets, hold-downs (protection against tipping), angular brackets (sliding protection), and perforated belts.

The joints between the panels can be of three types: head-head joint, LVL joint, and half-wood joint. The LVL joint requires the realization of a milling in the panels for the housing of the LVL board, which generally runs parallel to the direction of the fiber of the external layers of the panel. Internal single/double joints require more accurate profiling and on-site fitting but have the advantage of providing a double shear connection and are more resistant to normal and out-of-plane loads. Lastly, in the half-wood joint, the recess typically extends for a depth equal to half the thickness of the panel and for a variable width (see Fig. 7.14).

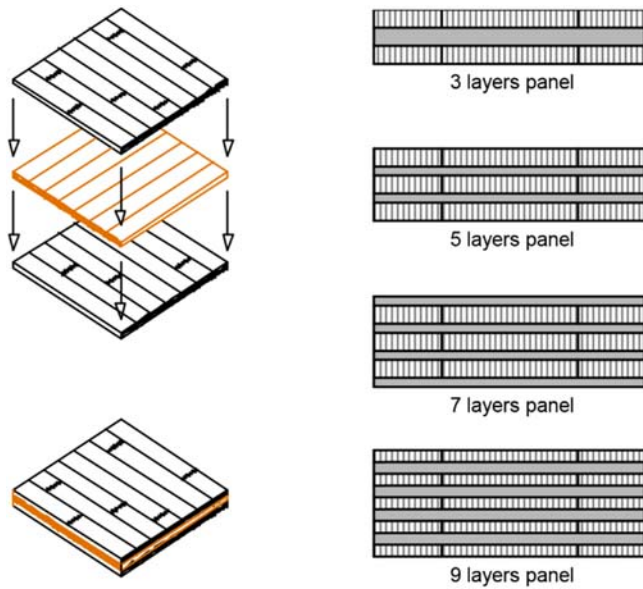


FIGURE 7.12 CLT panel assembly.



FIGURE 7.13 Assembly of a CLT building structure. Courtesy of Edward Williams Architects, Canducci Group, Agnese Sanvito photographer.

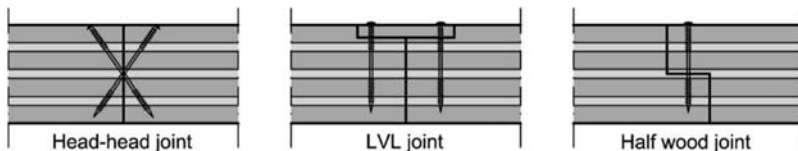


FIGURE 7.14 CLT joint types.

To guarantee the tightness between the joints, it is recommended to use compressible sheaths, sealing foams, adhesive tapes, or rubber seals respecting the application indications provided by the manufacturers. In order to reduce the transmission of noise between adjacent habitation units and between adjoined walls, it is possible to insert protection strips and gaskets between the panels.

Particular attention must be paid to the ground connection in order to protect the wood from humidity. To this end, the wall panel is normally laid with a waterproof strip on curbs made of particularly water-resistant wood (larch), metal or concrete, and fixed to the ground by angles and hold-downs.

Thanks to the high degree of prefabrication, the CLT system allows rapid and highly precise assembly, reducing unexpected events. The high engineering of the production process, which uses robotic machines and CAD/CAM tools, allows to manufacture structural elements already equipped with openings and provided with housings for the electrical and water system networks. BIM integration also allows to simulate assembly operations and examine supply of materials, reducing waste and scraps to a minimum and acting in maximum safety during the construction phase (see Fig. 7.15).

The possibility of drawing up an assembly manual, together with the use of dry metal connection systems, also makes the CLT structural construction simple and practicable by any worker, even nonspecialized, in fact opening commercial routes also in countries where the construction techniques in wood are not consolidated.

Structural performance of CLT can be further improved by reinforcing the timber panels with tensioned cables, translating to engineered wood the consolidated techniques developed for prestressed concrete elements (Pampanin et al., 2010). Dubbed Pres-Lam (pres laminated timber), and also compatible with glulam and LVL construction elements, this technology requires housings milled directly in the timber mass in which bars or cables are laid nonadherently and blocked at both ends via steel slabs or anchors, to allow post-tensioning of the whole element to a desired degree (see Fig. 7.14). Load bearing of reinforced elements is greatly increased, allowing to build structures with greater spans and heights. CLT already good structural behavior in case of earthquake is also further improved by Pres-Lam integration. In fact, when subjected to seismic stress, conventional CLT structures redirect most of the force to the rigid steel connectors (screws and brackets) which may undergo plastic deformation and, in most cases, need replacement or even to take down the entire building that is not safe or functional anymore. Pres-Lam instead replaces rigid connectors with tensioned cables to hold the structure together. These allow a degree of freedom between wood elements, permitting the whole structure to oscillate during the seismic event with a rocking movement, dissipating the earthquake energy elastically and fully returning to the original state without any permanent plastic deformation. External ductile elements can be inserted between cables to take the blunt of the dissipation stress, providing a visual check of the structure integrity as well as being easy to replace, if necessary, after the earthquake.



FIGURE 7.15 Prefabricated CLT panels. *Photo by the author.*

Another promising development of CLT is constituted by dowel laminated timber (DLT) that aims to address the issues related to the adhesives used in CLT manufacturing process to join the different wood planks, which affect their sustainability, recyclability, and broader environmental impact. In particular, adhesives such as urea-formaldehyde (UF) are harmful to the environment due to the emission of toxic gases like formaldehyde and VOCs during use, under high-temperature conditions and changes in relative humidity. Although environmentally friendly bio-based adhesives have been developed, synthetic petroleum-based adhesives still have wider uptake due to their lower cost and better properties. Also known as “brettstapel” or “dowellam,” DLT wood panels are manufactured from softwood planks laminated in the longitudinal, transverse, and diagonal directions and connected by hardwood dowels, without any use of adhesives or metal fasteners such as nails or screws, with the added benefit of greatly improved recyclability, as well as allowing some degree of site fabrication. Conventionally, DLTs manufacturing employs dowels made of hard wood (beech, yellow birch, sugar maple) at 8% moisture content which are driven into the planks. With the softwood planks at 12%–15% moisture content, the hardwood dowel swells to find equilibrium, fixing the panels tight without the need for glue (Ramage et al., 2017). Laminated timber planks can also be fastened with hardwood dowels via high-speed rotational welding, which exploits the friction between the dowel and lamellas to increase the temperature, thereby softening the lignin and forming a bond between dowel and planks. Finally, dowels can be joined to the wood planks via epoxy adhesives, in quantity substantially smaller compared with CLT or glued-laminated beams (Sotayo et al., 2020).

7.5.2.2 Engineered structural bamboo

A promising alternative to the use of wood as structural construction material is today represented by engineered bamboo products.

Bamboo is a fast-growing, rapidly renewable resource with mechanical properties like those of timber which presents, as a construction material, many advantages in terms of low cost, ease of acquisition, and versatility.

Native to all continents except Europe and Antarctica, bamboo is a giant grass from subfamily bambusoideae and family poaceae or gramineae, with one of the faster grows on earth: it can reach the full height of 15–30 m within a period of 2–4 months with a daily growth rate up to 100 cm (David et al., 2020).

Among more than 1250 bamboo species worldwide, fewer than 100 have potential for structural use, commonly *guadua angustifolia* (the most valuable commercial species in South America), *dendrocalamus asper*, *phyllostachys edulis* (moso; the most valuable commercial species in China), and *bambusa blumeana* (David et al., 2020).

Unlike trees, bamboos only exhibit primary growth and not secondary growth maintaining their diameter throughout their life and only growing vertically, not broadening, over the years (see Fig. 7.16). Bamboo grows as a system of roots (technically, rhizomes) that produce culms having longitudinal fibers aligned within a lignin matrix, divided by nodes (solid diaphragms) along the culm length. The thickness of the culm wall tapers from the base of the culm to the top.



FIGURE 7.16 Bamboo trunks. Photo by the author.

As a functionally graded material, the bamboo fibers also vary within the culm wall decreasing in density from the exterior to the interior.

Regular extraction of some of the mature culms does not affect the health of the overall root network. Although bamboo culms can reach full height in as little as 3 months, a period of maturation from 3 to 6 years is required before they have optimal strength for structural applications (David et al., 2020).

During its growth, bamboo can absorb even more CO₂ than trees. Based on a study conducted in China, the annual carbon fixation of bamboo forest is 5.1 t/ha yr, which is 1.46 times that of Chinese fir at the fast-growing stage and 1.33 times that of tropical mountain rain forest (Sun et al., 2020).

Physical and mechanical properties of Bamboo are generally better than conventional timber species. Compressive strength of bamboo is two times higher than concrete, and tensile strength is close to steel. Compared to structural wood, bamboo has higher fiber shear stress, allows wider spans, and can be curved without breaking (Sun et al., 2020).

However, the native geometrical shape of bamboo culms and its anisotropy makes difficult to use it in modern construction as it is. Conversely, engineered bamboo products take advantage of its excellent material properties, mitigating variability in material properties while providing regular shapes, more attractive to the construction industry.

Using industrialized manufacturing processes, several different types of bamboo composite materials, or engineered bamboo, have emerged in recent decades for replacing wood in structural applications. They include laminated bamboo lumber (LBL), glue laminated bamboo (glulam) and, more recently, cross-laminated bamboo (see Table 7.9).

Engineered bamboo products are mainly manufactured in regions where bamboo is a locally available natural resource, including South America, Africa, and Southeast Asia. China is currently the world's largest exporter of engineered bamboo, accounting for over half of the global trade (David et al., 2020). The manufacturing process varies according to the specific engineered bamboo, but commonly includes splitting, gluing and pressing, as well as postprocessing. In the splitting step, bamboo culms are split to half-split culms, strands, and strips. In the gluing and pressing step, these randomly mixed bamboo strands or strips are glued using resin matrix, and pressed into sheet, lumber, and other engineered bamboo products. The longitudinal fibers are maintained and oriented along the same direction, preserving the inherent strength of raw bamboo. Finally, a postprocessing step including heating or cutting is required to form an engineered bamboo product with a regular shape and more stable properties.

Among engineered bamboo products, particularly interesting is “glue laminated bamboo” with a trademark of glulam (referring to the concept of glulam or glued laminated wood) that can be cost-effectively used as structural elements (Xiao, 2020).

The structural glulam elements are made by laminating glulam sheets, which are typically 20–40 mm thick, produced by using a modified bamboo veneers (plybamboo) production process. The production of glulam has six steps: raw bamboo selection; splitting bamboo strips; netting bamboo curtains or mats; gluing with adhesives; hot-pressing; postprocessing (Sharma & Van der Vegte, 2020; Xiao, 2020).

Within the process, all steps but the last are aimed to produce standard glulam sheets with dimensions of 2440-mm long, 1220 mm wide, and 30 mm thick. Based on the design of the specific structure, the glulam sheets are shaped and laminated to form the final structural components. Typical glulam structural components use sheets with bamboo strips arranged with 80% in the longitudinal direction and 20% in the transverse direction, referred to as 4:1 sheets. There are usually 15 or fewer layers of bamboo curtains, each having a thickness of about 2 mm.

Overall, the ignition temperatures, the effective thermal inertia, and the thermal response parameter for laminated bamboo present similar values when compared to some timber species, especially softwoods (Chen et al., 2019).

Another interesting engineered bamboo product are the cross-laminated *Guadua*-bamboo (G-XLam) panels developed and tested at the University of Bath (UK) with the support of British firm Amphibia BASE, that show a twofold increase in density and modulus of elasticity when compared to analogous cross laminated (CLT) panels. The thickness of G-XLam panels is almost a fifth of CLT panels with the same number of layers. Although a desirable feature in stiffness driven design, this implies a high slenderness ratio, which presents a structural challenge in overcoming buckling. Nevertheless, potential engineering applications for G-XLam panels include sandwich panels and stressed skin structures (e.g., monocoques, where thin but very stiff layers are separated by a core or internal structure that increases the second moment of area and reduces buckling).

Notwithstanding its improved properties in engineered products, natural bamboo has recently gained wide attention as a potential reinforcement material for concrete, replacing conventional steel rebars in underdeveloped regions where those are not affordable by the communities or difficult to source, in view of its low cost and environmental impact, good flexural strength, and easy availability in stems several meters long (Kaiser et al., 2020). Experimental testing showed performance shy of conventional steel/concrete beams with the same geometric characteristics, but nevertheless suitable for light or temporary constructions and increasable by improving the bamboo/concrete bonding through wiring

TABLE 7.9 Mechanical properties of main engineered wood and engineered bamboo products (Sun et al., 2020).

Type	Density	Parallel compressive strength	Transverse compressive strength	Parallel tensile strength	Transverse tensile strength	Parallel shear	Transverse shear	Flexural strength	Elastic modulus
	kg/m ³	Mpa	Mpa	Mpa	Mpa	Mpa	Mpa	Mpa	Mpa
Glulam	484.00	26.100	2.60	53.00	2.10	6.20	-	42.93	12200.00
Reinforced glulam	503.60	-	-	-	-	-	-	48.45	12440.00
CLT	492.00	18.30	14.40	-	-	-	1.63	22.42	11670.00
Laminated bamboo lumber	646.00	77.00	22.00	90.00	2.00	16.00	-	80.00	12000.00
Glubam	890.00	51.00	26.50	82.00	-	4.60	16.00	99.00	10400.00

or corrugating the strips. Particular care should be taken in ensuring bamboo does not absorb water from the cement mixture, which would impede curing in the areas around the reinforcing strips and, worse, cause bamboo expansion and radial cracking in the concrete. This can be addressed by heat treating the bamboo or applying oil or bitumen-based paints (Kathiravan et al., 2021).

In any case, the use of bamboo as a construction material must go through a preliminary preservation process, because it is inherently vulnerable to termites and fungal attack. In construction, bamboo is generally preserved using borax boric acid solutions through several techniques, such as immersion, gravitational, or vertical soak diffusion, and injection using compressor machines. Borax boric acid has proven effective and able to extend the life span of bamboo (Nurdiah, 2016). However, the use of chemicals in the preservation process arises concerns about the impact of the waste water to the environment. Therefore, several studies of bamboo preservation using organic ingredients have been conducted in an attempt to find the more environmental friendly preservation method.

7.5.3 High-performance insulators

The goal to achieve buildings with very high energy performance, characterized by a very low or almost zero annual energy requirement, has made it essential to provide, with specific insulation materials, an adequate thermal insulation of the opaque closures of new and existing buildings in order to reduce heat losses in winter and heat gains in summer (Casini, 2020a). However, as energy-efficiency standards for buildings become more and more stringent, using a traditional insulation material often means having to accept increasingly thick layers of insulation in walls, floors, and roofs. In renovation projects, provided it is possible to increase insulation thickness at all, significant esthetic and functional compromises are often required to fit more insulation on the inside or outside of the building envelope (Casini, 2016a).

It is therefore evident that traditional materials, products, and technologies are often not adequate to meet this challenge of upgrading the energy efficiency of buildings. Instead, what is indeed necessary are advanced solutions able to combine the energy performance with the building architectural quality and the highest livability, ensuring the achievement of the optimal cost–effect ratio.

Thanks to the huge progress in the field of materials science and nanosciences, innovative insulation products, that can offer high thermal insulation and thermal capacity performance with very low thickness, are making it possible to accept the challenge of energy efficiency of buildings, allowing to take effective action, with more than satisfactory results, even in renovation of historical buildings subjected to architectural restrictions.

In particular, recent advancement in the development of insulation and smart materials has allowed to obtain a new class of super insulating materials (SIMs) with a thermal conductivity below 0.02 W/mK that allow a reduction of the insulation thickness by as much as a factor of five, and of PCMs products to be used as components in low inertia building systems such as lightweight opaque closures and interior partitions or translucent closures to considerably increase their thermal capacity (building integrated thermal storage systems).

7.5.3.1 Super insulation materials

Recent advancements in the development of insulation materials have allowed to obtain high-performance thermal insulators (SIMs) with a thermal conductivity below 0.02 W/mK, compared to an average value of conventional insulating materials comprised in the range of 0.025–0.040 W/mK (see Table 7.10).

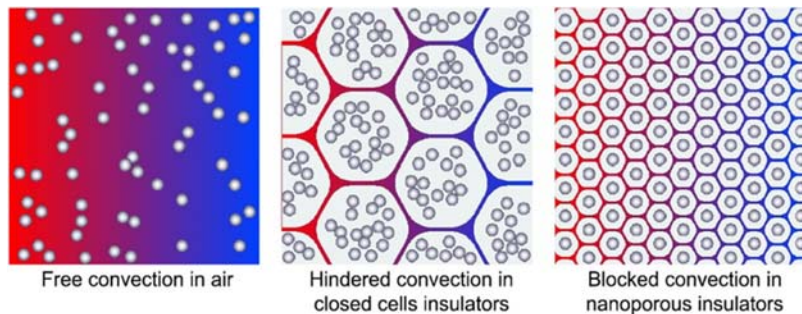
Such performance is achieved thanks to the higher rarefaction of air inside the insulation materials either due to nanoporous solid structures (nano-porous insulation materials), application of a partial vacuum (vacuum insulating panels), or by a combination of both methods (VIPs with nanoporous core). In nanoporous materials, high porosity reduces heat conduction through the solid part, while the small size of the pores reduces the radiation and the conduction in the gas. Reducing the pore size to nanoscale level increases in fact the collisions between the gas molecules and the pore walls leading to suppressed gas conduction (Knudsen effect) (see Fig. 7.17).

Conduction in the gas will also drop with any decreases of pressure that can be obtained. Ideally, a vacuum inside the pores produces the best insulating properties. Practically, the smaller the pores become, the less vacuum needs to be achieved for the same insulating properties. Due to the low thermal conductivity of nano-porous materials, it is possible to obtain high thermal resistance values of building envelope with extremely thin insulating layers making these products particularly suitable for energy retrofit of existing buildings.

Nano-porous insulation materials currently available on the market, also defined nano-insulation materials due to the nano dimensions of their porous structure, include fiber mats additivated with silica aerogel (FRABs); VIPs with

TABLE 7.10 Thermal conductivity of main insulation materials.

Insulation material	Thermal conductivity	Thickness (mm) for achieving
	λ mW/mK	$U = 0.25$ W/m ² K
Super insulation materials (SIMs)		
Vacuum nanoporous insulating panels (VIPs)	8	30
Fiber-reinforced aerogel blankets (FRABs)	13–14	50–55
Transparent aerogel insulation materials (TIMs)	-	70
Conventional insulation materials		
Phenolic foam	20–25	75–95
Polyisocyanurate (PIR)	22–28	80–105
Polyurethane (PUR)	22–38	75–145
Extruded polystyrene foam (XPS)	25–37	95–140
Expanded polystyrene foam (EPS)	30–45	115–165
Rock wool	34–40	150–170
Cork	41–55	155–200
Wood fiber	39–61	145–225

**FIGURE 7.17** Knudsen effect in nanoporous insulators.

silica nano-porous core (vacuum nanoporous insulation panels); transparent sheets or glass panes with cavity filled with nano-porous materials like aerogel (TIMs).

These nano-porous insulating products are made of aerogel (air + gel), a solid material with minimal weight per volume unit obtained through the supercritical dehydration of a colloidal gel, by replacing its liquid component with gas. Aerogel can be derived from gels made of inorganic or organic materials of different nature, including silica, carbon, metal oxides, graphene, clay, starch, and cellulose, for several applications such as insulators, sensors, actuators, electrodes, thermoelectric devices, or to trap space dust particles (Acharya et al., 2013).

Among various aerogels, those based on silica (dubbed silica aerogels) are the most widely used for thermal insulation, due to their properties and their relatively simple and consolidated preparation method. Consisting of more than 90% air, aerogels represent the solid substance with the lowest density recorded (silica aerogels can reach 3 kg/m³) (Sun et al., 2013) with a nano-porous structure characterized by interconnected pore sizes typically ranging from 5 to 100 nm and an average pore diameter between 20 and 40 nm (Fig. 7.18) (Aegerter et al., 2011).

In order to be used as insulating products for building application, silica aerogels are mixed in granule form in mortars, plasters, and concrete, but mostly are integrated in a fibrous support structure obtaining an insulation mat (FRAB) (Fig. 7.19) composed of 40%–55% silica, 20%–45% PET/glass fiber, and 0%–15% additives.

FRABs have a very low thermal conductivity ($\lambda = 0.015$ W/mK) with a constant thermal performance for wide operating temperatures (from -200 to +200 °C), good noise insulation, and good resistance to fire, from Euroclass C



FIGURE 7.18 Monolithic silica aerogel. *Courtesy of Aspen Aerogels.*



FIGURE 7.19 FRAB. *Courtesy of Ama Composites.*

for FRABs with PET fibers matrix to A2 for FRABs with glass fiber matrix only. FRABs also show high hydrophobicity values while maintaining high water vapor permeability and present excellent aging resistance, ensuring maintenance free operating life and the possibility of further reuse of the products (O'Connor, 2015).

VIPs are composite nanoinsulation materials constituted by an inner core of open pore structure material enclosed in a multilayer airtight plastic or aluminum envelope, inside which air is extracted creating vacuum, with internal pressure values of 0.1–5 mbar (Fig. 7.20). Available as panels 10–50 mm thick, VIPs hold today the record of thermal insulation, with thermal resistance values as low as 0.005 to 0.002 W/mK (Kalnæs and Jelle, 2014).

Concerning the panel core, market available panels employ nano-porous materials such as pyrogenic or fumed silica. Their thermal conductivity at operating pressures up to 50 mbar is 0.003 W/mK, arriving at a still good value of 0.020 W/mK at atmospheric pressure following rupture or gas leak, ensuring an acceptable service life (0.008 W/mK thermal conductivity after 30 years). As regards the panel envelope, its function is to protect the panel during handling and installation, but especially to slow down as much as possible the entry of air and vapor within the core, in order to ensure optimum performance over time.

FRAB and VIPs products are suitable for any type of building, new or under renovation, but are particularly convenient for external and/or internal interventions of building refurbishment or retrofit, especially of historic buildings subject to architectural constraints, and in all cases when it is necessary to increase energy efficiency and living comfort in as little space as possible.

Compared to aerogel insulating products such as FRABs, VIPs show even better thermal conductivity performance (rated $\lambda = 0.007\text{--}0.008$ W/mK compared to 0.015 W/mK). On the other hand, FRABs are much less delicate during both installation and operative life, can be easily adapted on site, and show no degradation of performance over time. On-site flexibility and low thickness make aerogel blankets a recommended choice for the correction of thermal bridges in new constructions and even more in existing buildings. Structure thermal bridges alone may account for more than 30% of a building energy consumption and often lead to local condensation, decay, and mildew growth. VIPs inherent vapor impermeability can also be limiting if a degree of breathability of the building envelope is desired.

In order to meet both requirements of thermal insulation and those of maximization of daylighting, a new category of light diffusing insulating materials has been developed in the last decade able to combine high direct transmission of visible solar radiation with low heat transmission (Paneri, Wong, & Burek, 2019; Sun, Wilson, & Wu, 2018).

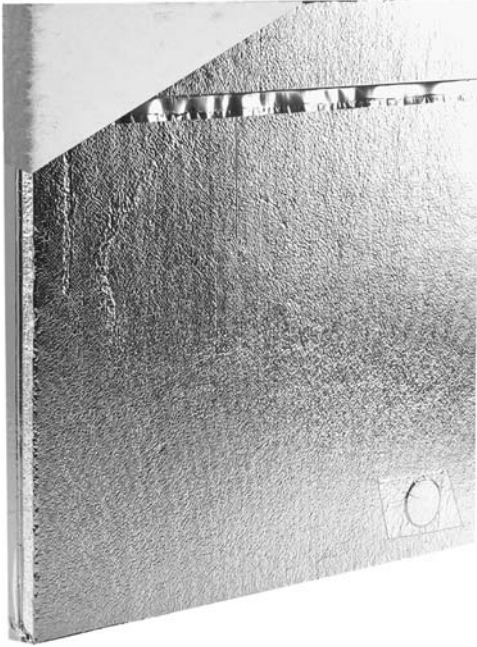


FIGURE 7.20 Vacuum insulating panel core and envelope. *Courtesy of va-Q-tec AG.*

These products are made by placing aerogel particles in 0.7–3.5 mm size range in the cavity between glass or polycarbonate panes obtaining light diffusing panels of unmatched thermal performance ($U = 0.30 \text{ W/m}^2\text{K}$ in 70 mm thickness). Aerogel TIMs allow to obtain a high visual comfort, free of glare phenomena, due to their light diffusing behavior that transmits daylight inside diffusely in all directions. Since they do not allow vision through granular aerogel, TIM cannot be, however, substituted of glass where external visibility is required.

Nano-porous insulation materials are beginning to enter the market in various niche applications. Cost, still roughly 10 times higher than traditional insulating materials, is a primary barrier to greater application of NIMs; nonetheless, aerogel cost has been steadily decreasing over the last few years, with a global market increased tenfold between 2003 and 2019 (Berardi, 2019). In case of VIPs, there are also concerns about lack of versatility, since they must be manufactured to size and cannot be adapted during installation.

7.5.3.2 Phase change materials

TES systems are becoming more and more attractive and have been recognized by several national and international agencies as an effective mean in reducing energy consumption and climate altering gas emissions. Furthermore, TES have a high potential in energy sectors as they allow the partial shift of peak load demand to off-peak periods, this way levelling the gap between energy supply and demand and easing the load on energy grids. Thermal energy can be stored by means of a change in the internal energy of materials, in the phenomena of thermochemical heat, sensible heat, latent heat, or any combination thereof. Among these, latent thermal energy storage systems utilizing PCMs can indeed contribute in increasing energy performance and fostering new and existing buildings toward a higher energy efficiency.

PCMs are property changing smart materials that exploit the phenomenon of phase transition to absorb or release heat (called latent heat) without increasing their internal temperature. The energy supplied or subtracted from the material during the phase transition is in fact used to break or form chemical bonds while keeping the kinetic energy of the body constant and hence its temperature stable. This way it is possible to split heat capacity from body mass, in order to obtain the same beneficial effects with lighter materials and a significantly reduced thickness.

Using PCMs, the ability to attenuate and time shift air temperature fluctuations in a room does not depend on the more traditional thermal capacity to accumulate external sensible heat without warming rapidly (sensible heat storage), but on the material ability to accumulate the external heat in the form of latent heat to undergo a phase transition. During phase transition, PCMs are able to accumulate a quantity of thermal energy between 100 and 250 kJ/kg in the form of latent heat, compared with the specific heat capacity of building materials which varies from a maximum of 1.5–2 kJ/kg (wood and compact plastics) to a minimum of 0.8–0.3 kJ/kg (bricks and metals).

Ultimately, through the use of PCMs, the building envelope tends to assume even more the characteristics of the human body skin, whose main thermoregulation mechanism to maintain a constant body temperature is precisely subtraction of heat as latent heat through evapotranspiration and sweating. During daytime, when air temperature exceeds a certain value (the so-called operating temperature at which the PCM begins the phase change, typically between 23° and 26°C), the excess heat is used by the PCMs to undergo the phase transition (e.g., from solid to liquid state) and thus subtracted from the environment. At night, when the temperature drops below the set point, the PCM returns the accumulated heat to the environment undergoing the reverse phase transition (liquid—solid) (Fig. 7.21). This way it is possible to damp the temperature oscillations of an indoor environment and maintain a state of comfort. Obviously, in order for PCMs to perform their function, daily temperature must exceed the melting point to allow the phase transition, then drop below the melting point in order to start a new cycle the following day. If this is not allowed by environmental temperature conditions, systems containing PCM whose cooling is induced by forced ventilation or by using panel integrated cooling coils are to be employed.

PCMs with different operating temperatures can be applied in any building element, enclosure, or partition, as additional components or directly integrated in the construction materials, enhancing the energy storage capacity of new or existing building envelopes, especially in lightweight construction, allowing to obtain high performance in extremely reduced thickness and mass. PCMs are also used in cooling systems as cold accumulators (with operating temperatures from 5°C to 18°C), in heating systems as hot accumulators (temperatures around 55°C–60°C) or as high temperature accumulators for solar cooling applications (over 80°C) as well as integrated with renewable energy systems, for instance, in removing excessive heat from PV panels or storing solar thermal heat for subsequent release and thus preventing performance decay caused by overheating, especially in BIPV installations where module ventilation may prove more difficult (Kant et al., 2020). Experimental testing evidenced delays of 2 hours and decreases of up to 9°C of peak temperature of the PV module with the integration of macroencapsulated paraffin wax (Curpek and Cekon, 2020).

PCMs used in building construction generally exploit solid—liquid transition, even if it is characterized by a lower exchange of latent heat than that achievable in liquid—gas phase change, as it involves a smaller volume variation resulting in more simplicity in the accumulation management system and greater affordability.

Depending on the type of material used for latent heat accumulation, PCMs are divided into two main categories: organic PCM, including paraffin waxes (C_nH_{2n+2}), nonparaffin waxes such as fatty acids ($CH_3(CH_2)_{2n}COOH$) and other organic nonparaffinic PCM like sugar alcohols; inorganic PCM, including hydrate salts (M_nH_2O) and metallic materials with low melting temperatures. Each category has its own advantages and disadvantages for use in building construction from the thermal, physical, chemical, environmental, and economic points of view. Most used materials are, as already said, paraffin (organic materials), hydrated salts (inorganic materials), and fatty acids (organic materials). Among organic PCMs, research is focusing on finding environmentally friendly suitable replacements for paraffin waxes, which are extracted from fossil sources, and for salt hydrates. Dubbed bio-based PCMs, these materials are based on fatty acids and their derivatives (alcohols, amines, and esters) or compounds, made from the underutilized and renewable feedstock, such as vegetable oils and animal fats. Bio-based PCMs include polyethylene glycol, polyols, palmitic, lauric, stearic or myristic acid, coconut, palm or soy oil, as well as palm, soy or beeswax (Nareesh et al., 2020). Compared to paraffin waxes, however, they show lower thermal conductivity and may need the integration of graphene nanoplatelets or carbon nanotubes to be suitable for TES applications.

To be used in building applications, PCM products are normally encapsulated inside specific hermetic packages to provide containment of the material in the liquid and solid states, to prevent changes in its chemical composition, to

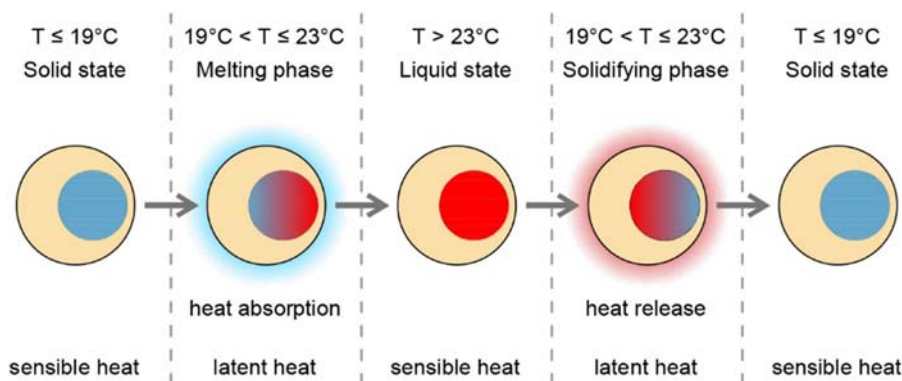


FIGURE 7.21 PCM operation.



FIGURE 7.22 Macroencapsulated PCM. *Courtesy of va-Q-tec AG.*



FIGURE 7.23 BASF micronal microencapsulated PCM. *Photo by the author.*

avoid interactions with the environment, to increase compatibility with surrounding materials, and to improve handling and reduce possible variations of the external volume. Macroencapsulation is carried out by enclosing PCMs in containers such as tubes, spheres, panels, and other shells, which can act directly as heat exchangers or in turn be incorporated into other elements (see Fig. 7.22). It is the most used form of encapsulation and involves containers larger than 1 cm. The microencapsulation method provides for individual particles or droplets of solid or liquid PCM, constituting the core, to be surrounded or coated with a continuous film of polymeric material with high molecular weight, the shell, obtaining microcapsules in the micrometer to millimeter range (see Fig. 7.23). Yet another method of encapsulation resorts to the so-called shape-stabilized PCMs, in which a supporting material, such as high density polyethylene (HDPE), is compound to a PCM like paraffin wax.

Thanks to the possibilities provided by microencapsulation, PCM products can now be used in different ways, integrated in construction materials or as additional building components finding application in walls, ceilings, floors, glazing, and HVAC systems. In particular, PCMs integrated in construction materials include concrete blends and pre-mixed plaster blends; drywalls (gypsum boards, plaster panels) and composite panels; ceiling and floor tiles (microencapsulated or composite boards); insulation materials (microencapsulated, shape-stabilized, macroencapsulated); concrete bricks; structural concrete; windows and glass bricks. Building components containing PCM instead include pouched mats, panels, rusticated mats, bags, and blocks. The combined use in inner insulation application methods of both SIMs and PCMs can allow in a reduced thickness to improve thermal insulation without losing the benefits of high thermal mass.

While the principle of PCMs use in buildings is relatively simple, PCMs behavior depends on multiple parameters, including climatic conditions such as solar radiation and ambient temperature; indoor thermal loads; building use and characteristics; design choices such as the presence of shading elements; the type and amount of PCM chosen and its configuration, orientation, and location within the building. In this picture, it is apparent that an efficient PCM application requires the identification of adequate support strategies, along with detailed dynamic simulations of the thermal behavior of the building in the expected conditions of use, through software such as EnergyPlus, ESP-r, and TRNSYS, particularly recommended for their versatility and reliability (Casini, 2016b).

7.5.4 Dynamic windows

In the last two decades, with the goal of smarter and greener buildings, transparent closures have become one of the main research fields in the construction sector. The objective is to obtain a new generation of advanced windows, able to fully adapt to the environmental conditions in a dynamic way to ensure, in full synergy with the building systems and equipment, an efficient, continuous, and automatic management of all matter (air and vapor) and energy flows (heat and solar radiation) in accordance with climate, user behavior, and market conditions of energy.

A new generation of glazing has therefore entered the market, which, leveraging advanced key enabling technologies such as nanomaterials or smart materials, is not only capable of offering better performance compared to traditional solutions, but also of fulfilling new functions such as power generation, self-cleaning, self-heating, and light and radiation dynamic control (dynamic glazing or switchable glazing).

Dynamic glazing, thanks to the integration with inner chromogenic layers, allows to obtain smart windows able to control incoming solar radiation, in order to guarantee maximum visual comfort and to manage at best solar gain in both hot and cold seasons.

Dynamic glazing represent the best solution both for new constructions and existing buildings renovations, allowing better visual comfort and significant energy and environmental savings if well integrated with lighting and air conditioning control systems.

According to their operation, dynamic glazings can be distinguished, in passive, self-regulating systems or active, user's adjustable systems (Rezaei, Shannigrahi, & Ramakrishna, 2017; Tällberg, Jelle, Loonen, Gao, & Hamdy, 2019).

Passive systems respond autonomously to natural stimuli such as light (photochromic glass) or heat (thermochromic and thermotropic glazing), without any external induced input. This characteristic leads to an easier installation and good reliability with the disadvantage for the users of not being able to directly control them according to their needs (Granqvist et al., 2010; Saeli, Piccirillo, Parkin, Binion, & Ridley, 2010).

Active systems, on the contrary, can respond to an external electrical stimulus by changing their optical characteristics, facing variations in internal and external environmental conditions in order to address the user's demand.

Active systems can be controlled directly or connected to the building management system, in order to respond to changes in external (temperature, solar radiation) or internal climatic conditions (temperature, artificial and natural lighting levels, heat gains, presence of people), or the needs of users, allowing to adjust the intensity of penetrating visible and infrared radiation significantly reducing energy consumption for air conditioning and lighting (savings are estimated at more than 20%).

Active dynamic windows can play therefore a pivotal role in the advanced building envelope, allowing greater freedom in architectural design, better visual and thermal comfort and improved energy efficiency enabling a climate adaptive building shell fully adjustable to any weather condition or users preference. (DOE (United States Department of Energy), 2014).

Main electrically controllable active systems on the market include electrochromic (EC) glass, suspended particle devices (SPD), and liquid crystal devices (LC/PDLC).

Among these technologies, each with different characteristics, performances and costs, only EC are fully suitable for use in the building envelope, whereas SPDs are commonly used in vehicles and PDLCs mainly for interiors' privacy glass, with recent application also in solar control glazing, thanks to the inclusion of dye molecules in the liquid crystal mixture (Licrivision) (IEA SHC TASK 56, 2019).

EC glazing (see Fig. 7.24) is at the moment the most mature and effective active dynamic glass technology for buildings, and the one with the best proven durability, with installed systems still in full operation since early 2000s and commercial products offering 10 year warranty and boasting a theoretical service life from 30 (Sageglass, 2017) up to 50 years (View Dynamic Glass, 2017).

New emerging technologies are currently being researched and developed with the aim of improving performance, economy and durability of EC devices, by either refining established technologies, for instance, through nanotechnology applied to electro-chemical operation (nanocrystal composites), or employing alternative approaches such as chemochromic (gasochromic glass), based on polarized particles (electrokinetic pixels), electro-mechanical (elastomer deformation window), or purely mechanical (liquid infill windows).

7.5.4.1 Thermochromic glazing

Among passive dynamic glazing, thermochromic glazing (Pleotint, Ravenwindow, Solarsmart etc.) is the most interesting on the market (Aburasa et al., 2019).



FIGURE 7.24 Electrochromic windows. *Courtesy of EControl-glas.*

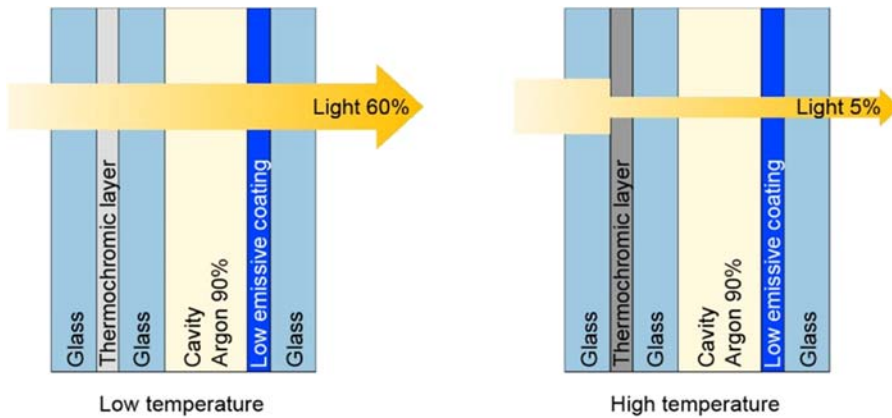


FIGURE 7.25 Thermochromic glazing operating scheme.

Thermochromic glazing is capable of autonomously modifying its optical properties according to the external surface temperature, which determines a chemical reaction or a phase transition between two different states. The material therefore remains clear when there are temperatures lower than the transition one and becomes dark for higher temperatures (see Fig. 7.25). The interval of the transition temperature is generally between 10°C (maximum transparency) and 65°C (minimum transparency). The properties of thermochromism can be observed in a wide range of organic and inorganic compounds and in films of metal oxides, such as vanadium oxide (VO_2), which by switching from semiconductor to metallic state acquires a reflective behavior highly sensitive in the infrared zone.

Research is currently focusing on improving performance of VO_2 , the most used material for thermochromic windows. This includes employing vanadium dioxide in its monoclinic form (VO_2 (M)) (Kim, Roh, Jung, & Kim, 2019), adding it with cerium dioxide (Saini, Dehiya, & Umar, 2020) or further doping it with tungsten ions then adding titanium dioxide, to improve performance and gain photocatalytic properties (Salamati, Kamyabjou, Mohamadi, Taghizade, & Kowsari, 2019), subjecting VO_2 to oxygen plasma bombarding (Jin et al., 2019), or adding silica nanoparticles (Schläefer et al., 2019).

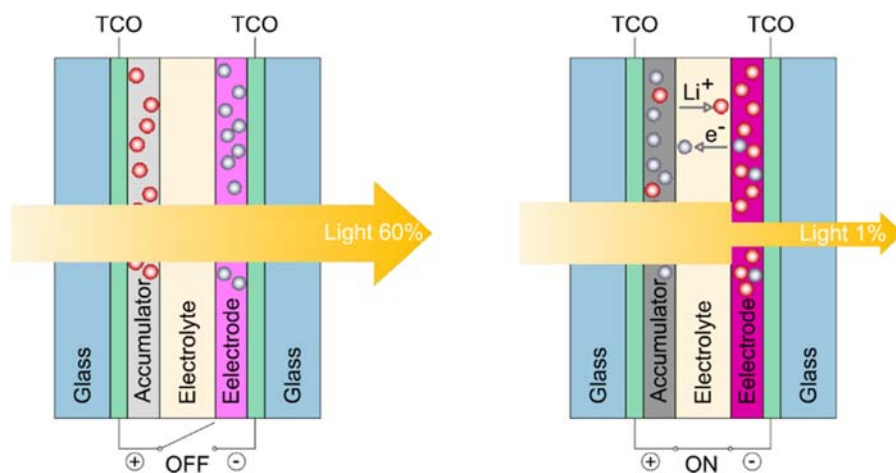
At this time, the most reliable technique for the manufacture of thermochromic glazing is the insertion of thermochromic materials directly into plastic film of polyvinyl butyral (PVB) with a thickness of 1.2 mm, introduced for the first time on the market in late 2010.

Since PVB is one of the most used products for the production of laminated safety or acoustic glass, this solution allows in fact the best integration in the manufacturing processes and the possibility to provide at a reduced cost a higher quality product. Switching time is in the order of a few minutes, and typical ranges of visible light transmission (VLT) and solar heat gain coefficient (SHGC) in correspondence of clear and dark states are reported in Table 7.11. Among the disadvantages, in addition to the impossibility of user control, thermochromic glazing may not reach the temperature required for switching to the dark state even in the presence of solar radiation with the drawback of not eliminating glare for users. Duration is guaranteed for an operating time of at least 20 years, and they are cheaper than active control dynamical systems ($\text{ROI} < 4$ years).

Research is underway for finding other candidate materials for thermochromic window applications, which include perovskite (Zhang et al., 2019), leuco dyes, or dyes embedded in polymer matrix, nanomaterials such as

TABLE 7.11 Main thermochromic glazing on the market.

Temperature	VLT	SHGC	Ug	VLT	SHGC	Ug	VLT	SHGC	Ug
	Pleintint Suntuitive Clear			Innovative Glass Solarsmart			Ravenwindow		
Low	60%	0.37	1.36 Argon	57%	0.37	1.36 Argon	33%	0.28	1.36 Argon
High	13%	0.17		12%	0.18		5%	0.18	

**FIGURE 7.26** Electrochromic glazing operating scheme.

quantum dots and plasmonics, photonic crystals, conjugated polymers, schiff bases, or liquid crystals (Garshasbi & Santamouris, 2019).

7.5.4.2 Electrochromic glazing

EC materials belong to the category of property-changing smart materials and are able to autonomously and reversibly change their color due to oxidation or reduction reactions as a response to an external electrical stimulus. Glazing employing these chromogenic materials can thus change its optical characteristics of transparency and adsorption of solar radiation according to users' needs, by simultaneously reducing VLT and near infrared (NIR) transmission through the window (Cannavale, Ayr, Fiorito, & Martellotta, 2020).

The central part of an EC device is a five layers coating applied to the glass pane (see Fig. 7.26) constituted by an electron accumulation layer (counter-electrode, $\text{Li}_x\text{V}_2\text{O}_5$), an ion conductor layer (or electrolyte, usually LiAlF_4), an electrode layer (commonly tungsten trioxide WO_3 or niobium pentoxide Nb_2O_5), and two outer layers made of transparent conductive oxides (TCO).

When voltage is applied, Li^+ ions pass from the accumulation layer to the electrode determining a change in color from transparent to dark in the electrode layer (cathodic coloration), or in the accumulation layer (anodic coloration), or in both, according to the EC materials employed. The device is made transparent again by turning off the electrical stimulus, triggering the return of ions from the electrode to the accumulation layer.

EC products on the market allow a wide range of glass pane sizes in different shapes, independent modulation of up to three control zones on the same pane (Sageglass Lightzone) or gradient in-pane tint transition (Sageglass Harmony). They can be self-powered by photovoltaic battery systems applied to the window edge (ConverLight AW) without the need of power supply wires, with easier installation in particular for substituting existing windows. A promising development is the application of EC coating to flexible PET substrates by roll-to-roll web coating, with the aim to obtain inexpensive EC foils that can be directly laminated to glass, with the further possibility to superimpose two of these to achieve even lower colored-state transmittance (Granqvist, 2019).

Color of EC glazing on the market is typically blue, due to WO_3 commonly used as EC material with a modulation of transparency from clear (device off) to dark (device on) in intermediate control states (usually four) (Sbar, Podbelski,

Yang, & Pease, 2012). SHGC is typically comprised between 0.49 in the full clear state and 0.09 when completely tinted with VLT variation from 60% to 1% (see Figs. 7.27 and 7.28 and Table 7.12).

Switching between the different control states requires a minimal amount of electricity (2.5 Wp/m^2) and even less is needed to maintain a desired tinted state (less than 0.4 W/m^2), thanks to the bistable configuration property of EC materials.

Since the first applications in 2000s, relevant projects have demonstrated many advantages in the use of active dynamic glass, ECs in particular, such as savings up to 60% of the needs of artificial lighting, a reduction of the cooling load up to 20% and of peak power up to 26%, with the possibility of resorting to plants of smaller size, along with a good users' acceptance of this technology mainly because of the reduction of glare, reflections, and discomfort near the windows (Casini, 2018).

However, a wider spread of EC is still slowed by a number of drawbacks, both technical and economical, and its operation versatility has also room for further improvement. In particular, optimal window versatility calls for separate control of VLT and NIR transmittance, as ECs still control them simultaneously and achieve limited selectivity—that is, possibility of high visible light transmittance while, at the same time, blocking unwanted NIR radiation. Research is also experimenting on hybrid EC-TC dynamic glazing with the aim to separate NIR and visible light control and broaden radiation tuning spectrum. This can be achieved, for instance, by a $\text{VO}_2/\text{LiTaO}_3/\text{WO}_3$ sandwich structure

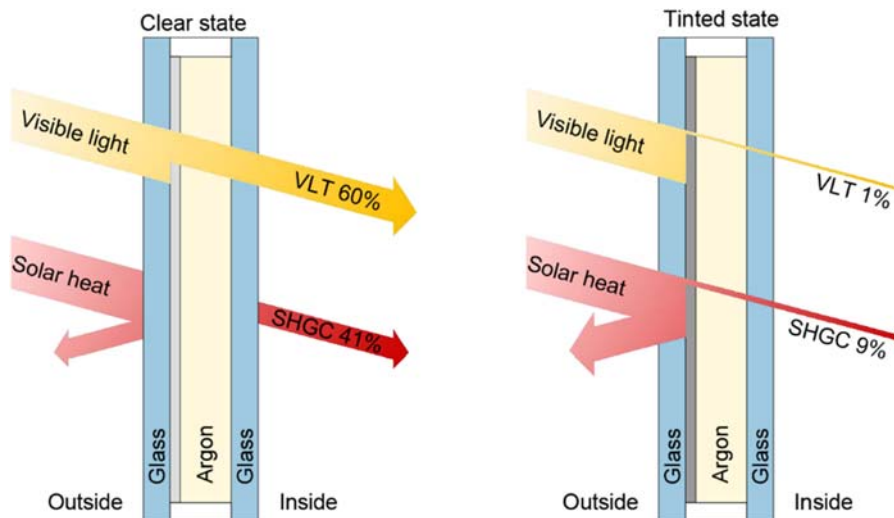


FIGURE 7.27 Electrochromic glazing control states.

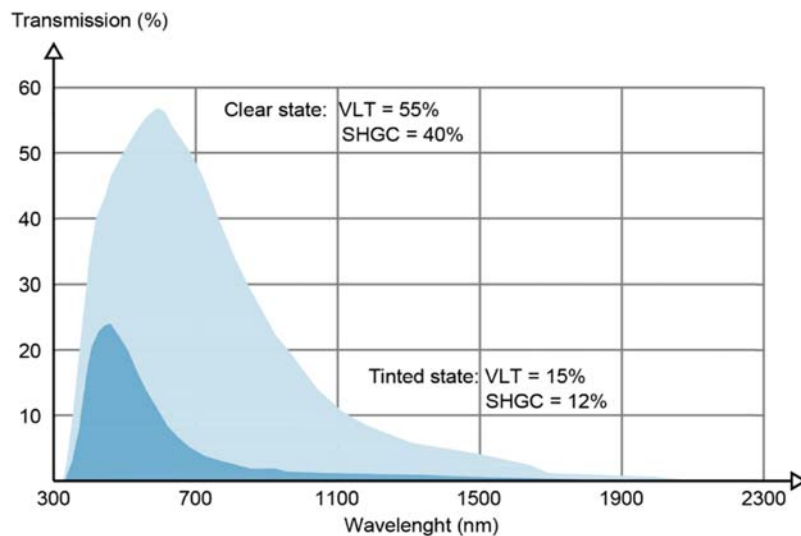


FIGURE 7.28 Spectral transmission of electrochromic glass in different tint states (EControl-Glas).

TABLE 7.12 Main electrochromic products on the market.

Tinted state	SGG Sageglass			View Dynamic Glass		
	VLT	SHGC	Ug	VLT	SHGC	Ug
0	60%	0.41	1.64	58%	0.41	1.59
1/3	18%	0.15		40%	0.28	
2/3	6%	0.10		6%	0.11	
3/3	1%	0.09		1%	0.09	
Tinted state	EControl-glas			Converlight		
	VLT	SHGC	Ug	VLT	SHGC	Ug
0	56%	0.42	1.10 (Low-e)	67%	0.46	1.12 (Low-e)
1/3	n/d	n/d		n/d	n/d	
2/3	n/d	n/d		n/d	n/d	
3/3	10%	0.10		36%	0.25	

(Jia et al., 2019). Specialized applications, such as fine arts or drawing activities, would also benefit from better color neutrality and/or hue fine-tuning, and the addition of opacity control would allow better privacy for sensible environments.

The main issue in the application of active dynamic glazing is represented by both the high cost of the products and the still limited technical information among designers, industry professionals and users. Regarding the cost, at the moment, it still remains high for a large-scale application both in the residential and commercial buildings, with an extra cost of EC windows compared to traditional insulating glass units of around 215 €/m² with a payback period of around 30 years for residential buildings and 60 years for commercial ones. To promote a wider diffusion, market analysis suggest to reach an extra cost lower than 65 €/m² by 2025, ensuring a payback time not higher than 12 years for residential buildings and 22 years for commercial ones (IEA SHC TASK 56, 2019).

7.5.5 Smart coatings

The application of advanced coatings in buildings, such as transparent or opaque paints and thin films, allows to improve mechanical, physical, and chemical performances of building materials and components by imparting them new properties, both fixed (antireflection, scratch resistance, UV resistance, water resistance, etc.) and dynamic (chromogenics, self-cleaning, self-healing, luminescence, antibacterial, etc.).

Thanks to specific surface treatments of building elements in the construction phase, today is in fact possible to:

- make surfaces active in contributing to the maintenance of requirements of hygiene and health (air-purifying, self-cleaning, antibacterial);
- improve thermal behavior of the building envelope making the surfaces reflective to sun radiation or to the internal infrared radiation (thermal responsive);
- make surfaces active in light emission (photoluminous);
- improve surfaces' response to external environmental wear, making them more resistant to corrosion, abrasion, impacts and scratches, solar ultraviolet radiation, water and fire, and even able to repair themselves (self-healing).

7.5.5.1 Air purifying coatings

The interior and exterior surfaces of buildings (including external paved areas) can make an important contribution to improving air quality by removing pollutants from the atmosphere that is in their direct contact.

This is achievable by using products with air purifying characteristics, applying them to the surface of building components or directly embedded in the materials mix (floor tiles, panels or fixtures, cement etc.).

There are several products on the market claiming air purifying characteristics. Most of these employ photocatalytic agents such as titanium dioxide (TiO₂) or tungsten trioxide (WO₃) nanoparticles activated by sunlight or environment

lighting, others, such as zeolite, do not require any light for their air purifying action and are more suitable for interiors applications.

Among photocatalytic construction and building materials, TiO_2 is the most widely used photocatalyst. TiO_2 is a common semiconductor material that has long been used as a white pigment in paints, cosmetics, and food. Of the three crystalline forms in which TiO_2 is present in nature (anatase, rutile, and brookite), the anatase type is the most widely used because of its higher photoactivity. The extensive use of TiO_2 in photocatalytic building materials is due to its numerous advantages (the first use of TiO_2 to decompose pollution was reported in 1977): it is chemically stable, safe, widely available, and relatively inexpensive; it presents a higher photocatalytic activity compared with other metal oxide photocatalysts; it is compatible with most traditional construction materials, such as cement, without changing any original performance; it is also effective under weak solar irradiation in ambient atmospheric environment.

The general mechanism of photochemical catalysis using TiO_2 under UV light irradiation (wavelength less than 385 nm) follows several stages that conduce to the formation of highly reactive agents capable of decomposing organic (benzene, dioxin), and inorganic (NO_x , SO_x , CO , NH_3) substances, pesticides, carcinogens particulates, and airborne bacteria and turning them into harmless products such as sodium nitrates (NaNO_3), sodium (CaNO_3) or calcium (CaCO_3) carbonate (see Fig. 7.29). These properties along with its photo-induced superhydrophilicity make TiO_2 photocatalytic surfaces substantially self-cleaning and mold free.

NO_x removal capacity makes photocatalytic products particularly interesting for air depuration in urban areas. Photocatalytic reagents can be used in both external and internal environments. Outside they can be integrated in cement and mortar mixtures (Italcementi TxActive) for plaster and cladding slabs, in pavements for sidewalks and squares (BioTi Ecopav), in roofs tiles, in paints (Marraccini Paintek). Inside buildings, photocatalytic materials can be integrated into paints (Airlite, Caparol Capasan, Keim ECOSIL Me) or ceramic tiles (GranitiFiandre Active, Mirage Hy-PRO24) suitable for kitchens, bathrooms, schools, or hospitals, where they can purify bacteria and VOC compounds in rooms exposed to natural light or illuminated with UV lamps.

As most photocatalytic processes are activated only by UV light waves, research is focusing in expanding these effects to a broader spectrum of sunlight, in order to increase its efficacy and enable photocatalytic action also at night or in interiors devoid of daylight. In view of its aggressive behavior toward organic compounds, TiO_2 coating of polymer surfaces such as plastic requires inorganic barrier layers to protect substrates from oxidation.

TiO_2 has the drawback of requiring UV light to perform its oxidizing reaction against organic pollutants and is thus limited in interiors application to rooms with sufficient natural lighting and UV transparent windows or by providing artificial UV light. Furthermore, the photocatalytic effect is understandably absent at night. In alternative to photocatalytic products, suitable for interiors applications are gypsum-based finishing materials such as plasters, drywalls and false ceiling tiles embedded with zeolite (Knauf Cleaneo, Gyproc Activ'air). Due to its nanoporosity, this natural mineral is characterized by high sorption and ion exchange capacity and has proven effective in reducing indoor pollutants concentration and removing unwanted smell, reducing diseases such as sick building syndrome. For example, formaldehyde is decomposed in carbon dioxide and water. Zeolite air purifying action does not require any light, nevertheless

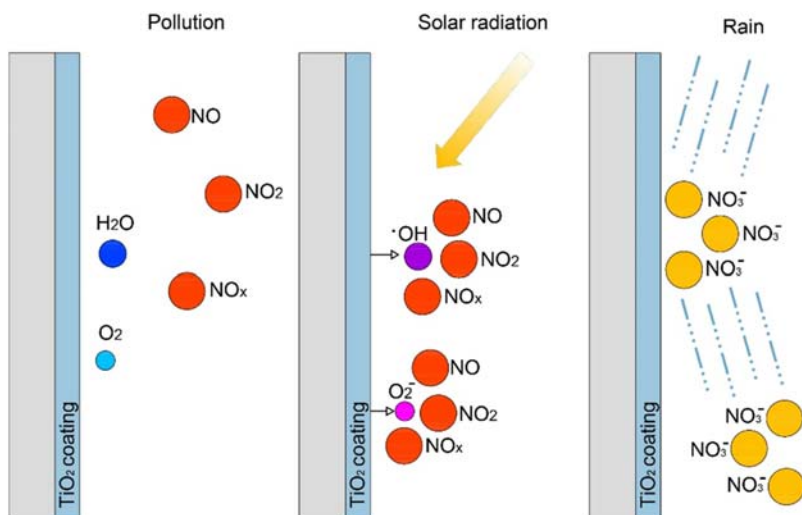


FIGURE 7.29 Purifying effect of a wall coated with photocatalytic paint.

sufficient air ventilation and a cover ratio of at least 0.3 m^2 for every cubic meter of room space are recommended for maximizing the effect. Porous gypsum zeolite materials are able to tackle most indoor air pollutants.

7.5.5.2 Self-cleaning coatings

As a common phenomenon, the esthetic appearance of building surfaces gradually decays with time. Building surfaces are continuously soiled by greasy and sticky deposits, which result in a strong adherence of composite materials mainly originated from the atmospheric aerosol pollutants. As a consequence, visual appearance is affected by dirt built up on the surface. Without constant and proper maintenance, it may be difficult to restore the buildings' esthetic properties.

For these reasons, much attention are gaining the so called self-cleaning surfaces, which claim excellent dirt and water repellent characteristics and in some cases even air purifying and pollutants neutralization properties. Achieved by surface curing, coatings or chemical substances embedded in the building materials themselves, self-cleaning properties allow understandable advantages in terms of higher energy efficiency, reduction of maintenance costs and environmental impacts, and improving of both indoor and outdoor air quality.

In particular, self-cleaning surfaces ensure best operation of building elements such as cool roofs and thermoreflective coatings, in which dirt accumulation translates to worse performance; require less maintenance interventions, translating in less building downtime related to cleaning and less expenses for operators and equipment (detergents, scaffolding); prevent large quantities of detergents to be dispersed in the environment, and often even contribute to air purification and pollutants reduction.

Self-cleaning properties of a surface derive from its capacity of bonding with water (surface's wettability) and can be obtained through two opposites processes: one based on the surface hydrophobicity (water repellent action), the other on its hydrophilicity (water attractive action).

In particular, the two main approaches to make surfaces self-cleaning either prevent dirt and water from attaching to the glass surface (water-repellent action) or degrade organic and inorganic dirt and let it wash away by rainwater (water-attractive action). According to these two main processes, self-cleaning products on the market can be divided in two main technologies, exploiting coatings with superhydrophobic or on the contrary superhydrophilic characteristics (water contact angles above 120° or lower than 60° , respectively) (Fig. 7.30).

Regarding superhydrophilic behavior, TiO_2 -induced photocatalysis is a promising technology also for self-cleaning applications. In addition to its photocatalytic properties, TiO_2 demonstrates an intrinsic photo-induced surface superhydrophilicity. In fact, differently from other photocatalytic materials, when water is adsorbed on this semiconductor material irradiated by UV light, it spreads forming a thin film instead of grouping in water droplets. When water is rinsed over the surface, contaminations like oil can be washed away.

The phenomenon is due to oxygen vacancies determined by the UV radiation being replaced by dissociated water molecules, OH groups, which make the surface hydrophilic. The greater the surface exposure to UV radiation, the smaller becomes the angle of contact between the water and the surface itself. After about thirty minutes under a UV light source of moderate intensity, the contact angle tends to zero, meaning that the water has a tendency to completely coat the surface. TiO_2 -based surfaces can maintain their hydrophilic properties indefinitely as long as they are irradiated by UV light. After illumination stops, super-hydrophilic behavior remains for about two days. Depending on processing techniques and chemical composition, a given TiO_2 surface can have a more super-hydrophilic and less photocatalytic character, or vice versa.

The self-cleaning effect of TiO_2 is due to the combined, synergic effects of photo-induced super-hydrophilicity and photocatalytic degradation of organic deposits, which make the surface antistaining and antisoiling without the need of any chemical detergents (Fig. 7.31).

Finally, hydrophilic coatings are inherently antistatic, since their conductive metal oxides provide a low resistance pathway to dissipate electrostatic charges and prevent electrically charged dust particles to be attracted.

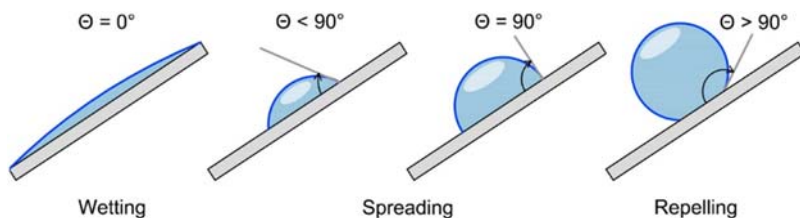


FIGURE 7.30 Surface wettability and contact angle θ .

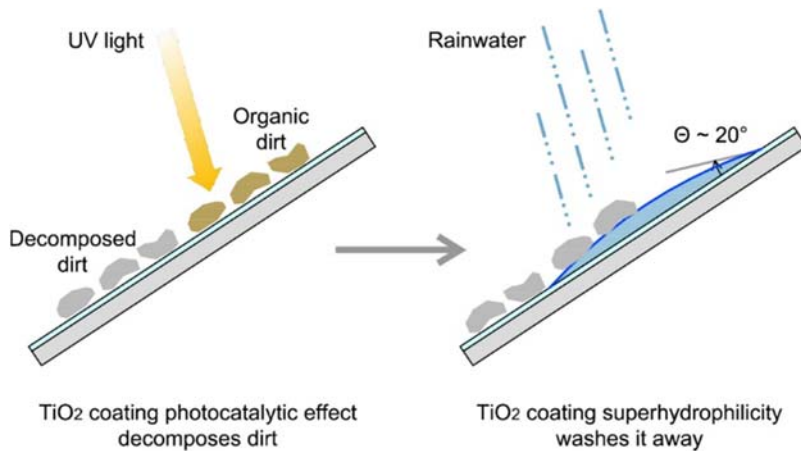
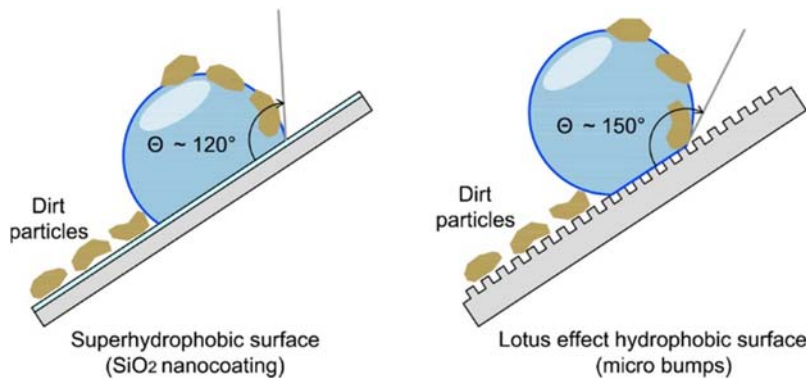
FIGURE 7.31 TiO_2 self-cleaning effect.

FIGURE 7.32 Water contact angles of different surface materials.

In addition to TiO_2 surfaces, an alternative superhydrophilic self-cleaning solution, albeit less effective, is the inclusion of silicon dioxide nanoparticles on the outer layers: water molecules in the air are adsorbed to the wall and form a water molecular film, to which dirt attaches without soiling the paint layer beneath and is easily removed by passing rain (Nichiha Nichiguard). The water film is also electrically conductive and acts as an antistatic layer in preventing dust attachment. This solution, however, offers limited protection against algae and fungi and requires additional protection agents to prevent their growth. Furthermore, these coatings have limited effect in heavily polluted areas or against rust or viscous dirt and require frequent cleaning.

Regarding superhydrophobic behavior, it can be achieved either by low surface energy materials such as fluorinated polymers like Teflon, which show contact angles as high as 120° , or by extraordinary high nano-scale roughness, enough to trap air beneath water drops and prevent them from adhering to the surface, achieving contact angles up to 150° (see Fig. 7.32).

The latter approach is an example of biomimicry, as this behavior has been observed in lotus leaves since the 1970s; these exhibit a microbumpy surface constituted by cells 20 to $50\text{ }\mu\text{m}$ in size covered by $0.5\text{--}3\text{ }\mu\text{m}$ hydrophobic wax crystals: in fact, this phenomenon is largely known as “lotus effect” as named by its discoverers Barthlott and Neinhuis.

Lotus effect can be achieved with microstructured surfaces achieved by depositing a powder made from hydrophilic polymers or nanoparticles of silicon dioxide. Available products on the market include ceramic roof tiles or façade paints such as StoColor Lotusan with high resistance to algae and fungi growth.

For wood protection against water, BASF has developed a hydrophobic coating which obtains lotus leaf effect by incorporating silica and alumina nanoparticles and hydrophobic polymers.

Textile surfaces such as retractable awnings may also achieve partial self-cleaning behavior, with microscopically fine hairs or spikes on the surface of the fabric to prevent water or dirt from coming in direct contact with the surface, allowing easy dirt removal by rainwater (Markilux Sunsilk SNC).

In view of their geometry induced characteristics, lotus effect surfaces are usually sensible to mechanical loads that may alter their microstructure, unlike real lotus leaves that are able to continuously regenerate. Furthermore, tensides

like soap or other detergents temporarily inhibit hydrophobicity by reducing water surface tension, making lotus effect treated surfaces unsuitable for bathroom facilities applications. Fat also disrupts hydrophobicity, so a single fingerprint is enough to leave a mark.

The other approach to super hydrophobicity provides for perfectly smooth surfaces, achievable by nanoparticles or fluoride coatings. Contact angles are a little smaller than those achievable by lotus effect, but on the other hand, these surfaces are fat-repellent as well (Ultratech Everdry, Dow Corning Z-6689, Nanoseal Vision Protect). Dubbed “Easy to Clean” coatings, they are usually manufactured from silanes solutions modified with fluorine compounds to further decrease surface energy. On application, these solutions undergo a sol-gel process, as the nanoparticles concatenate in a dense web gel and saturate all microasperities of the treated surface, forming a compact layer once evaporation is complete.

As sol may dry even at room temperatures, hydrophobic treatment can also be directly carried out by consumers, and several coatings come in DIY kits for self-application.

Easy to clean coatings show, however, little durability, and treatments must be replicated after a certain amount of time.

Regarding glazing, while glass is inherently hydrophobic by itself, its surface is, however, still rough and microscopically porous and thus subject to dirt and bacterial deposit. Superhydrophobic coatings employ nanoscale polymers or silica nanoparticles (SiO_2) to fill discontinuities and provide a perfectly smooth surface. This way water droplets have an exceptionally high contact angle (θ), up to 180° , and are instantaneously flushed away, carrying dirt particles with them without leaving any mark.

Super hydrophobic coatings are difficult to apply during the glass slab manufacturing process, and alternative physical processing methods such as ion etching and compression of polymer beads, or chemical methods such as plasma-chemical roughening, still result in hazy and fragile products. On site application is on the contrary simple (some of these coatings come in DOY kits for self-curing of desired surfaces), with the main drawback of limited duration over time of the hydrophobic effect, which might require re-application after less than a year. Several nanotech-based hydrophobic coating are currently available (Nanotech Coatings, Balconano, Diamond Fusion), also for curing mirrors, tiles, kitchen worktops, and the likes.

Finally, superhydrophobic coatings find also an important application as antigrffiti and antistain surface treatment. Graffiti is in fact a significant challenge for architectural heritage materials. Graffiti affects a wide variety of surfaces, the cleaning is costly and, quite often, the penetration into the pores contained in the substrate material induces an irreversible effect onto the painted surface. Acrylic paint in fact easily attaches to porous surfaces such as concrete, natural stone, and plaster and is difficult to remove, requiring large quantities of water and environmental hazardous detergents.

Antigrffiti coatings have been developed by functionalizing SiO_2 or polymers nanoparticles dispersed in a water or alcohol medium to form a coating repellent to both water and oil simultaneously. As a result, the coated surface becomes nonstick and easy to clean, and able to withstand repeated graffiti attacks.

To enable hassle-free cleaning of the substrates, fluorinating agents have been used to lower surface energy of the coating by migrating onto the coating surface. This offers good hydrophobicity reducing the adherence of staining agent to substrates. Also, outstanding thermal and oxidative stability, low coefficient of friction, and good chemical resistance are achieved with its use. Fluoropolymers exhibit a great deal of oleophobicity since the extent of electronegativity and low polarizability of fluorine atoms in the backbone or side chains induce hydrophobic and oleophobic properties in the coatings synthesized from them. Furthermore, most commercially available antigrffiti paints are siloxane/silicone-based formulations. They repel most of the waterbased paints and markers and can also applied on substrates like plastic, composite material, wood, and metal.

7.5.5.3 Antibacterial coatings

The need to ensure disinfection or prevent unwanted growth of biological agents such as bacteria on building surfaces and objects that come in contact with people has led in the recent years to concerns over the large use of disinfectants, mainly due to the costs and environmental impact associated and, most worryingly, due to the rise of more and more strains of bacteria resistant to antibiotics. As such, surface coatings that possess the ability to kill or inhibit reproduction of bacteria, called “antibacterial” or “antimicrobial,” have become highly desirable due to their inherent resistance to deleterious effects such as contamination, discoloration, staining, or smell and have been the subject of vast research and development in the last decade.

Main mechanisms that antibacterial coatings employ to neutralize bacteria and other biological agents are the following:

- photocatalytic reactions that produce aggressive reactive oxygen species (ROS), the most common being $\text{OH}\bullet$, $\text{O}_2^-\bullet$, and H_2O_2 to oxidize the cell membrane leading to its disruption and attack the cell's internal components (Gardini, Lüscher, Struve, & Krogfelt, 2018);
- biological attack to bacteria functions either by attacking or modifying its DNA, binding its enzymes/proteins or interrupting the transmembrane electron/ion transport, disrupting cell respiration;
- direct mechanical interaction to kill bacteria by puncturing their cellular walls and causing leakage of the cell's cytoplasm.

Materials that show photocatalytic characteristics include ZnO and, in most applications, TiO_2 metal oxides, which strong oxidizing effect has the ability of destroying bacteria, viruses, and molds. Several researches have in fact shown that bacteria such as *Escherichia coli* are effectively killed by UV irradiated TiO_2 . This antimicrobial effect is mainly due to the highly aggressive hydroxyl radical $\text{OH}\bullet$ synthesized. Photocatalytic properties of TiO_2 can be further improved by combining it with other semiconducting and antifouling materials such as Cu_2O and ZnO, enhancing its antibacterial properties due to the reduction in band gap. TiO_2 biocidal effect is also viable to control biological growth on sun exposed concrete surfaces, avoiding unsightly stains due to the growth of biofilm especially in frequently wet areas and preventing chemical degradation of concrete surfaces. Since photosynthetic algae grow where sunlight is available, photocatalytic technology is an effective solution. One drawback of photocatalytic coatings is their dependence on UV ray (either supplied by sunlight or UV lamps), as biocidal operation at night or in interiors with artificial lighting is strongly reduced.

The potential to kill bacteria via biological attacks is instead evidenced in several metals and is dramatically improved when in form of nanoparticles, thanks to the increased contact area (Ogunsona, Muthuraj, Ojogbo, Valerio, & Mekonnen, 2020). In this form, metal nanoparticles can be integrated as chemically active ingredients (AI) in coatings and building materials to provide antimicrobial characteristics. Several products belong to the AI group, employing copper, iron, tungsten (Matharu, Ciric, Ren, & Edirisinghe, 2020) but mostly silver and silver oxide nanoparticles due to their biocidal action against more than 640 kind of microorganisms (bacteria, viruses and fungi). These are available for interior and external use and come as coatings, paints (Sigmarests Immun), or tiles (Casagrande Padana Bios). Silver nanoparticles may be dispersed in the coating or embedded in alumina-silicate zeolite carriers (AgION). The continuous leaching of superfine silver ions inhibits bacteria by stopping bacterial energy metabolism and electrolyte transport, by slowing or stopping DNA replication or by binding to the bacterial cell wall causing it to collapse or burst. As such, silver ions are active against a broad range of gram-positive and gram-negative bacteria, have a low risk for bacteria resistance, and are effective in low concentrations. However, significantly less activity is observed against fungi when compared to bacteria.

Silver nanoparticles are synthesized by physical processes—evaporation-condensation or laser ablation of metallic bulk materials in solution—or more usually by chemical approach, obtaining colloidal dispersions via reductant substances such as borohydride, citrate, or elemental hydrogen; they are usually added to water-based copolymer resins for application. Antibacterial paints and tiles are understandably suited for use in facilities requiring high levels of hygiene, such as healthcare or daycare structures. Contact surfaces such as light switches, door grips, and handles are typical germ accumulators and are suitable for antibacterial treatment to prevent germs spreading. Although inferior to bacteria repellence, silver nanoparticles resistance to fungi and algae growth also make them suitable for exterior finishes for walls (Bioni Perform) and roofs (Bioni Roof), where they ensure long lasting performance for cool roof coats.

Finally, mechanical antimicrobial action requires polymers engineered to become inherently impervious to microorganisms growth due to their surface characteristics.

Researchers at MIT developed an antimicrobial paint able to kill hazardous microorganisms such as influenza viruses and pathogens bacteria (*Escherichia coli* and *Staphylococcus aureus*), thanks to its surface microstructure. This consists of spiky polymers that poke holes in the membranes that surround influenza viruses. Influenza viruses exposed to the polymer coating are essentially wiped out: testing showed more than 10,000-fold drop in the number of viruses on surfaces coated with the substance (Haldar, An, Álvarez de Cienfuegos, & Klibanov, 2006).

AM Technology microhygienic protection similarly provides for a “nanotechnological barbwire” developed during the curing of the coat, thanks to the double polymerization process of the binding agent. Upon coming in contact with the coating, the cell wall of microorganisms will be electrocuted and punctured by the electrically charged surface, killing them.

Mechanical action has the advantage over most surface antibiotic treatments of being immune to resistance development by bacteria. Dead microorganisms may, however, deposit on the surface and constitute a fertile biofilm for further bacteria growth, so regular cleaning is required.

All coatings herein described exhibit continuous biocidal activity, which may not be necessary in the absence of harmful doses of bacteria. Additionally, in certain scenarios, continuous activity can lead to adverse effects of the biocide on the surrounding environment. Research is currently focusing on designing smart biocidal coatings, which exhibit activity only when required such as in the presence of significant bacterial colonization. This behavior can be obtained by applying microencapsulated biocides or fungicides agents such as antibiotics, antimicrobial peptides (AMP), metal (or metal oxide) nanoparticles (NPs), quaternary ammonium compounds (QAC), cationic dendrimers, and hydrogen peroxide, and triggering their release to external stimuli (mainly pH, temperature, light, magnetic field, electric field, mechanical force, ultrasound, ionic strength, and concentration of biochemical agents) that signal the infection (Mitra, Kang, & Neoh, 2020).

7.5.5.4 Thermal responsive surfaces

Thermal performance of building's opaque closures, such as roofs and walls, can be increased through the application of advanced coatings or paints able to make the surfaces reflective to the infrared radiation (thermal reflective surfaces) or to improve their thermal capacity (latent heat storage surfaces).

Thermal reflective surfaces are meant to improve building thermal insulation performance by reflecting some of the heat exchanged with the outside by radiation (Fig. 7.33). When applied on inner surfaces, they help reducing thermal losses during winter by reflecting back inside the heat radiated by warm bodies and heating systems (IR thermal radiation) that would otherwise leave the building. Exterior applications on the other hand reflect part of incoming solar heat (NIR radiation), keeping the building cooler during summer and reducing the urban heat island effect typical of densely populated areas (cool coatings).

In particular, sun radiation reflective coatings can sensibly improve the thermal insulation of buildings surfaces (and of roofs in particular) in summer period in places characterized by high values of solar irradiation (cool roofs). It is in fact evident that the higher the absorption coefficient of the surface exposed to the sun, the higher is the incoming heat flow that can lead to significant phenomena of interiors overheating. In warmer climates, the benefits obtained in terms of reducing energy consumption for summer cooling are in fact significant (up to 25% for low insulated roofs) and, together with reasonable intervention costs, make these investments cost-effective even in the short term (less than a year in many cases).

Thanks to the new advanced cool color technology, building materials in traditional colors such as gray or brick red can reach sun reflectance values of 0.4–0.5, whereas white colors have values around 0.8 and common colored products do not exceed values of 0.1–0.2 (see Fig. 7.34).

Cool colored coatings in fact achieve the same spectral response of traditional materials, such as terracotta tiles, in the visible range (wavelength between 400 nm and 700 nm) which characterizes the color response of a surface. At the same time, they are able to reflect much more energy in the near infrared spectral band (between about 700 nm and 2500 nm), which includes more than 52% of solar radiation energy.

Most products on the market achieve this effect by exploiting a top layer capable of reflecting the visible component of the desired color but transparent to the other wavelengths, which can thus reach a previously deposited substrate characterized by a high infrared reflectance, such as titanium dioxide, and then be reflected in the atmosphere (see Fig. 7.35).

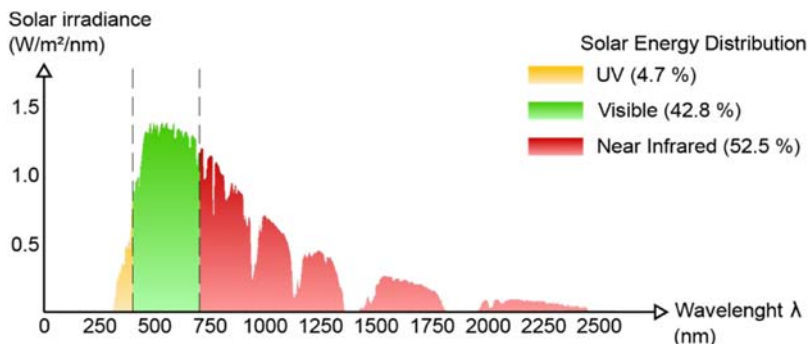


FIGURE 7.33 Normalized solar spectrum energy distribution.

Solar reflectance (cool colour)	0.41	0.44	0.42	0.91
Solar reflectance (standard)	0.04	0.21	0.22	0.80
	Black shingle	Grey shingle	Terracotta roof tile	White acrylic paint

FIGURE 7.34 Cool colors and regular colors solar reflectance values.

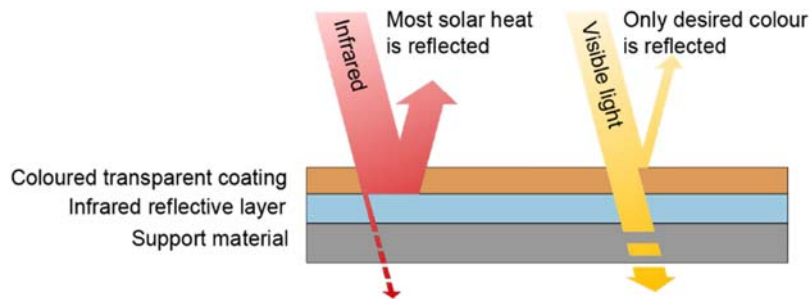


FIGURE 7.35 Cool color coatings.

NIR reflective products in the market consists today mostly of organic (especially acrylic) paints based on titanium dioxide, applied as a simple coating, or sheet waterproof roofing products with bright white (Derbigum Derbibrte) top finishes or aerogel-based coatings (Ama Thermogel) that can be also applied stand alone in case of white surfaces. Best white cool roof coatings combine solar reflectance values around 90% with thermal emittance around 95%, and their diffuse appearance reduces unwanted glare phenomena. Current record values for radiative cooling belong to the BaSO_4 nanocomposite film and acrylic paint developed by researchers at Purdue University in 2020, which achieved a solar reflectance of 98.1% and a sky window emissivity of 0.95. During field tests, the BaSO_4 film stayed more than 4.5°C below ambient temperature and achieved an average cooling power of 117 W/m^2 (Li, Peoples, Yao, & Ruan, 2021).

NIR transparent colored layer instead contains pigments normally in the nanoparticle form based on polyvinylidene fluoride (PVDF), silicate polyester, or acrylic resins with silicon oxide (Cooltile IR or BASF Xfast), or obtained by adding normal paints with specific inorganic pigments based on spinel (blue—black dye) and rutile (yellow—orange dye), produced by companies such as Heubach, Altiris, or Asahi Kasei ensuring high levels of reflectance and thermal emittance in a wide range of tones, even darker ones (cool colors).

Much interesting is the application in cool roofs of thermochromics technology, allowing for paints and coatings able to vary their color and reflectance performance according to temperature, thus combining heat load reduction in summer with heat gain exploitation during winter. Thermochromic paints and coatings available on the market are usually based on organic leuco dye mixtures composed by three elements: the first component is a cyclic ester which determines the final color of the product in its tinted state, the second is the color developer, a weak acid that imparts the reversible color change to the thermochromics material and is responsible for the color intensity, and finally the third component is usually an alcohol or an ester with a fixed melting point, and controls the color transition temperature. When temperature rises, the thermochromics layer becomes translucent, revealing a clear, highly reflective TiO_2 layer beneath. The thermochromics mixture is microencapsulated and isolated from the paint base and binders in order to preserve its properties over time.

Researchers from Athens University compared summer performance of traditional, “cool roof” and thermochromics paints in several colors; in the case of black coating, the thermochromics one measured surface temperatures up to 15.3°C lower than traditional paint and 8.3°C lower than “cool colored” paint (Karlessi, Santamouris, & Synnefa, 2009).

On the other hand, the thermochromics roofing tile Thermeleon, patented by MIT graduates, is based on a phase-change polymer gel layer over a dark, heat absorbing substrate. At lower temperatures the solution is clear and

colorless, allowing the black backing to absorb most solar radiation. When temperature rises above a fixed set point, in a range from 0°C to 100°C, the polymer phase separates from the gel turning the solution into a mixture of polymer and solvent with different refractive indexes and the tile becomes white and light scattering. Tests showed that the tile was able to absorb 70% of solar radiation in winter mode and to reflect 80% in summer mode.

Cool roof coatings may also take advantage of the added thermal storage potential provided by PCMs, with beneficial effects in maintaining thermal comfort and temperatures stability in the indoor environment (Kalaiselvam & Parameshwaran, 2014).

Microencapsulated PCM pigments with particles size in the 17–20 µm range, containing paraffin wax with 170–180 kJ/kg latent enthalpy, can be mixed to any color paint material. Application of these PCM color coatings proved effective in reducing surface temperature by up to 7°C–8°C compared to conventional color coatings of the same tint, a performance slightly higher than correspondent cool color paints. As such, PCM paints can be considered a viable method to incorporate latent heat storage systems even in the roof surface.

PCM coating can be applied also to the inner wall and roof surfaces to absorb internal heat and improve interiors comfort. Products such as Winco Thermo Confort are engineered for thin applications of few mm. The coating contains a 75% proportion of microencapsulated bio-based PCM, with 184 kJ/kg enthalpy. Heat absorption range is 23°C–26°C, releasing heat at 18°C–22°C upon solidification.

Finally, thermal insulation of inner surfaces can take advantage also from the application of infrared radiation reflective coatings obtained by including in the paint blend hollow microspheres of ceramic (Insuladd, Nanoceramix, Thermoshield, Thermodry) or glass (3 M Glass Bubbles), nano-molecules of Hydro-NM-Oxide (Nansulate) or aerogel particles (Ama Thermogel) with the added benefit of protection against corrosion, rust, and mold.

7.5.5.5 Photo luminous coatings

With the goal to harvest energy from the environment and reduce the consumption of fossil fuels for lighting, photoluminescent coatings have been developed to make building materials glow at night without the use of electric energy.

In particular, photoluminescent materials are smart energy-exchanging materials capable of absorbing solar light and re-emitting it at a different wavelength in the visible spectrum. When the time delay between absorption and emission is in the fractions of seconds, the photoluminous effect is called fluorescence, whereas when the time delay is longer, and there is still a decayed afterglow after the excitation source is removed, the effect is instead called phosphorescence. By varying the nature of the photoluminous material, and particularly its embedded impurities, emitted light in various colors can be obtained.

The fluorescence effect is commonly used in fluorescent lighting where a fluorescent agent (a compound of three or more halophosphates) absorbs UV radiation emitted by the electroluminescent gases (neon, argon, xenon, krypton) and re-emits it in the visible range.

Photoluminescent materials are widely employed in the fields of interiors decoration (phosphorescent or fluorescent paints) and building materials, such as glass bricks containing phosphorescent crystals able to glow in the dark (TGP Veluna, Seves Luminescent Glass Block). As for the phosphorescent materials, of particular interest is Starpath Spray-On developed by British based Pro-Teq, which can be applied on the surface of any concrete, asphalt, or wood pavement, to make it glow without the need of electric energy. This special coating absorbs light radiation during the day to return during the night after sundown. The coating, which is also nonslip and water resistant, is currently being tested in the central park of Cambridge in the United Kingdom, where it was sprayed on a total area of 150 m² (the application time is only 30 minutes, allowing to have a surface ready for use after approximately 4 hours from the application). The coating is also antireflective and is available in 11 different colors.

The concept was further developed leading to the launch of Starpath Pro, which forgoes the spray on application for the safer, more environmentally friendly solution of a ready to use photoluminous blended stone aggregate. Installation simply requires mixing the aggregates with a specific two-part polyurethane resin binder for three minutes, and once spread and levelled the surface will be ready for foot traffic in 4 hours. The product can only be applied to a hard substrate such as concrete or tarmac. The result is a natural appearance pathway in the daytime which transforms into a soft blue luminescent glow at night (see Fig. 7.36)

Similarly, the project Smart Highway in the Netherlands provided for making road surface markings of a 500 meters stretch of highway N329 at Oss with paint enriched with “glow-in-the-dark” luminescent powder in place of traditional street lamps. The phosphorescent paint is charged by sunrays during the day and provides up to 10 hours of night illumination. The same team turned 600 meters of the Van Gogh cycle track in Nuenen into a visual art piece, inspired by the “Starry Night” painting by the same artist, thanks to the photoluminescent pavement. The effect was obtained by



FIGURE 7.36 Photoluminous pavement. *Courtesy of Pro-Teq Surfacing Ltd.*

incorporating individual paving granules with a photosensitive coating in shades of green and blue and then depositing them on a bed of concrete. Solar energy stored during the day is sufficient for up to eight hours of night lighting, and in cloudy days is aided by LEDs integrated into the paving and powered by solar panels.

7.5.5.6 Self-healing surfaces

Self-healing characteristics, or the ability of a surface to heal itself without any external intervention, are very desirable in a number of coatings, be them esthetic paints and lacquers or more durable coats to protect underlying materials, such as wood, steel, concrete, and plastics, from harsh environments. Developed for high end applications such as aeronautics, ship industry, bridges, or wind turbines rotors, they have also found use in the building industry for protecting steel and concrete structures in harsh environments. Benefits obtainable are related to the reduction of both costs and environmental impact related to maintenance of ordinary buildings and infrastructures; however, self-healing can even enable new, extreme engineering applications by preventing corrosion and oxidation to enter the substrate via cracks and discontinuities that may develop on the surface finish.

Main mechanism exploited for self-healing is the integration in coating or directly in the materials of two types of microcapsules, respectively, containing a healing agent and its catalyst (see Fig. 7.37). When the coating is damaged by cracks, scratches, or abrasion, capsules in that region are ruptured, releasing both the healing agent and the catalyst. As they mix, a polymerization reaction occurs, filling in the damaged area and preventing crack propagation or damage to the substrate. Microcapsules diameter and shell-wall thickness also vary according to application; however, microcapsules size (up to 100 μm) still prevents them from esthetically demanding applications such as thin, glossy coatings, which would result granular to the touch. Much care must be taken in designing and manufacturing the microcapsules, for they must be resistant to solvents, be able to be dispersed or spray applied, be stable in storage, be able to form a composite with the dispersion matrix, and crucially must break open on cracking of the coating.

A number of different solutions are available to provide self-healing characteristics to different coating materials with two main approaches.

The first uses microcapsules filled with dicyclopentadiene, a relatively inexpensive monomer, and a ruthenium-based catalyst.

The second approach, called “autonomic materials self-healing technology,” is instead based on polydimethylsiloxane (PDMS) and can be tuned for elastomer coatings such as urethane and silicone coats (microencapsulated vinyl terminated PDMS resins), thermosetting coats such as epoxies and vinyl esters (microencapsulated hydroxyl-terminated PDMS, silyl ethers and viscosity modifiers), or UV cured powder coatings (microencapsulated blends of PDMS resins), each coupled with a corresponding catalyst.

A limiting factor for the application of these technologies is the requirement for developing cracks to intercept both healing and catalyst agents capsules to initiate the healing reaction. This in turn demands an even and dense distribution of both, whereas catalyst capsule naturally tends to segregate rather than disperse evenly. In addition, limited quantities stored in microcapsules may not be sufficient to fill larger cracks. A possible solution to address these last issues is by resorting to hollow microtubes instead of microcapsules, to provide larger quantities of healing agents and aid in intercepting ruptures.

Main issues related to two-part healing agents, namely, the uneven distribution of microcapsules throughout the coating and the high cost of catalysts, are encouraging research toward one-part polymerizable healants. Promising candidates are isocyanates and silanes, which are capable of polymerizing in the presence of water, and are therefore

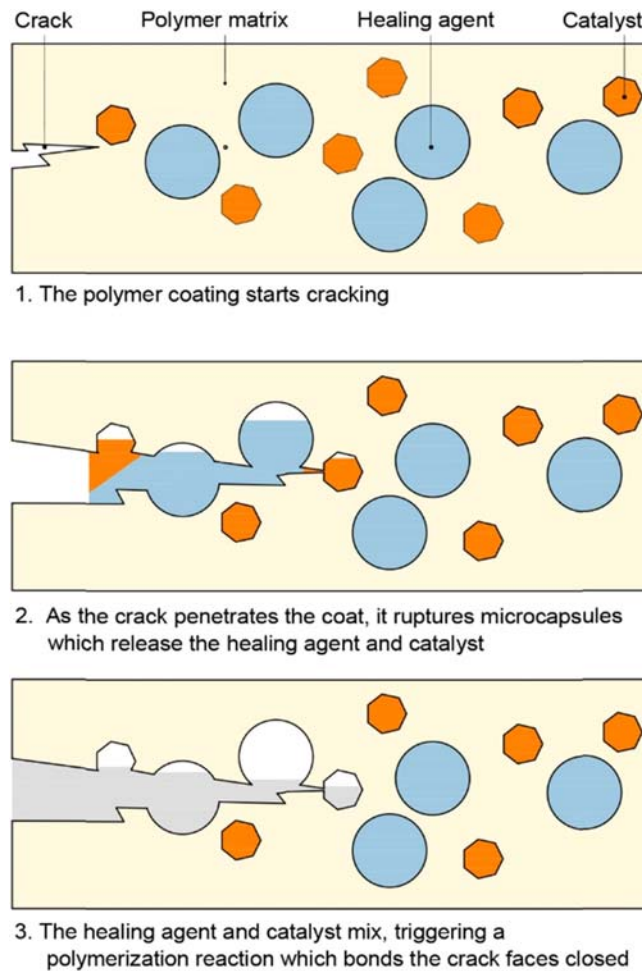


FIGURE 7.37 Self-healing coating operation.

suitable for several coating applications, especially in corrosion protection (Zhang et al., 2018). Also interesting is the proposed encapsulation of linseed oil with self-assembled graphene oxides microcapsules to obtain self-healing effect in waterborne polyurethane coatings (Li et al., 2017), with the added benefits of enhanced lubricating properties of the coated surface (Li, Cui, Wang, Zhu, & Wang, 2017).

For polymeric surfaces, other self-healing approaches have been developed involving the addition of thermoplastic healing agents to a harder, thermoset plastic base. If heat is supplied, the thermoplastic inclusions change viscosity and are able to cope with small cracks and ruptures. Some materials may also undergo a reversible polymerization process, which involves mixing and heating the monomers required then cooling them slowly, allowing for the development of reversible Diels-Alder polymerization reaction to form a cross-linked material with strength comparable to traditional structural epoxies (Zhu, Liu, Gan, & Long, 2020). Upon rupture, the material is clamped and heated and a reverse polymerization process occurs, mending the cracks. However, a decisive drawback is the requirement of heat for the healing process to take place, in some cases up to 120°C; this is incompatible with most buildings applications and may be suitable for high temperature applications such as exhaust systems of hot pipes.

Concrete-specific self-healing coatings are also under research and may prove extremely useful for roads and pavements. There, superficial cracking allows water to penetrate the concrete and destroy it as it expands and contracts with temperature variations.

Scientists from Yonsie University, South Korea, developed a sunlight-activated, catalyst-free self-healing coating constituted by a healing agent (MAT-PDMS) paired with a benzoin isobutyl ether photoinitiator. These are encapsulated in UF polymer capsules and applied to the concrete surface via a sol-gel reaction. When superficial cracking occurs, the healing agent is released from ruptured microcapsules and fills the damaged region. Upon photo polymerization induced by sunlight, a layer to protect against water permeability and chloride ion penetration is developed. Coating application also makes concrete hydrophobic. Researchers claim this coating to be both inexpensive, since preparation is eased by

not needing a catalyst, and environmentally friendly, as it could reduce maintenance on roads, bridges, and other concrete structures.

7.5.6 Mimetic photovoltaics

As an application of the PV technology, building integrated photovoltaic (BIPV) systems have attracted increasing interest in the last decade and have been shown as a feasible on-site renewable power generation technology to cover energy needs of new and existing buildings. The relationship between PV and construction has therefore evolved in the years through gradual steps of innovation, resulting in a progressive technological transfer of PV technology in the building technical elements, from the simple addition of PV in already existing elements (building adapted photovoltaics, BAPV), up to the layering of the building skin with active parts that can combine energy production with the provision of other major functions such as sound and thermal insulation, rain screening, and solar radiation protection.

As in the XXI century the demand for more intelligent and energy-efficient green buildings became more ambitious worldwide and the building codes became more stringent on the way toward zero or positive energy buildings, the global market in the BIPV sector evidenced a global compound annual growth rate of $\sim 40\%$ from 2009 up to 2019 with a value of USD 7.5 billion in 2019, expecting to reach USD 11 billion by the end of 2026, growing at a CAGR of 5.62% between 2019 and 2026 (IFF Market Report, 2020).

Currently, several products for the building integration of photovoltaic technologies are available on the market, characterized by advanced design, flexibility, attention to detail, variety in color, shape, and transparency degree, in order to meet any requirement. Only in Europe, the present market of BIPV systems for buildings is supported by more than 100 manufacturers of commercially available products (Taylor & Jäger-Waldau, 2019). Thanks to the enormous progress in PV technology development (cost-wise and performance-wise), PV systems can now be integrated on any surface and in any building element, from roof tiles, to flat or curved windows, to ETFE cushions, to shading elements, pavements, up to street furniture elements, representing a strategic part of the future building vision (see Table 7.13).

Today, the main BIPV products available on the market include solar roof tiles or shingles, rain-screen façade elements, windows and glass façades, skylights, and flexible PV panels for roofs and facades (Jelle, 2016; SolarPower Europe, 2019; SUPSI, 2017).

The expected massive use of PV in the building sector will require a re-imagination of the solar envelope not only from a technology point of view but also from the esthetic one.

In this picture, the modification and optimization of the esthetic appearance and color of BIPV elements is attracting increasing interest. As BIPV modules determine the esthetics of the whole building, appearance plays an important role for the acceptance of BIPV applications. So far, the coloring and texture of PV, namely, its ability to be camouflaged or “designed,” has been considered an essential requirement for market acceptance of PV façades.

Instead of a BIPV finding its value just in its physical role of functionally replacing an element of the building skin, the main value of BIPV products is now the capacity to become “invisible,” manufactured as similarly as possible to existing building components, and suit their requirements inconspicuously (see Figs. 7.38 and 7.39).

This strategic objective has led to intensified research and development aiming to create mimetic BIPV products that come in a variety of colors and sizes, while at the same time being as close as possible to existing building components, to its requirements and how it is considered by the construction industry.

TABLE 7.13 PV modules best lab efficiency (Green et al., 2021).

PV technology	Module dimensions (cm ²)	Efficiency (%)	Manufacturer
Si-monocrystalline	13177	24.4	Kaneka
Si-multicrystalline	>14000	20.4	Hanwha Q-cell
Copper indium gallium selenide - CIGS	841	19.2	Solar Frontier
Cadmium telluride - CdTe	7039	19.0	First Solar
Perovskite	804	17.9	Panasonic
a-Si two junctions	>14000	12.3	Tel Solar
Organic	200–800	11.7	Zae Bayern



FIGURE 7.38 Mimetic PV roof on an historical center. *Courtesy of Solaxess.*



FIGURE 7.39 Mimetic PV roof tiles in Pompeii Archeological Park. *Courtesy of Dyaqua.*

Mimetic BIPV solutions could be adapted to the variety of materials, colors, and shapes that can be seen today in the center of cities, where a diversity of buildings from different eras and construction solutions coexist with each other, with a great potential of application on protected heritage buildings within complex urban settlements, in historical contexts such as Dyaqua “Invisible Solar” PV tiles installation in Pompeii Archeological Park in Italy in 2018 (Fig. 7.39), or on multistory buildings facades (such as high rise buildings or blocks of residential units) that do not have enough roof area to meet the energy performance requirements (on tall buildings the roof space is generally too small, and parts of the roof are often occupied for other purposes such as technical installations and increasingly also for vegetation).

The market overview of state-of-the-art mimetic BIPV products clearly reveals that for all parts of a BIPV module (PV-active layers, encapsulation layers, glass), there are technical solutions available for coloring or texturing, changing the esthetic effect (IEA PVPS Task 15, 2019).

Main solutions include:

- colored and textured PV cells and modules for solar roof tiles or shingles and rain-screen façade elements;
- semitransparent and colored PV thin film for applications on windows and glass facades, skylights, shading structures and solar-shading devices, balcony glazing.
- invisible PV solar system for windows, skylights and canopies.

7.5.6.1 Colored and textured building integrated photovoltaic modules

A first form of esthetic integration of PV modules can today be achieved due to the huge progress in terms of conversion efficiency of thin film technology, and CIGS technology in particular. Thanks to their monolithic, “all black” deposition, thin film modules can in fact be pleasingly integrated in rooftop and façade applications with frameless modules without any visible cell or connection, incorporating them seamlessly into building facades rainscreen and cladding. Colored thin film modules can also be obtained by screen-printing the front glass elements or by controlling light reflections. On the other hand, conventional c-Si modules appearance can be improved by covering the front ribbons with small stripes (Ertex Solar) or eliminating them altogether by employing back contact technology. With metal wrap through architecture, for instance, cells are no longer welded at the connection points, but stuck with conductive glue

on a conductive back sheet that acts as a contact and connection for the positive and negative contacts, enabling a gap-free and connection-free appearance (Trienergia, Invent) (Slooff et al., 2017).

In addition to thin film PV, different customization techniques can be identified in the current practice and future developments to obtain colored or textured BIPV modules using conventional c-Si solar cells. They include:

- anti-reflection coatings on c-Si solar cells;
- special solar filters as layers, coatings, or interlayers with colors or patterns;
- modified front glass by printing, coating, or alternative finishing.

Products with colored anti-reflective coatings on solar cells (c-Si)

As bare crystalline silicon (c-Si) presents high reflectance values (around 30%), both monocrystalline and multicrystalline PV cells include AR coatings on their surfaces, having a coating thickness optimized to increase the efficiency conversion and giving to the cells their typical blue color.

Different colors such as blue, green, yellow, orange, and pink can be obtained by changing the AR coating thickness, leading to a shift in the reflection minimum to the near-infrared range, and boosting the reflection in the visible spectrum, with the drawback of lower energy yield of the PV cell, 7.5% to 12.8% less efficiency with worse performance from lighter colors (Lofsolar, SUNERG X, VGS, Azimut) (Røyset, Kolås, & Jelle, 2020).

This kind of solution is finding vast application for pitched roofs, where they minimize the visual impact of the PV panel near standard tiles or shingles, or for glass-to-glass products for skylight applications.

Another upcoming approach for tuning the color of standard c-Si solar cells relies on plasmonic coloring. A 8 nm thick layer of silver (Ag) nano-particles with a diameter between 50 and 150 nm is created by pulsed sputtering on the surface of standard c-Si solar cells, inducing plasmonic light scattering at around 450 to 550 nm and causing a color change from blue to green, insensitive to the angle of observation. Performance analysis of the c-Si cells before and after coating shows that the power of the cells is decreased by less than 10% when the nano-coating is applied. Alternative colors should be obtainable by varying the nanoparticles material (e.g., using gold instead of silver would result in red colors) or the sputtering time (affecting the nanoparticles diameter and thus the reflection spectrum) (Peharz et al., 2017).

Products with colored/patterned interlayers and/or special solar filters

To affect the appearance of the PV panel, it is possible to laminate an interlayer with a certain color/pattern inside the module, either as an additional encapsulant sheet or acting as the encapsulant itself.

To obtain the desired pattern, conventional film printing techniques from the graphics industry or semitransparent inks that allow light to pass through can be used. With this technique, high-resolution images printed on a film with special inks are laminated between cells and the cover glass. After the module is laminated, only the printed image can be seen on the surface while solar cells behind are no longer visible (Kaleo-Solar, Ilooxs) (see Fig. 7.40). Other manufacturers provide esthetic overlays to apply directly to the solar module akin to a graphics vinyl (SolarSkin).



FIGURE 7.40 PV module laminated with printed interlayer. Credit: Kaleo Solar.



FIGURE 7.41 Invisible photovoltaics. *Courtesy of Solaxess.*

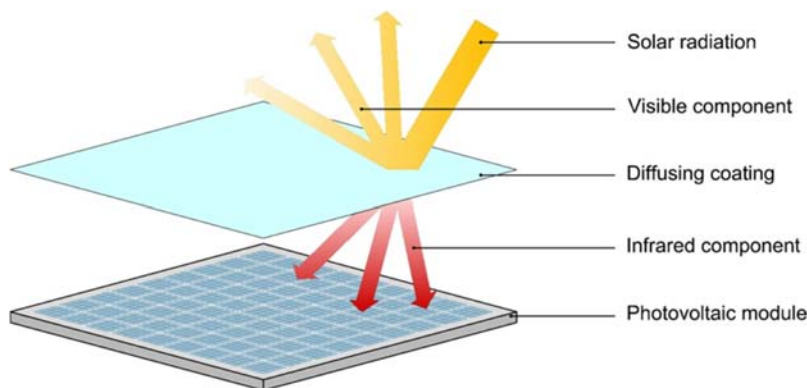


FIGURE 7.42 White photovoltaics.

Particularly interesting is the technology developed by the Swiss company CSEM and commercialized by Solaxess that allows to make photovoltaic modules in variety of colors, including white, without cells and connections visible, allowing better esthetic integration in buildings (see Fig. 7.41).

This is achieved, thanks to a selective and diffusing nanotechnological film, laminated in front of the glass cover beneath an ETFE protective sheet, able to diffuse the entire visible spectrum of solar radiation without affecting the transmission of the infrared component, which can be converted into electricity by the photovoltaic cells beneath (see Fig. 7.42). This scattering selective filter consists typically of a plurality of transparent dielectric layers with different refractive indexes, stacked on top of each other. Any photovoltaic technology based on crystalline silicon may thus be used for the realization of white or colored modules, although heterojunction crystalline silicon solar cells are the preferred choice as they combine higher open circuit voltages compared to standard silicon solar cells (730 mV instead of 630 mV), with an excellent response in the infrared part of the solar spectrum. Performance of a white heterojunction solar module reaches 11.4% measured under the AM 1.5 spectrum, with a 38% loss of efficiency compared to the same cell technology having usual appearance.

Coming as a lightweight, flexible film (147 micron thick and 203 g/m² area density), this technology can be integrated into the manufacturing process of new panels, on flat or curved surfaces. Furthermore, the modules' white surface allows solar cells to work at temperatures 15°C–20°C lower than conventional panels, greatly enhancing their efficiency (PV electrical output decreases with temperature at rates of 0.3%–0.5% per degree Celsius). White solar panels may also act as cool roofs, saving energy in buildings while keeping the interior cooler and thereby reducing the costs for air conditioning.

Products with coated, printed, specially finished, or colored front glass covers

A strong new trend is to use different surface treatments applied to the front glass cover, as are usual in the building sector. These methods include the application to the glass of a special spectrally selective coating or a ceramic printed cover, designed to disguise the underlying photovoltaic components of the module or to introduce new design elements.

Thin film techniques like physical vapor deposition (PVD) and chemical vapor deposition (CVD) allow a new approach to generate colors with interference coatings for PV modules with high color saturation and homogeneity and a low power impact. Both techniques are already widely used in the glazing industry for other type of coatings.

Using a sputtering process, SwissINSO SA manufactures color treated front glass for BIPV modules. Kromatix technology, developed by SwissINSO SA in partnership with EPFL (Swiss Polytechnic Institute), combines a multilayered reflective coating on the inner side of the glass with a diffusive surface treatment on the outer surface, reinforcing the masking effect of the colored filter and preventing glare effects (see Fig. 7.43). The interference reflective coating is created via low-pressure sputtering nano-deposition on the inside face of the glass sheet, whereas the light-diffusive treatment is obtained by etching microscale polygons (10 μm high and 100 μm across) on the outside, replacing the usual specular reflection with a diffuse one and improving solar transmittance inside, while providing a pleasing mat appearance (Jolissaint et al., 2017). The conversion efficiency of modules with a white front glass is 11.4%, instead of 19.1% for standard modules (IEA PVPS Task 15, 2019). Different colors such as gray, terracotta, blue, bluish-green, green, and yellow can be realized (See Fig. 7.44). One of the largest installations of Kromatix glass elements is in Copenhagen, Denmark, with the façade of the CIS building clad in 70 x 70 solar panels in various shades of blue (See Fig. 7.45).

Researchers at Fraunhofer institute devised an AR, colored front glass for PV modules exploiting 3D photonic structures, an example of biomimicry based on the wings of the Morpho butterfly. The shimmering shades of blue and green that characterize these insect are not the product of pigmentation, but result from the 3D nanostructure of the wings surface, in which thin film interference effects and structure effects interact (photonic structure). This effect was replicated by applying on the rear face of the front glass a multilayer Bragg stack with alternating high and low refractive index dielectric layers on a rough substrate, via a combination of structuring and sputter coating. This way, a homogeneous appearance with saturated color is achieved, that can be further enhanced by applying a texture on the front side in order to improve the color tolerance and suppress glare effects. Green, red and blue solar modules evidence a 7% power loss compared to a module with an uncoated glass cover. Mixed RGB colors can be composed out of functional layers for red, green, and blue (Bläsi et al., 2017).

Another approach to treating BIPV modules resort to the application of ceramic material to the front glass substrate (ceramic fritting) to disguise the underlying photovoltaic components of the module or to introduce new design elements (Colorblast, Heliartec Pixasolar, Ertex Solar). This way it is possible to achieve a much greater freedom in terms of colors or image reproduction, with full color, marble, wood (see Fig. 7.46), bricks, or graphic effects obtainable at the expense of light transmittance toward the PV cells and, ultimately, of energy yield. Conventional methods for ceramic application include digital printing, screen printing, roller coating, “curtain” coating and spraying, with digital printing providing best image fidelity and screen printing being the most commonly used.

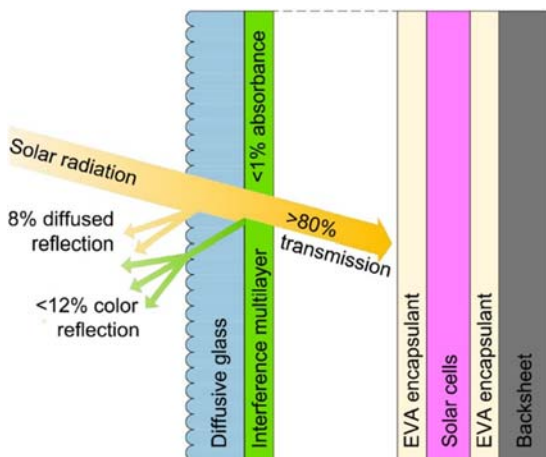


FIGURE 7.43 Kromatix colored PV operation.



FIGURE 7.44 Kromatix color palette. *Courtesy of SwissINSO.*



FIGURE 7.45 Kromatix PV panels on Copenhagen International School. *Photos by the author.*

Digital printing is mostly similar to traditional inkjet printing and provides for the application of a thin layer of ceramic frit ink obtaining a translucent appearance, with barely visible stripes in the printing direction. Image quality is the best among fritting techniques, allowing full-color photography or vector graphics with resolution up to 720 dpi.

In screen printing method, a paste containing the ceramic pigment and matrix particles is distributed over and pressed through a framed screen onto the glass pane. The geometrical parameters of the mesh constituting the screen and the viscosity of the paste determine the thickness of the applied coating. The printing screen can be masked, such that partial printing with patterns such as spots, stripes, or free forms can be achieved. After drying, the enamel coating is fused onto the glass substrate by firing in a furnace, a step part of the thermal toughening process for the glass substrate. Depending on the processing parameters, the thickness of screen-printed fritted (or enamel) coatings is typically between 25 μm und 35 μm (Kanellopoulos et al., 2015). Using this process, it is possible to print several colors (Wilson & Elstner, 2018).

In the PV module, the enamel coating is usually on the inner surface of the glass cover, adjacent to the cell encapsulant layer. Outside surface is uncoated glass, which is easier to clean than the enameled surface but subject to glare phenomena. Some manufacturers provide a diffusing, silk-finished external glass to better mimic the texture of conventional building materials.



FIGURE 7.46 Pixasolar ceramic inkjet printed PV modules. *Courtesy of Heliartec.*

The perceived color of the fritted/enamelled surface is determined by the size, type, and optical density of the pigment particles in the ceramic coating. White titanium dioxide particles scatter radiation over the whole solar spectral range without significant absorption, whereas colored pigments absorb in some parts of the visible spectrum and reflect the remaining wavelengths, and finally black pigments absorb strongly in the visible range of the spectrum, which may raise operating temperature of the module (Kutter et al., 2018). At the same time, since most panels are black or dark in color, specifying a lighter colored surface may require more pigment particles compared to a darker one, resulting in darker colors having a higher performance than lighter colors. As some radiation is lost by reflection or absorption in the ceramic coating, the photovoltaic power output will be reduced in comparison with the same cells with an uncoated glass cover. For 40% area coverage with the print, the transmittance loss of the glass pane measured in air relative to the unprinted glass substrate was 33%, whereas the decrease in short-circuit current was only 18%.

7.5.6.2 Semitransparent and colored thin-film photovoltaic glazing

Among the different ways of integrating photovoltaic technologies into the building envelope, the one related to the glazed components is particularly interesting for the possibility of combining energy production, protection from solar radiation, daylighting control, and color quality.

In addition to the more traditional glass-glass photovoltaic systems, manufactured by inserting crystalline cells inside two glazed panes, it is now possible to create transparent and colored closures using photovoltaic technologies based on inorganic (a-Si, CdTe, CIGS) or organic (OPV, dye-sensitized solar cells - DSSCs) material semitransparent thin film.

Thin film technology allows today to realize a semitransparent photovoltaic film that has a thickness ranging from a few nanometers to tens of micrometers of active material. There are many techniques to deposit thin films on a substrate, such as chemical bath deposition (CBD), PVD or sputtering, electro deposition, screen-printing, pulsed laser deposition, and spray and atomic layer deposition (ALD) (Husain et al., 2018). Thin films can be applied inside two glass panes or on the inner side of the external glass of a double or triple glazing (position 3). The semitransparent thin film, in addition to producing electricity, allows at the same time sunlight in, avoiding UV and infrared radiation, and permits vision through the glass. Different degrees of transparency (normally 10%, 20% or 30% up to fully opaque) can

be chosen depending on the degree of solar protection or light transmission required. Glass can have any shape (circular, trapezoidal, triangular) and can also have a curved profile.

Semitransparent inorganic thin film technology is usually based on amorphous silicon (a-Si) or on CdTe (Alrashidi et al., 2020). CIGS technology holds the efficiency record for thin film (23.3% for NREL concentrator cells) but semitransparent application is still being researched. The power of the module depends on the technology used, which determines the efficiency of conversion of solar radiation, and on the degree of transparency of the film. Increasing transparency decreases electric power.

Semitransparency of PV layers can be obtained for example for a-Si PV modules thanks to laser treatment of the active layer that is partially removed in order to increase the light transparency. For CIGS solar cells, researched solutions for semitransparent application include partial removal of the semiconductor layer, deposition on holed substrates or nano-thin deposition on transparent conducting electrodes. Solibro Research has experimented with partial removal of the semiconductor layer by both water-jet polishing and dry sand-blasting by using screen printing as a mask; the latter approach was found to perform better. A semitransparency of 40% can be achieved while the PV module efficiency is reduced by 45%–50% due to additional edge effects from the removal. The developed removal process with dry sand-blasting is versatile and can virtually produce any pattern as long as the semiconductor is connected such that current can pass through. Another approach to CIGS semitransparent application provides for the co-electrodeposition of Cu-In-Ga mixed oxides on a submillimetric hole-patterned molybdenum conductive substrate, followed by thermal reduction to metallic alloys and selenisation. This selective deposition technique grows the thin film only on Mo covered areas, preserving transparency of the device according to the degree of perforation (Sidali et al., 2018). A final method concerns the substitution of the opaque molybdenum conductive substrate with a transparent fluorine-doped tin oxide-coated glass, on which ultra-thin CIGS absorber layers are deposited with thickness in the order of 200 nm, compared to conventional values of more than 1 μm . Obtained values for VLT and conversion efficiency are 18.59% and 6.46%, respectively (Shin et al., 2019).

Semitransparent thin film technology can be successfully combined with colored PVB as the back encapsulant to obtain PV colored glass with various degrees of transparency (Onyx Solar, Soltech Energy). Customized and standard PV glazing products are offered by the manufactures, showing different mechanical, thermal, optical, and electrical characteristics and can be applied for skylights, façades, canopies, flooring, and walkways. As the photovoltaic thin film is sputtered onto the front glass cover during production, the energy output is not affected by the colored encapsulant behind it.

In alternative to the colored polymer film, mass-colored glass can be used in the back cover in any glass-to-glass PV technology; the result is semitransparent BIPV modules with different sizes and colors. The color and transparency can be designed to optimize the solar factor, enhancing the thermal comfort inside the building.

Another opportunity is today offered by PV modules based on OPV cells or DSSC modules. Thanks to these new materials used to convert the solar light into electricity, it is possible to obtain modules in different colors and transparency, with several manufacturers providing materials (H.Glass and Solaronix for DSSCs) or ready to use modules (Heliatek and Opvius for OPVs).

OPV cells are formed by one or more layers of photoactive polymers comprised between two metallic electrodes. These materials are characterized by high optical absorption, allowing the use of very thin flexible films suitable also for plastic substrates and for installation on cloth, curtains, canopies, or furniture elements (see Fig. 7.47). Economic, high output processes such as roll to roll manufacturing are viable, as is spray application, promising a much lower cost of manufacturing compared to inorganic PV technologies. Conversion efficiency is however still limited to 11.7%, and durability over time of OPV modules exposed to UV rays is still a concern.

DSSCs, also known as Grätzel cells after their inventor, belong to the category of hybrid solar cells, as they use both organic and inorganic components. Generally these cells employ a layer of microporous TiO_2 impregnated with both inorganic or organic photosensitive pigments (dye sensitized). Most used inorganic dye is ruthenium; organic dyes usually consist in plant-derived anthocyanins or animal derived porphyrins. These are enclosed by two TCO layers which can be directly integrated on supporting glass as coatings (see Fig. 7.48). DSSC have thermal stability issues due to the use of liquid electrolytes: at low temperatures the electrolyte may freeze, blocking the production of power and potentially causing physical damage, whereas at high temperatures, the liquid expands, making the sealing of modules difficult. A notable example of architectural integration of DSSC cells is the SwissTech congress Center of Ecole Polytechnique Fédérale in Lausanne (see Fig. 7.49).

In particular, the efficiency of DSSCs has been increasing steadily (from $\sim 7\%$ to $\sim 14\%$) over the last two decades. Although still less efficient compared to silicon solar cells, organic dye-sensitized solar cells using natural pigments have several advantages, such as a wide selection of colored and transparent hues, lower dependence of energy

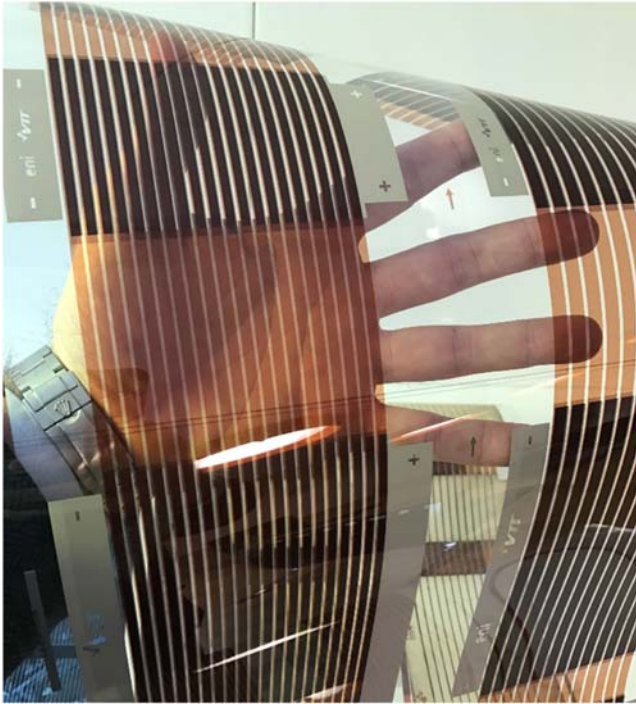


FIGURE 7.47 OPV solar cell. *Photo by the author.*

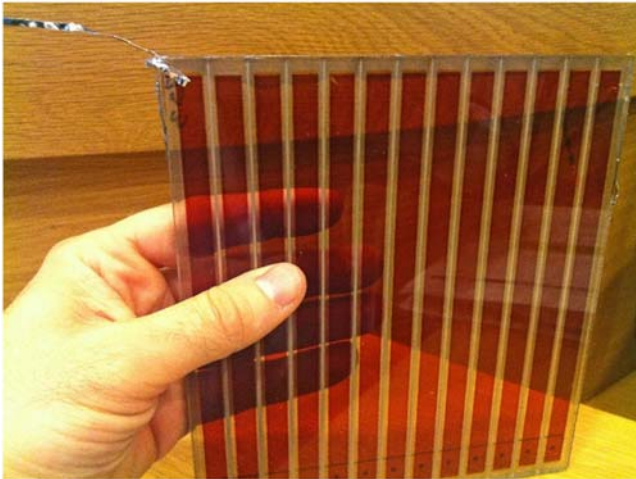


FIGURE 7.48 Dye sensitized solar cell. *Photo by the author.*

generation on the angle of incidence and the intensity of sunlight, easier and less expensive manufacturing process, light weight and flexibility (Lee & Yoon, 2018). DSSCs' potential makes them suitable for multiple applications such as solar-control fins and louvers, sun-shading canopies, as cladding for curtain wall façades and rear-ventilated façades, semitransparent windows, sliding shutters, or street furniture.

7.5.6.3 Invisible photovoltaic solar system for windows, skylights, and canopies

Luminescent solar concentrators (LSCs) represent a promising solution in relation to the seamless building integration of solar-powered architectural components, thanks to their ability to produce renewable energy preserving the transparency of glazed surfaces.

LSCs are transparent slabs capable of absorbing specific ultraviolet and infrared wavelengths in the nonvisible light specter, and then re-emitting them by luminescent effect as invisible infrared at a longer wavelength. Some of this

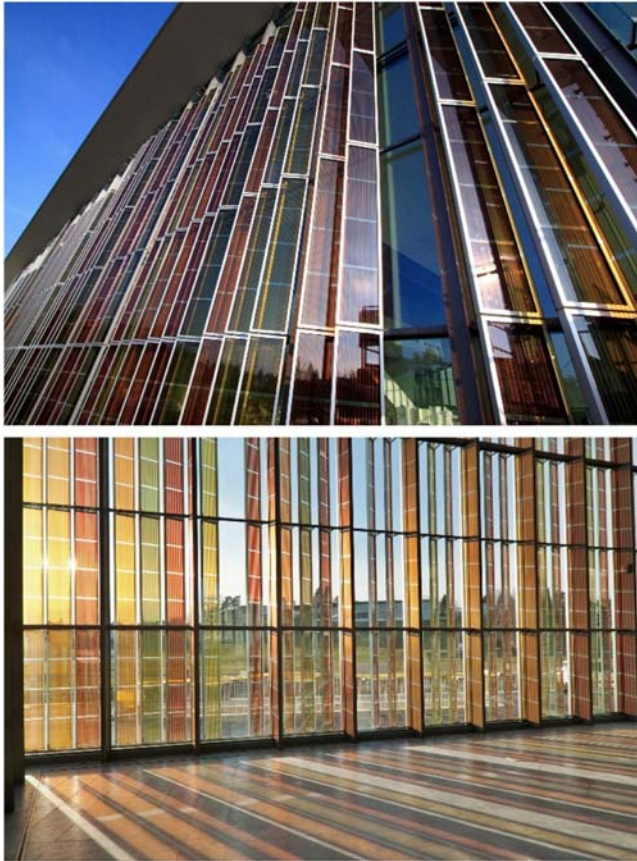


FIGURE 7.49 DSSC BIPV facade, SwissTech Convention Center, Geneva. Credit: Solaronix SA.

re-emitted radiation is trapped by total internal reflection in the polymer plate by virtue of its high refractive index and is thus directed to the panel frame where thin strips of conventional photovoltaics convert them into electrical energy (see Figs. 7.50 and 7.51). Solar radiation falling in the visible range remains instead almost unchanged, giving LSCs a transparency up to 90%, although opaque LSCs are also viable.

Suitable materials for LSCs include organic salts (Zhao, Meek, Levine, & Lunt, 2014) as well as vitreous or polymeric glassy materials such as PMMA doped with tiny amounts of fluorescent dyes (Aste et al., 2019).

Currently, research developments are addressing one downside of one of the most used re emitting materials, inorganic salts, namely, their tendency to re-adsorb some of the radiation emitted. A viable solution is to substitute them with quantum dots custom engineered for a larger separation between adsorption and emission bands (Stokes shift) with the added benefit of eliminating toxic heavy metals such as cadmium from quantum dots composition and optimizing their absorption and emission to avoid any color casting of transmitted light (Meinardi et al., 2015). Another approach to limit light self-absorption is resorting to derivatives of benzothiadiazole, a semirigid molecule that allows a fast molecular rearrangement of the excited state and more efficient radiative emission of photons, with a Stokes shift ten times larger than conventional LSCs (Iagatti et al., 2017). The absorption spectrum is tunable from 400 to 600 nm, covering large part of the visible spectrum, thus color cast is present but can be chosen among a large palette of colors, from yellow to orange, red and violet. Colored LSCs are suitable for integration in windows and openings in which color neutrality is not necessary, such as transom windows or skylights: in these applications, thanks to the process of transmission and absorption/re-emission, LSC plates in warm colors such as yellow or orange provide less solar radiation in the visible wavelength, but with a higher luminous content and a more comfortable color temperature (Aste et al., 2017).

Currently, LSCs are gaining interest among a variety of operators, both in the building and energy sectors, for their promising properties of good efficiency even with diffused light, low investment costs and increased durability due to reduced cells overheating as a result of selective concentration compared to conventional PV systems. In particular, Italian energy company Eni has focused, through its own Research Center, on LSC development, with several patents of suitable fluorescent colorants deposited and a prototype application in Rome, an electric bikes recharging station

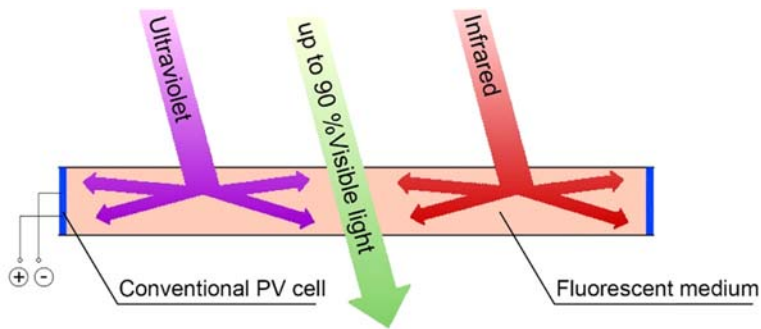


FIGURE 7.50 Transparent luminous solar collector.

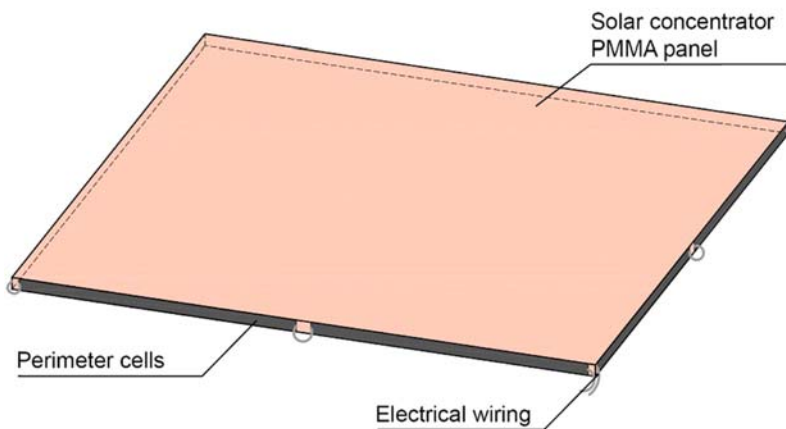


FIGURE 7.51 LSC panel. Photo by the author.



featuring 192 photoactive yellow glass panes totaling 60 m^2 and 500Wp of installed power (Aste, Tagliabue, Del Pero, Testa, & Fusco, 2015). Australia based ClearVue sells LSC glass based on a PVB laminate layer able to redirect UV and IR radiation toward PV cells at the edge of the frame, claiming 70% VLT with no color cast and a yield of 40 W/m^2 . The technology was demonstrated in Perth first in an 18 panes glass atrium in a shopping center, making power production trackable on the web (Clearvuepv), then in a Solar Greenhouse. In Holland, a consortium led by the University of Eindhoven has tested highway noise barriers that integrate colored LSC, validating that 1 km of energy generating barriers can supply up to 50 households with electric power (Kanellis et al., 2017). More recently, in Solar Decathlon Middle East 2018 competition in Dubai, the Italian solar house “Restart4Smart” by Sapienza University of Rome included a demonstrative off-grid PV system based on LSC composed by 20 fluorescent red PMMA modules integrated on the electric vehicle canopy for a total power of 70Wp (see Fig. 7.52) (Casini, 2020c). Current performance is, however, still shy of best semitransparent PV technologies, with efficiency values around 1.5% for market products, but is expected to rise up to 3% due to advancements in dyes, optimized antireflective coatings and improved solar cells, with a price of €14 for a $50 \times 50 \text{ cm}$ module (Aste et al., 2019).

Similar to LSCs, luminescent down-shifting species (LDS) absorb diffused and direct light within the ultraviolet region (200nm–400 nm) and re-radiate it to a tuned wavelength band within the 500nm–700nm range. LDS sheets encase a conventional semitransparent PV cell spanning the entire windowpane, which is fed the re-emitted light to improve its efficiency. Although more easily incorporable in windows than their LSCs counterparts, LDSs



FIGURE 7.52 Canopy with LSC panels of Sapienza University solar house. *Photo by the author.*

performance is still undermined by loss mechanisms induced by the addition of the LDS layer directly into the cell (Bonato et al., 2019).

7.6 Conclusion and future trends

The diffusion of advanced materials is contributing substantially to increase the productivity of the construction sector and, at the same time, to improve the buildings' performances in terms of comfort, safety, energy efficiency, and environmental quality.

Three main trends are pushing the development and the adoption of advanced materials in construction. The first is the growth of digital fabrication processes such as CNC machines, robotics, and 3D printing, aimed at reducing time and costs, at achieving shapes with optimized performance/material ratio and at allowing high degrees of freedom in architectural solutions, that require novel raw materials suitable for automated construction.

The second is the global goal to design ever more intelligent, safe, comfortable, and affordable buildings that require materials with enhanced and new properties able to implement dynamic and energy generating building envelopes integrated with the building automation, and predictive maintenance systems.

The third is the necessity to promote a more sustainable construction industry through manufacturing processes and materials able to reduce the environmental impact of buildings throughout their entire life cycle, which requires materials suitable for a circular economy approach.

These trends can find today full support in the great advancement in nanotechnology and smart materials sciences, biotechnology, AM, and advanced digital design tools enhanced with AI and machine learning that have finally started to move the construction industry toward a new era.

Nanotechnology is certainly offering essential innovations for the development and formulation of innovative building products with increased mechanical, physical, and chemical properties, with application potential in all technical elements, from structures to opaque and transparent closures, internal partitions, to systems and appliances. The new class of smart materials is finding application in architecture in a high number of products and systems, especially in building envelope components which can most take advantage of their properties of adaptation to different use conditions. The development of a new generation of multifunctional nano- and smart-coatings is currently a hot technological topic for enhancing the properties of all building surfaces, including their durability, safety, and health, up to climate mitigation and self-healing. Advancement in digital fabrication is also showing enormous potential in terms of new architectural possibilities, precise material processing, structurally effective shapes and graded assemblies, and lower environmental footprint of construction.

Currently most advanced research activities are focused on SMMs for 4D printing of dynamic responsive building envelopes or self-assembly elements, and on the combination of biology and technology in order to create sustainable components through living matter, such as bacteria or fungi, also with self-regenerative properties.

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Advanced building construction methods

8.1 Prefabrication and off-site construction methods

Building prefabrication is not a new concept, having boomed in the United States in the 1940s and in the UK and in Europe in the 1960s. Back then, however, it was the product of post-war economies with the need for quick and cheap reconstruction and a shortage of materials and labor, leading to the perception of prefabricated housing as an ugly, cheap, poor-quality option that is still common nowadays (Hwang, Shan, & Looi, 2018). In recent years, prefabricated construction has evidenced instead a renewed interest by designers and contractors, spurred by the evolution of both the technological and the socio-economic environment. In fact, the great challenges caused by the rising construction demand, sharp cost pressures, and increasingly acute environmental problems have attracted extensive attention to prefabrication in the global construction industry.

Traditionally, construction work is carried out entirely on-site using cast in situ technologies characterized by a fixed jobsite, formworks and falseworks, wet trades, scaffolding, and extensive waste, and delivered by using self-contained projects, which themselves consist in a temporary organizational form with a designed beginning and end (Lu, Chen, Xue, & Pan, 2018). Off-site construction processes instead manufacture and assemble building elements, components, and modules in off-site factories and then transport them to site for installation. This method has proven to improve workflow continuity and productivity, to minimize construction wastes, to streamline agents and subcontractors involved, as well as to reduce construction duration (Arashpour, Wakefield, Blismas, & Maqsood, 2015; Kamali, Hewage, & Sadiq, 2019). Prefabrication basically entails the transfer of a substantial portion of the construction work from the traditional site to a factory or other manufacturing shops, favoring a massive production approach as seen in the manufacturing industry. A construction project is considered as prefabrication if it either uses individual prefabricated building components (e.g., façade, staircases, and slabs) or is entirely based on the assembly of prefabricated building modules.

According to the degree of the off-site work undertaken, off-site construction methods can be divided in a five-level taxonomy of prefabrication adoption at different levels (see Table 8.1) (Gibb, 2001).

Currently, conventional on-site construction uses a majority of level 0 tasks (concrete pouring, brick laying or carpenter work, MEP fixing, rendering and waterproofing) requiring extensive cut-to measure, mixing, and reworking activities. Level 1 prefabricated components are employed where suitable, for instance, for prefabricated lintels, precast load-bearing slabs, and can be required for higher tech components (doors, windows, air ducts, cladding elements are usually tailor made off-site with minimal room for on-site adjustment).

Great potential resides instead in level 2–4 prefabrication, or in a mix of these within the same project, since this allows for 70%–95% of a building to be prefabricated in a factory before transporting it for onsite assembly (Thai, Ngo, & Uy, 2020).

Nonvolumetric assembly (level 2), also known as panelized solution, includes 2D panels, consisting in perimeter walls, vertical partitions, and prefabricated floor slabs or roof sections. These allow the widest flexibility in terms of building type and layout, but on-site installation is more complex and time-consuming in terms of both MEP connections and finishing compared to higher levels of prefabrication.

Volumetric assembly (level 3) envisages the manufacture of an entirely self-contained 3D room, or part of a room, fully fitted-out with MEP fixtures and finishing, requiring only few structural and systems connections on-site.

Lastly, a modular building (level 4) is designed from the ground up to be entirely composed by 2D and 3D sections, even load bearing, all prefabricated in off-site facilities, transported to site, and lifted in place with minimal work required for connections.

Main prefabrication activities include one or more of the following approaches (Bock, 2015):

- building component manufacturing (BCM), in which basic materials (concrete, bricks, wood, steel, etc.) and low-level elements are transformed into high-level building components, such as precast concrete elements, steel trusses, wood structural elements, or cladding elements;

TABLE 8.1 Levels of prefabrication development.

Prefabrication levels	Description
Level 0	<i>No form of prefabrication</i> Projects are fully cast in situ, bulk materials are supplied in excess to compensate waste for cut to measure (e.g., concrete, cement, insulating materials, floor/roof tiles, plaster)
Level 1	<i>Component and subassembly</i> Components are prefabricated to measure and specification and installed without requiring any adaptation (e.g., steel beams and columns, windows, façade panels)
Level 2	<i>Nonvolumetric assembly</i> Large, multifunctional 2D panelized components are prefabricated to specification and directly installed mostly with dry connectors (e.g., precast concrete or wood wall panels and floor slabs already fitted with insulation, finishing or technical systems)
Level 3	<i>Volumetric assembly</i> Some 3D rooms are fully prefabricated with walls, floor, and roof and already equipped with systems and finishing, on-site installation is limited to dry fasteners and MEP connectors (e.g., volumetric bathrooms, kitchens with usable space enclosed)
Level 4	<i>Modular building</i> Most of the building is constructed by assembling fully prefabricated 3D modules which also form the fabric of the building structure, on-site installation is limited to mechanical and technical connections and successive detailing and waterproofing (e.g., modular hotels, barracks, residences)

- large-scale prefabrication (LSP), in which high-level building components obtained via BCM are subsequently combined into 2D or 3D building units, to be employed stand-alone or part of modular structures;
- additive manufacturing (AM), also known as 3D printing, for the creation of optimized and customized building parts in a variety of materials, ranging from diminutive components to large-scale elements.

Today, the new approach to modular construction leverages the possibilities provided by advanced materials as well as by the wider digitalization of the construction process, to enhance design capabilities and variability, improve precision and productivity in manufacturing, and facilitate logistics, shifting its focus towards the topics of sustainability and esthetics, and pursuing the higher end of the market. In particular, the evolution of digital tools is radically changing modular construction, improving the design of the different building modules, the coordination of the processes within the construction facility, as well as the optimization of the logistics of just-in-time delivery to the final construction site.

Prefabrication is widely considered as a way to ensure cleaner production, by preventing the production of waste while increasing efficiencies in the uses of energy, water, resources, and human capital, and several studies have reported its main benefits that include:

- reduced and more certain build costs and overall lifetime costs of the building;
- accelerated and more reliable build schedules that result from parallel workflows (e.g., allowing for the assembly of components off-site while foundations are being poured on-site or while permits are being processed);
- more controlled conditions for weather, quality control, improved supervision of labor, easier access to tools, and fewer material deliveries;
- lower environmental impact of the final construction site because of reductions in material waste, air and water pollution, dust and noise, and overall energy costs;
- better working conditions and increased worker safety through reduced exposures to inclement weather, temperature extremes, and interfering or hazardous operations (e.g., components traditionally constructed on-site at heights or in confined spaces can be fabricated off-site and then hoisted into place using cranes);
- fewer conflicts in work crew scheduling and better sequencing of tradesmen;
- reduced requirements for on-site materials storage and fewer losses or misplacements of materials (Tam & Hao, 2014).

In particular, modular construction is believed to cut building times by as much as 50% and costs up to 20%, especially in conditions when the type of structure has a degree of repeatability, the unit size suits land transport, and when

value density allows the savings of shifting activities to the plant to outweigh logistics cost, and is expected to reach a total market of \$130 billion by 2030 in Europe and United States (Bertram et al., 2019).

Manufacturing components in a factory has been shown to cut CO₂ emissions by up to 60% compared to conventional construction, with a reduction of traffic movements by up to 40%. In fact, conventional building sites typically see a constant flow of vehicles delivering materials and shipping out waste, whereas factories organize deliveries to minimize traffic. Using Big Data, the scheduling of deliveries can be planned and optimized to reduce frequency, avoid peak times and reduce double handling on site, all contributing to improving sustainability. Moreover, prefab construction can cut waste by up to 90% compared to conventional building (Mtech Consult Ltd, 2007), thanks to the help of data analytics and smart planning as well as due to multiple modules being constructed simultaneously in the modular construction facility, allowing materials that would be discarded on a normal construction site to be reused for other projects. Furthermore, prefabricated buildings tend to be much easier to disassemble at the end of their operating life—it is sufficient to reverse most operations carried out during construction—allowing a great reduction in debris from demolition as well as the possibility to reuse building elements in other locations and configurations or recycle them for new projects.

With the right technological support, prefab construction is safer, faster, and more reliable than conventional building work. Factories typically offer a more controlled working environment compared to construction sites, with static workspaces and more structured supervision. This makes it easier to implement specific safety processes and procedures such as physical distancing for hygienic or sanitary reasons. Site-based activities, on the other hand, commonly include a lot of interaction between workers.

Off-site construction is today increasingly recognized by the global construction community in many countries and regions, and policymakers have identified prefabrication to be a matter of course in their construction strategies. China, for instance, has recently set forth a 10-year goal to apply prefabrication to 30% of the domestic newly constructed buildings, whereas in Singapore prefabricated prefinished volumetric construction (PPVC) has been mandatory for selected residential government land sale sites from 2014. In Malaysia, public projects over a certain cost threshold are required to obtain a minimum Industrialized Building System score of 70.

Currently, modular construction is already widely diffused in Japan, where the construction sector capitalized on synergies with other manufacturing industries and the high volume of modular units ensures economies of scale, along with a strong focus on quality, particularly with respect to earthquake resistance. In Scandinavian countries, where short daylight hours and cold weather make prefabrication in controlled environments a viable solution, 45% of housing is currently built using off-site manufacturing (in Sweden, around 85% of new homes are built using some form of industrial construction) (Bertram et al., 2019).

In the United Kingdom and the United States, modular construction accounts for approximately 20% of total hotel construction projects. In North America growth in the total market share for permanent modular-construction real-estate projects was 51% during the period of 2015–18, and total revenue growth for the segment increased by a factor of 2.4 (Bertram et al., 2019).

The progressive transition to off-site construction is expected to somehow disrupt the construction sector as a whole, leading to increased adoption of standardized, factory made components, less labor on-site, different construction material employed, and even different tools used on the job. Projects will rely on standardized digital platforms—from client engagement through to manufacturing and assembly—which will narrow the set of options and suppliers to those able to provide the required expertise and integration. Construction products will favor materials that are easier to transport and have better eco-credentials (e.g., cross-laminated timber, steel), instead of concrete and bricks that currently dominate conventional construction sites due to their low cost and easy adaptability. Lastly, the many different tools used onsite by workers (e.g., heavy equipment, installed tower cranes, power tools) for extended periods of time will be replaced by fewer machines (mostly flexible cranes and wrenchers/screwdrivers) used ad hoc in the assembly phase, with different tools employed in the different prefabrication factories (e.g., gantry cranes, construction robots) according to the specific activity carried within (de Laubier, Burfeind, Arnold, Witthöft, & Wunder, 2019).

Overall, advanced prefabrication requires an integrated approach that involves designers, contractors, and clients, and expects a high investment even before setting up the building production pipeline. Surveys conducted with industry professionals involved with modular construction evidenced shared constraints such as the need for extensive coordination prior to and during construction, the need for additional project planning and design efforts, the increased transportation and logistics considerations, the requirement for an early commitment or a higher initial investment compared to conventional construction methods (Hwang et al., 2018).

The key from wider adoption of off-site construction approaches and for best reaping the benefit associated lies certainly in the integration of digital technologies at all stages of the construction process, which can greatly support the

detailing and accuracy needed at the planning, design, prefabrication, transport, on-site assembly, and final disassembly phases. In this picture, building information modeling (BIM) is by far the keystone technology that allows great benefits by itself but, moreover, can connect horizontally the several advanced processes which find application throughout the prefabrication value chain, such as radio-frequency identification (RFID) and global navigation satellite system (GNSS), extended reality (XR), LiDAR and 3D photogrammetry, and artificial intelligence (AI) (Wang, Wang, Sepasgozar, & Zlatanova, 2020).

In particular, BIM at the design stage allows to check and review detailed models to ensure compatibility with the planned fabrication processes and prepare the associated digital information (design for digital fabrication, as described in Section 6.5) as well as to simulate and optimize assembly sequencing with 4D BIM methods (see Section 4.2.3).

RFID and GNSS technology (described in Section 9.5) can be applied effectively in supply chain management to automatically identify object information and track inventory and status of materials within the prefabrication facility and during transport and assembly on-site.

Extended reality can be used to support on-site construction with augmented reality technologies to reduce errors of on-site assembly and repair tasks and to inspect prefabrication elements with the 3D BIM model, whereas virtual reality (VR) can guide production process, for example, crane lifting, in a safer and more efficient way and present near-real-time construction progress.

3D photogrammetry and laser-scanning via LiDAR (see Section 6.1) allow to capture valuable information of the building lot, useful to operate with the tighter tolerances required by advanced prefabrication techniques and to develop virtual environments for XR, and of the construction site, to track progress, refine logistics, and ensure conformity of assembly by superimposing as-built and as-designed models.

AI can be leveraged at the planning stage to optimize design of prefabricated components, also via parametric and generative design approaches (see Section 6.4), in supply chain and logistics to estimate construction and transportation costs, to optimize factories and suppliers selection, and in assembly scheduling to optimize and predict the construction tasks.

Lastly, prefabrication entails a range of costs and constraints associated with transportation and assembly and with limited on-site customizability of structures, which can pose particular challenges when information about build sites is scarce or inaccurate. In this scope, effective strategies to promote a wider adoption of prefabrication include encouraging close collaborations between project stakeholders during the early phase of the project, the use of BIM level 2 or level 3 shared digital design tools to improve coordination and facilitate communication between stakeholders, as well as the availability of training courses for project team and workers to enhance their knowledge and skills.

8.1.1 2D panelized solutions

Prefabricated 2D sections allow a significant improvement of productivity without significant constraints in terms of building layout, even allowing the higher degree of freedom required to design large open-plan offices or high-end residential projects characterized by lower repeatability. Each wall or roof/floor section can be fully fitted with interior or exterior finishing and with necessary conduits for electrical systems, HVAC and plumbing, with doors or windows, and even with fixtures or furniture. Compared to bigger 3D modules, 2D panels can be packed in flat packs for much easier and cheaper transport, allowing to move materials for a significantly greater floor area at one time: maximum panel size for conventional road transport is 13.5 m length and 3.5 m height, and it costs approximately \$8 per m² floor space to ship 2D panels around 250 km, compared to almost \$45 per m² for the 3D equivalent (Bertram et al., 2019).

On the other hand, the assembly work onsite, albeit much simpler than a traditional build, is more complex and labor-intensive than putting together 3D modules, and requires additional internal finishing, having more wall-floor-roof connections to carry out on-site.

2D sections can be load bearing or can be applied to an external structural frame, such as with curtain wall construction. They can be manufactured in precast concrete, steel, or timber, according to the expected performance of thermal resistance and inertia, noise insulation, and weight, in terms of both structural loads and on-site lifting. Envelope wall sections are commonly made with wood or steel frames and cement or wood fiberboard planking. Integrated ventilation ducts can be specially fire protected (Miloni, Grischott, Geier, & Boonstra, 2011). Design of the single prefabricated section shall take into account eventual reinforcements, anchor points, or protection needed for transport and on-site lifting.

Engineered wood products such as cross laminated timber (CLT) are particularly suited for 2D prefabrication, since they are compatible with a number of automated facility processes (CNC cutting, milling, screwing, or nailing) and

allow for quick and streamlined assembly of massive structures with high degrees of thermal inertia and seismic resistance.

China-based Broad Group specialized in highly industrialized 2D prefabricated towers, based on floor sections and curtain wall panels equipped with engineered facilities and finishing in the factory, then assembled in the construction site by welded and bolted joints. Broad Group has completed over 30 buildings, including a 15-story hotel built in 6 days; a 30-story hotel built in 15 days, and the 57-story “J57 Skytown” tower built in 19 days from 2736 modules prefabricated over 4 months and a half, thanks to the high standardization of elements and streamlined logistics (production, storage, delivery, assembly) (Generalova, Generalov, & Kuznetsova, 2016), notwithstanding vast labor and equipment on-site.

A particularly interesting application of prefabricated 2D panels is for deep energy renovation of existing buildings, in which prefabricated envelope sections (perimeter walls and roof) are applied on top of the existing building elements adding their own integrated multifunctional components for climate control, energy saving, building physics and esthetics, with limited interventions on the preexistent building envelope (Op’t Veld, 2015; Pittau, Malighetti, Iannaccone, & Masera, 2017).

8.1.2 3D volumetric assembly

3D volumetric solutions entail the off-site prefabrication of entire, self-enclosed building sections, such as rooms or part of rooms, comprised by walls, floor, and roof slabs, delivering the potential for higher efficiencies and time savings compared to 2D panels. Benefits include the possibility of realizing in a controlled facility high-quality and fully fitted-out units, complete with fixtures, lining, doors, windows, and all required MEP systems, with on-site labor reduced to lifting in place and connecting systems with standard connectors, with even fewer operations compared to 2D panels prefabrication.

The trade-off consists in transportation costs and size limitations, with maximum width allowed for road transport limited to 2.55 m in Europe and to 3.5 m in the United States. This makes 3D volumetric approach most suitable for rooms with more intricate finishing, particularly wet rooms such as bathrooms and kitchens, which quality may benefit most from industrial off-site manufacture and which higher value allows to offset the logistic costs. Less technology-intensive rooms such as offices or residential quarters may on the contrary see the advantages linked to prefabrication counterbalanced by the transport costs and could be incompatible with the rigid grid structure dictated by size limitations, making those better suited for a 2D prefabrication approach.

3D prefabricated units are usually made of timber, steel, or concrete, with the first two more common due to weight advantages.

By themselves, 3D units have seen limited use in the years as prefabricated blocks for wet areas, linked to the building core or to central corridors, obtaining self-contained bathroom and kitchen areas that gathered plumbing works in one place.

Nowadays, the true potential of 3D prefabrication can be achieved with modular buildings, in which prefabricated 3D sections, and 2D panes, constitute the vast majority of the works, as illustrated below.

8.1.3 Modular buildings

A modular building comprises a set of modules that are built in an off-site fabrication center, also called modular manufacturing center and modular factory, delivered to the construction site, assembled, and placed on a permanent foundation (Abdelmageed & Zayed, 2020). This process is also known as modular integrated construction (MiC) in Hong Kong, permanent modular construction in United States, and PPVC in Singapore (Thai et al., 2020).

Each modular building normally has rooms consisting of mostly 3D modules along with 2D modules for specific applications. In a modular building, about 85%–90% of the modular construction work is done off-site and the remaining (10%–15%), including the foundation and utility hookups, is done on-site on the final project site (Kamali & Hewage, 2016). This modular approach is best suited for projects with a high level of repeatability and a high ratio of wet to dry rooms, that allows to leverage at best the benefit related to 3D prefabricated units, making it most suitable for hotels, apartment blocks, student residences, hospitals, and prisons. Repeatability does not mean all products need to look the same, however, since an accurate design can piece together different standardized modules to produce a customized end result.

Modular units can be stacked according to three main methods: core, podium, and infilled frame systems. In the core-based approach, modules are clustered around a steel or concrete stability core that absorbs lateral loads from

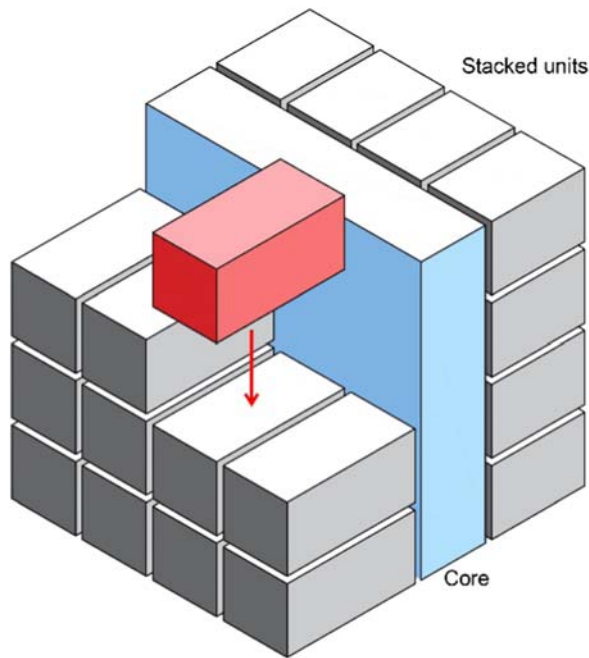


FIGURE 8.1 Core-based modular construction.

winds and earthquakes, leaving only gravity loads to the modular units (see Fig. 8.1). In the podium-based method, modular units are stacked on the top of a podium or platform designed as a traditional steel, concrete, or hybrid steel–concrete structure. This method is particularly suitable for mixed use buildings where the podium structure can provide open spaces for retail or commercial use or underground car parks. Lastly, in the infilled frame method, modular units are placed between the beams and columns of a primary framing structure which fully ensures the overall stability of the building (Thai et al., 2020).

According to the desired layout, 3D units can be manufactured with four closed sides to create cellular type spaces or can be partially or totally open-sided employing intermediate posts or corner supports to allow load transfer to the adjacent 3D blocks. By combining open and closed 3D units, it is possible to overcome the rigid grid dictated by the transportation size limits and create corridors or larger rooms.

In the United States, a growing number of colleges and universities are using modular approach to build dormitories and classrooms, with a 5%–10% saving of construction costs and quicker construction process. Modular construction currently accounts for 5% of United States market, with a 13% growth rate which reaches 30% in California, where the affordable housing crisis in the Bay area and the need to reconstruct entire towns after the recent wildfires have spurred the creation of high-tech prefabrication startup such as FactoryOS. In Australia, there has been a growing trend of hotels built using modular construction, as it can ensure the delivery of the hotels on schedule, and meanwhile, the cheap construction costs allow hotels to offer their guests a high-end hotel experience at a more affordable rate, enhancing their competitiveness. In the UK, an increasing number of homebuilders have launched prefab home divisions to build modular homes which are complete with light fittings, bathrooms, bookshelves and kitchens. Also, these homebuilders recognize modular construction as a good strategy to tackle the challenge in labor, namely, a shortage of skilled construction workers caused by an ageing workforce and the exodus of European workers due to UK leaving the EU. Car manufacturer Toyota Motor Corporation transferred its experience in the automotive sector into the prefabricated home sector, establishing an industry capable of assembling houses from room cells in up to 12 different sizes in 4–6 hours. In the factory, a room cell is prefabricated every 2.5 min. Customers can put together their dream home from over 350,000 single parts. Computer-aided design and manufacturing systems produce approximately 2000 components from around 25,000 parts, which in turn make up approximately 300 functional modules (Bock, 2007). Toyota Housing alone has sold more than 100,000 homes in Japan to date (Toyota Housing - About Us).

United States-based startup WoHo similarly proposes a heavily industrialized approach to prefabrication: its systems are made up of a series of discrete foundational components, mostly in steel and reinforced concrete, optimized for fabrication, transportation, assembly and operation, which can be scaled and configured to span both low-rise and high-rise, residential and commercial buildings. Arup Engineering collaborated to ensure the code compliance and constructability of the structural and MEP systems designed into its building components. WoHo proprietary software allows

customers to choose materials, facades, and other options, which are seamlessly integrated into the workflow of manufacturing and assembly. By providing a single, standardized platform for design, manufacture and construction, they promise to close the whole supply chain: every step is recorded and stored as part of the virtual history of each part and each element is encoded with smart tagging to enable full product versioning and tracing.

Recent notable modular buildings include 461 Dean Street, a 32-story residential tower designed by SHoP architects and engineered by Arup with 363 rental apartments made of 930 prefabricated steel 3D units combined with a variety of sizes, materials, and colors, which stands as the tallest modular building in the world (see Fig. 8.2). Each modular unit is 3 m high, up to 4.57 m wide and between 6.10 and 15.24 m long, comes equipped with all engineering systems (electricity supply, water supply, and drainage, HVAC), equipment (bathroom equipment, kitchen equipment, etc.), and finishing elements (lamps, switches, floorings, ceramic tiles, etc.) and was manufactured in a dedicated factory with an average production speed of 4 modules a day (Generalova, Generalov, & Kuznetsova, 2016). Rather than minimizing construction time on-site, in this case modular prefabrication allowed to achieve perfectly controlled quality, equipment completeness and interior finishing even in the very delicate intervention site in Brooklyn, NYC, with minimal disruption of surroundings (each prefabricated module was transported to the construction site by special trucks and installed “just-in-time” at night, with less than 20% work effectively done on-site) (Krulak, 2017).

In Honk Kong, Hip Hing completed in 2020 the InnoCell tower, the city’s first high-rise building to use modular construction. The 17-story building comprises more than 400 prefabricated housing modules, fabricated in a factory equipped with autonomous machinery such as robotic arms for automated assembly. These boxlike modular structures were installed on-site, with lifting taking no more than 30 minutes per module. A maximum of 15 modules were installed each day and all 418 modules were completely installed within 71 days. This allowed to complete InnoCell six months ahead of schedule and achieved 600,000 accident-free person-hours during construction. In the UK, firm Chapman Taylor designed a 220-bedroom hotel made from purpose-built steel containers, each complete with interior fixtures and fittings, full-height windows, carpet, wallpaper, ceiling and light fittings, all installed on site in less than 3 weeks. Ikea furniture manufacturer has invested in modular fabrication with his Boklok joint venture with Skanska contractor to sell affordable flat-pack houses developed and built by Skanska and designed by Ikea. Large volumes, low prices, and industrialized production allowed to build 4000 Boklok houses in Sweden, Denmark, Norway, Finland, Great Britain, and Germany. Ikea also partnered with Marriott International to open a chain of low cost hotels in Europe named Moxy Hotels, all built with modular construction.

Amsterdam-based citizenM is the first hotel business to build its assets entirely from prefabricated rooms and modular building blocks, and currently operates over 20 hotels with more than 4760 rooms worldwide, including the 21-story Bowery Hotel in New York City which become the world’s tallest modular hotel in 2019. The building’s first three floors were built using conventional concrete construction to support the upper levels, each constituted by 15 modules per floor around a concrete core with elevator shafts and stairs. Modular components were fabricated in Poland and then transported to Manhattan virtually complete with the facade attached, all mechanical and electrical features, a full bathroom, windows, doors, furniture, and flooring.

Other renowned companies that are expanding to the construction sector into the “house as a product” market include Amazon and Muji.

Finally, it is also possible to use a mix of 3D modules and 2D panels on a project or to combine those approaches with traditional site work (for instance, for the basement and first floor of a larger project). Typically, wet areas are

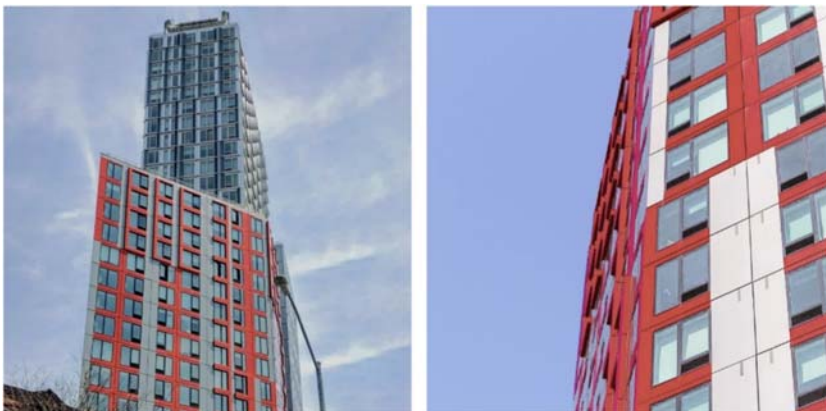


FIGURE 8.2 461 Dean st. modular building.
Photo by the author.

manufactured as 3D boxes, while the remainder of the building can be made from 2D panels. This optimizes the process for the two different areas of the building, bringing high-productivity improvements to the bathroom areas and maximum flexibility to all other areas. However, the manufacturing process required to deliver both solutions becomes more complex, as does coordination of the supply chain (Bertram et al., 2019).

8.1.4 Robotic off-site prefabrication

Although off-site prefabrication can be implemented with satisfactory productivity benefits by simply moving most construction activities into a factory and carrying out required tasks by hand, its true potential, that is, ensuring the highest quality with the lowest cost and time, can only be achieved by introducing robotics and other automation technologies into the manufacturing process, taking the construction industry into a similar realm to industrial manufacturing. Off-site automation systems have the main objective to improve the quality of prefabricated building components taking inspiration from the use of robots in other manufacturing sectors, such as the automotive and shipbuilding industries.

Since the 1960s, robots have played an increasingly important role in the automation of industrial production lines, replacing humans in performing tiring, repetitive, dangerous, or highly accurate tasks, with significant advantages in terms of both productivity and quality. Industrial robots are defined by ISO TR/8373 standard as “a manipulator with multiple degrees of freedom (DOFs), automatically governed, reprogrammable, multipurpose, which can be fixed in place or mobile for use in industrial automation applications.”

In the last decade, with the advent of the fourth industrial revolution, so-called Industry 4.0, which aims at the creation of autonomous and interconnected production contexts, the presence of robots has increasingly become an integral part of the manufacturing process, thanks to the development of advanced manufacturing solutions and of collaborative robots (cobots) (Gao, Wanyama, Singh, Gadhri, & Schmidt, 2020).

In particular, collaborative robots are designed to work safely with human operators, thanks to technologies like force feedback, low-inertia servomotors, elastic actuators, and collision detection that limit their power and force capabilities to levels suitable for contact with humans. More compact than conventional robots, cobots generally have lightweight frames with soft, rounded edges and minimized pinch points.

Unlike classic manipulators, cobots do not necessarily have to be programmed to perform a task, but can learn the sequence of actions to be performed work-in-progress, memorizing and replicating the sequence which is shown to them by the operator with whom the manipulator will cooperate. Many cobots employ intuitive hand-guiding mechanisms for teaching new tasks without the need to explicitly program the movements of the robotic arm.

Cobots can work closely with the operator sharing the same spaces, thus creating a system in which man and machine are no longer divided by barriers, photocells, doors, interlocks, etc. Collaboration takes place in what is called a collaborative workspace, a safeguarded area where the robot and human can perform tasks simultaneously during production operations (ISO 10218/ANSI RIA 15.06).

Robotic systems are mainly employed in the prefabrication construction industry for the production of modular and prefabricated housing components such as ceilings, walls, and roofs. In particular, robotics are considered helpful to deal with repetitive, highly quality demanding, and labor-intensive tasks such as tiling and concreting, improving the module production performance in factories by enhancing productivity, cost efficiency, quality, and safety (Yang, Pan, & Pan, 2019).

For instance, unique precast concrete panels for floor, wall, and roof, suitable for 2D and 3D prefabricated sections, can be manufactured by robotic multipurpose units. A robotic cleaning unit cleans the production table and set regular spacers, then a multifunctional gantry type robotic unit with two vertical arms places magnets on the steel production table and horizontal, vertical, and triangular reinforcement bars according to the CAD design data, and finally a concrete distributor spreads the right amount of concrete according to a CAD layout that provides openings for installation, windows or doors (Bock, 2007).

The DFAB house prototype by ETH Zurich demonstrated in 2019 Smart Dynamic Casting (SDC), an automated slip-forming process for concrete precasting composed by an actuated formwork able to change its shape, cement pouring rate and slipping speed to allow prefabrication of geometrically complex, structurally optimized concrete elements in a single pour without any material interruption and with integrated reinforcement (Sawhney, Riley, & Irizarry, 2020). Smart dynamic casting specifically aims at removing the need of individual made formwork for the construction of complex concrete structures, which can be prefabricated also with the use of multiaxis robotic arms (see Fig. 8.3).

Timber-based prefabricated panel systems are also compatible with extended automation, starting from the assembly of only the structural frame or structural frame and panels, to the inclusion of greater number of processes into the manufacturing for essentially fully complete walls with façade, windows and glazing, insulation and even



FIGURE 8.3 Smart dynamic casting prefabrication of concrete structures. © Gramazio Kohler Research, ETH Zurich.

weatherproofing (Orlowski, 2020). Computer numerical controlled (CNC) multiaxis machines are already adopted in the sawing and cutting phases, with multifunctional bridges allowing different subsequent processes such as nailing, stapling, cutting, and even thermal insulation and membrane wrapping. Panel movement, inspection, storage, and handling are then carried out by gantry cranes or butterfly turning tables. A successful case of automated timber prefabrication is Bensonwood's Unity Homes, serialized dwellings which are designed via BIM obtaining a building production model which stores all engineering information and can be directly deployed to their CNC equipment for a completely automated prefabrication process.

Researchers at ETH Zurich have developed numerous automated robot systems suitable for advanced prefabrication, with the objective to develop an integrated process of sketching, computational designing, calculating, and manufacturing timber structures, so-called Robotic Timber Construction, based on information sharing from the initial parametric design scheme to the robotic manipulation of single timber components to the constructive assembly of highly informed prefabricated architectural structures (Willmann et al., 2016).

Lindbacks, a modular construction firm in Sweden, uses Randek's industrial construction machinery to automate a variety of construction tasks including nailing, milling of openings, sheet cutting, gluing, inkjet marking, and sheet addition and handling. Other manufacturers employ CAD-generated data as a solution for the production of insulated walls that can be configured for different wall lengths, widths, and heights, as well as the number of wall layers.

Robotic building prefabrication has also been at the forefront of public research investment, with several national and international grants fostering research with the aim of promoting the ever-important substitution of the existing building stock in developed countries such as United States and Europe, which is increasingly failing to meet the required energy performance. In this picture, two notable projects funded by EU programs are Manubuild and Future Home. Manubuild consortium demonstrated prefabricated buildings in the UK, Madrid, and Stockholm, the latter 90% preassembled in a dedicated factory with a yearly capacity of 1000 apartments (Bock, 2006). Future Home project instead aimed to develop an Integrated Construction Automation (ICA) platform that encompassed all stages of construction process: designing the buildings in a modular way in view of their robotic erection, automatic planning and real-time adjusting of off-site prefabrication, transportation, and on-site assembly, as well as on-site automated and robotized transportation and assembly of the buildings' prefabricated parts (Uddin, 2013). Integral part of the project was the AUTMOD3 software environment for automatic modular construction, able to generate assembly sequences and motion paths for robots to automatically carry out the construction process and to provide a simulation tool to allow the assembly process to be visualized and inspected before execution (Padron, Cardenas, Diez, Abderrahim, & Balaguer, 2002).

Two main barriers still limit the transition of the prefabrication industry towards automation. A first barrier to this is represented by the significant upfront investment required for determining the optimal setup and then setting up a highly automated facility. A second barrier, moreover, is due to construction materials, which are currently supplied to the specification necessary for highly manual onsite construction. While skilled human labor can cope with

imperfections in materials, machine processing requires in fact greater precision, shifting the onus on the supply chain to deliver high-specification products at a comparable cost (Bertram et al., 2019).

8.2 Robotic fabrication on site

The term “robot” (coined in 1921 by Carel Capek from the Czech word *robota* which means “heavy work,” in turn derived from the Old Church Slavonic *rabota*, “servitude”) indicates a machine capable of carrying out certain actions with a degree of autonomy with the aim of assisting or replacing the human being. According to Robot Institute of America, a robot can be defined as a “reprogrammable, multifunctional manipulator, designed to move material, parts, tools or specialized devices through variable programmed motions for the performance of a variety of tasks.”

Robots can be classified based on several factors such as power source, shape, size, type of application, DOFs, mechanical structure (mobile or fixed), workspace geometry, motion characteristics, and levels of autonomy.

Concerning the level of autonomy (i.e., cognitive ability), robots can be classified in “non-autonomous” (requirement full or partial human involvement) or “autonomous” (no human involvement required).

Non-autonomous robots include teleoperated robots (e.g., operated or fully controlled by humans) or driven by a deterministic software that makes them perform the work in a repetitive way. These kinds of robots are typically used to fulfill specific tasks that they are able to perform more effectively than humans, or to work in hostile environments and with toxic or dangerous substances. Typical non-autonomous robots are industrial robots used in factories with the goal to obtain a more precise, faster, and lower-cost production without use or with reduced human labor.

Autonomous robots are instead characterized by the fact that they operate in total autonomy and independence from human intervention and are able to make autonomous decisions (not explicitly programmed by the manufacturer) even in the face of unexpected events. These robots are usually programmed with algorithms that refer to AI techniques: genetic algorithms, fuzzy logic, machine learning, or neural networks. Autonomous robots are mobile robots, suitable for carrying out tasks in environments not known a priori such as the construction site. Robots which replicate and resemble a man or an animal—real or imaginary—are instead generally called “automaton” or “android” (biomorphic robots) and are normally mobile and fully autonomous.

An ongoing evolution of biomorphic robotics is constituted by soft robotics, an interdisciplinary field that deals with robots composed of highly deformable soft materials, similar to soft-bodied organisms, capable of interacting with humans and the surrounding environment. The use of soft, elastic, and deformable components with variable stiffness is in fact a key factor to guarantee safe and effective interactions in unstructured environments, opening up to robots a wide range of application possibilities, also for mechatronics, ranging from new sensors to actuators, batteries, and flexible mechanisms. The aim of research in soft robotics is to develop soft materials which have the ability to show the deformability and mechanical compliance of biological tissues, based on the different actuation techniques such as fluids, gels, soft elastomers, soft polymer composites, and liquid metal-embedded elastomers (Gariya & Kumar, 2021). In this picture, due to the unconventional materials necessary and their complex geometry, 3D and 4D printing represents a promising method for the manufacturing of soft robots (Stano & Percoco, 2021).

The use of robots is becoming increasingly widespread in all three primary (agriculture and mining industry), secondary (manufacture industry), and tertiary sectors (services) in relation to the numerous advantages deriving from their application. These include:

- improvement of productivity, thanks to the possibility to perform tasks significantly faster and with higher endurance, reducing manpower, and costs;
- improvement of safety, thanks to the ability to operate in harsh and unsafe environments where humans are unable to work;
- improvement of quality due to the capacity to be more precise and accurate than humans.

These advantages appear to be particularly important for the construction industrial sector, which is characterized by great uncertainty in costs and construction times and by many accidents at work. In case of 3D printing, another advantage for the sector is the possibility of increasing the production rates transferring design data directly to 1:1 assembly operations and automated construction.

Despite all these benefits, the construction industry is one of the least automated industries among those that feature manual-intensive labor as a primary source of productivity. Robotics systems for construction have been developed since the 1960s and 1970s, the same time when other industries, such as automotive, started their automation. However, the adoption of robotics in the construction industry has been very slow, and robots still do not play a significant role in any step of a building’s lifecycle.

Reasons of this delay include professional skills shortage, risk-averse mentality coupled with concerns towards complex technology, cultural resistance against the adoption of innovative technologies, as well as high upfront investment and additional setup time needed by robotic equipment.

The construction worksite itself is, in addition, one of the primary obstacles to robotic automation. Construction tasks are notoriously difficult to automate: robots excel at repetitive tasks in a controlled environment, whereas construction sites could not be more opposite, and robots need to be able to adapt to the real-time variability in their environment with little to no reprogramming in order to be profitable and productive.

Today, significant technological advancements are pushing the building sector toward new advanced construction methods based on digitalization and robotics, which are finding application on a large scale.

Over nearly five decades of continuous evolution within the field of robotics, the abilities of robot systems have grown significantly, and their implementation levels are heading toward maturity. The recent advancements in the field of industrial robots have enabled the development novel robotic design systems, such as rapid prototyping and self-organized construction and assembly.

Currently, robotic technologies can be applied to on-site construction at varying degrees of integration with the different operations that are carried out in the construction site, from building demolition and disassembly to site preparation and excavation, up to structure assembly, wall laying, or finishing (Gharbia, Chang-Richards, Lu, Zhong, & Li, 2020).

In particular, on-site robotic fabrication can be implemented with the following approaches:

- single task construction robots (STCRs), which are developed and optimized to replace or support human workers in a specific construction activity;
- 3D-printers, consisting of a material extruder mounted on a mobile robotic arm or gantry, able to 3D print an entire structurally safe building based on a set of preprogrammed instructions;
- biomorphic robots, which mimic the structure of humans (even with working legs, arms, or hands) or animals to ensure the best compatibility with a variety of on-site activities;
- exoskeletons, which increase strength or relieve strain for human workers with wearable mechanical devices by providing lift support, weight distribution, posture correction, and other capabilities;
- autonomous vehicles, which include terrestrial, aerial, or nautical vehicles that can move autonomously on site to perform various tasks such as site preparation, materials delivery, surveying, and monitoring;
- robotic on-site factories, in which the whole construction yard is set up and structured as an industrial site and most operations are scheduled and carried out by different robots.

These robots can find application in any phase of the construction process from site investigation and preparation up to building maintenance and inspection (see Table 8.2).

As evident from Table 8.2, many of the construction robots are single-purpose robots designed to conduct specific tasks in controlled environments, which greatly eases development and programming but entails little capability to adapt their operations to unique work environments and different types of tasks. Conversely, general-purpose robots perform tasks more intelligently in unique and dynamically changing construction site conditions; however, they require multiple functional skills (e.g., navigation, localization, mapping, sensor control, manipulator control), and advanced programming of algorithms and AI to detail motions implementing the skills and the sequences between, considering the characteristics of tasks and work environments. The implementation of these functions can be streamlined by reusing widely accepted robot development frameworks, such as Robot Operating Systems (ROS), an open-source robotics middleware suite. Off-the-shelf, ROS-compatible robots are available from several leading manufacturers, allowing developers can create robot applications without significant reprogramming or modifications to hardware devices, and they have significant potentials to achieve robotization executing different types of tasks in diverse conditions in the construction environment (TBNetwork, 2021).

In particular, great potential concerns the development of task planning systems that can dynamically generate highly detailed elemental motions (e.g., grasping, moving, turning, picking) of robots using information from BIM and construction schedules (4D BIM) to extract control inputs such as exact 3D coordinates of moving paths, speed of the mobile base, and trajectory of the robotic arm's end effector. This can be achieved by exporting a sufficiently detailed BIM model from the authoring tool in IFC format (see Section 4.6.3) in order to provide the BIM world the robot shall work within. It is necessary to convert the exported IFC file into another format that can be read by a robot simulation tool (e.g., Simulation Description Format (SDF) for ROS Gazebo). IFC-SDF conversion can be limited to wall objects with the planar surfaces, for instance, to allow indoor navigation, or can fully cover all types of building components with diverse shape representations. Then, the ROS task planner receives the schedule information and the descriptions

TABLE 8.2 Main construction robots available on the market.

Construction phase	Construction activity	Machine typology	Manufacturer	Model
Site preparation	Site layout	Single task	Dusty Robotics	Dusty
	Demolition	Single task	Brokk, Aquajet	800, Aquacutter
	Excavation	Autonomous vehicle	Built Robotics	Dozer, CTL, Excavator
	Earthmoving	Autonomous vehicle	Volvo, Caterpillar, Komatsu	TA15, CAT Command, AHS
	Scaffolding assembly	Single Task	Kewazo	Smart Robotic Elevator
	Foundation laying	3D printer		
Structural works	Concrete casting	Single task	ETH Zurich	In-situ Fabricator
	Concrete formworks	Single task	Odico Construction Robotics	Robotic Hot-Wire Cutting
	Rebar positioning and tying	Single task	Advanced Construction Robotics	Tybot, Ironbot
	Steel welding	Single task	Welbot	Adaptive Robotic Welder
Construction	Rendering	Single task	Anex Industrial	Automated rendering machine
	Partition layout	Single task	DPR—Trimble, Nextera Robotics	Project Lion, Oliver
	Drywall laying	Humanoid	AIST	HRP-5P
	Drywall finishing	Single task	Canvas	Drywall finishing robot
	Brick laying	Single task	Construction Robotics, Fastbrick Robotics	MULE 135, SAM 100, Hadrian X,
	Plastering	Single task	Okibo	Plastering robot
	Wall fabrication	3D printer	Icon, Wasp	Vulcan, Delta
	Ceiling drilling	Single task	Hilti	Jaibot
	Painting	Single task	Welbot, MIST	Wall painter
		Autonomous vehicle	Apellix	Worker Bee
	Façade installation	Single task	Brunkeberg, Hephaestus	Cladding system, Vertical railing
	Floor tiling	Single task	CBot	Tiling robot
	All activities	On-site factory	Mace, Shimz	Rising factory, SMART
Labor assistance	Material delivery	Autonomous vehicles	Yale, Effidence, Intsite	Forklift robot, carrier, Autosite 100
	Work strain reduction	Exoskeleton		
Site inspection	Visual inspection	Biomorphic	Boston Dynamics, Watertower Robotics, ANYbotics	Spot, WTR, ANYmal C
	LIDAR scanning	Single task	Scaled Robotics, Doxel, Nextera Robotics	Autonomous Laser Scanner, Oliver
	Site survey	Autonomous vehicles	DJI	Phantom UAV
Maintenance	Ducts/pipes cleaning	Single task	LIFA	Duct Cleaner Robot
	Pv panels cleaning	Single task	Alion energy	SPOT Panel Cleaning System
	Façade cleaning	Single task	Kite robotics	Window Cleaning Robot

of specific tasks from 4D data along with the SDF file representation of the building shape. In the ROS framework, the developer can combine numerous subprocesses, called ROS nodes, into an application package, allowing to integrate project-specific and task-specific requirements that explain how a robot should or should not handle a certain task in the context of scheduling, safety, and spatial coordination. Based on these input files, the robot task planner generates detailed motions and movements of a construction (Kim, Peavy, Huang, & Kim, 2021).

Future perspective in robot science concerns the development of swarm robotics, which consist in a large number of mostly simple physical robots that can interact and work together as a group with a collective behavior to perform complex tasks. Inspired by colonies of insects such as ants, termites or bees and their social and building activities, which demonstrate the ability to efficiently solve complex problems through apparently simple rules, a robotic swarm formation would offer the advantages of efficient movement, redundancy, and potential for human guidance of the single swarm organism (Khan, Kasmarik, & Barlow, 2020). To perform the given task, each robot of the swarm reacts to the environment by processing the readings from many sensors, receiving messages from neighboring robots and then deciding how to move or which messages to send without any designated leader, allowing to produce emergent behavior beyond the capability of the individual role. This cooperation enables the desired advantages of the swarm system: the ability to run properly even if one or more its members stop functioning (robustness), the capability to work with either a large or small number of members with the same performance (scalability), and the possibility of changing the swarm behavior according to the varied situation (flexibility). Most promising applications of robotic swarms, and of unmanned aerial vehicles (UAVs) in particular, are autonomous search and rescue, fire-fighting, exploration in dangerous or inaccessible areas, and mining or agricultural foraging tasks, as well as construction. A swarm approach to robotic fabrication would employ large numbers of autonomous robots to build human-scale structures potentially much larger than themselves according to desired specifications. An example of swarm robotic construction is the TERMES system developed by researchers at Harvard University, which consists in mobile robots able to autonomously climb, navigate and manipulate specialized construction blocks to build user-specified structures according to a simple decentralized control algorithm (Petersen, Nagpal, & Werfel, 2011).

8.2.1 Single task construction robots

This category includes automated and robotic systems that are closely related to industrial manufacturing robots, since each is purpose developed and optimized to perform a specific activity in a repetitive manner, as with conventional assembly lines where different stations perform subsequent tasks.

This approach is very flexible because it can be easily adapted to be used in combination with other traditional construction methods, although this may generate other challenges such as the need for additional health and safety requirements, the difficulty to parallelize and to integrate with human workers activities, and the lack of integration with downstream and upstream activities (Delgado et al., 2019).

Differently from their factory siblings, a key feature required for construction robots is their ability to be deployed at any construction site, meaning they must be equipped with wheels or tracks or must be compact enough to be moved in boxes or containers.

Typical examples of STCRs are scaffold integrated robotic arms, smart autonomous plastering robots, robotic systems that paint walls, mobile robotic arms that assemble bricks, autonomous wheeled robots that lay floor tiles, concrete spraying robotic systems, welding robots, and demolition robots.

STCRs are mainly employed in the following activities: demolition, structure, bricklaying, finishing, and ceiling drilling.

8.2.1.1 Demolition robots

STCRs are particularly suited for demolition works, as they allow removing workers from some of the most dangerous activities due to the presence of noise, dust and the risk of collapse or explosions. Currently, available products such as Brokk (see Fig. 8.4), Aquajet or Husqvarna DXR series still employ human remote control for building selective demolition or disassembly, with completely autonomous operation in development (Corucci & Ruffaldi, 2016). These robots feature tracks and outriggers and can be equipped with various accessories for breaking, crushing, shearing, digging, shoveling, grapppling, surface removing and trenching of different materials. Several demolition robots employ high-pressure waterjets to perform selective hydrodemolition, allowing to remove concrete or tarmac leaving the rebars intact after the operation (see Fig. 8.5). ERO by Omerh is an automated hydrodemolition robot equipped with a centrifugal



FIGURE 8.4 Brokk teleoperated demolition robot. *Courtesy of Brokk.*



FIGURE 8.5 Hydrodemolition robot. *Credit: Aquajet Systems.*

decanter, able to suck up concrete debris crushed by waterjets, separate the waste mixture and package the cleaned material for easy reuse in the construction industry, all while recovering most of its operational water.

8.2.1.2 Robots for structural works

STCRs have found use also in the structural phase of building construction, both for steel and reinforced concrete structures. Concerning steel structures, these have usually a degree of prefabrication as components such as columns and beams are cut to size in the factory before being transported to the construction site and installed by nuts and bolts or welded connections. Welding robots such as Welbot's Adaptive Robotic Welder are robotic arms remarkably similar to those used for instance in the car manufacturing industry, but with reduced size and improved freedom and reach radius to achieve the higher flexibility required in the construction site. Thanks to its lightness (11–28 kg), this six-axis robotic arm can be set up in less than 5 minutes to perform workmanlike, AI assisted welding operations, including multilayer welds, with reliable quality. A trolley mounted version allows for specific welding duties such as connecting bored piles sections on-site.

Regarding reinforced concrete structures, robots currently allow to automate formwork preparation, rebar placing and tying, and concrete casting operations.

The application of robotics to formwork is particularly relevant, as it dictates the final shape of any concrete cast structure and constitutes therefore a major factor in determining the building design. Concrete, and contemporary ultra-high-performance concrete (UHPC) in particular, can in fact be cast in any shape, assuming the right additives were used, with the main effort and cost attributable to formwork depending on the complexity of the required form. Common formwork systems used in the building industry can only produce geometrically simple basic forms and allow deviations within the range of centimeters, leading to concrete parts that are limited to straight and rectangular basic

shapes with little room for optimization according to effective structural loads (Herrmann, Mainka, Lindemann, Wirth, & Kloft, 2018). The production of concrete elements that differ from these standards often requires 3D free-form formwork systems obtained either by manual construction or by automated manufacturing processes, such as CNC-milled wooden formworks or epoxy resin coated foaming polystyrene (EPS). These methods are characterized by very high production costs, as complex formwork is extremely labor intensive, and automated milling is heavily time consuming because it relies on incremental subtraction of material from the work object, with several passes over a given surface that typically translate to over 240 min/m² of machining time to arrive at industrial-grade surface smoothness (Søndergaard, Feringa, Stan, & Maier, 2018), with the added drawback of substantial waste of milled material.

In order to overcome these limitations, in the last years robotic hot-wire cutting (RHWC) and robotic abrasive wire cutting (RAWC) have been applied to formwork production, pioneered by Denmark-based Odico Formwork Robotics (see Fig. 8.6) (Cardno, 2019). Starting from the geometry of a given CAD-model, RHWC utilizes a robotically controlled, electrically heated wire to cut through foams like EPS, whereas RAWC employs a diamond threaded abrasive wire rotating on electrically propelled flywheels to model EPS, timber, natural or artificial stone and clay. Compared to conventional CNC-machining, RHWC and RAWC can only produce single curved and ruled surfaces and are limited in double curved geometries, but have the crucial advantage of a much faster process because reaching the production surfaces can be achieved in a single pass operation and allow to recycle cut-offs for new formwork material enabling a highly sustainable production cycle. In particular, a 1000 × 1000 × 150 mm curved geometry that takes more than 4 hours to produce with CNC milling can be obtained in less than 2 minutes with RHWC and in less than 20 seconds with RAWC (Søndergaard et al., 2018).

RHWC formwork was extensively used in the construction of the Kirk Kapital HQ building in Vejle, DK, by Studio Olafur Eliasson, which complex hyperboloid and paraboloid load bearing concrete structure required design and manufacturing of around 3800 unique EPS formwork units (Søndergaard & Feringa, 2017); other architectural firms that have used RHWC formwork techniques include SOM, Zaha Hadid Architects, and 3XN.

Both RHWC and RAWC are suitable for on-site deployment, thanks to their simple setup and compact size, as work is performed by a single robotic arm with a single production unit that can fit into a standard 3-m shipping container and a streamlined user interface that can be operated by a tablet.



FIGURE 8.6 RHWC (top) and RAWC (bottom) formwork production. Courtesy of ODICO.

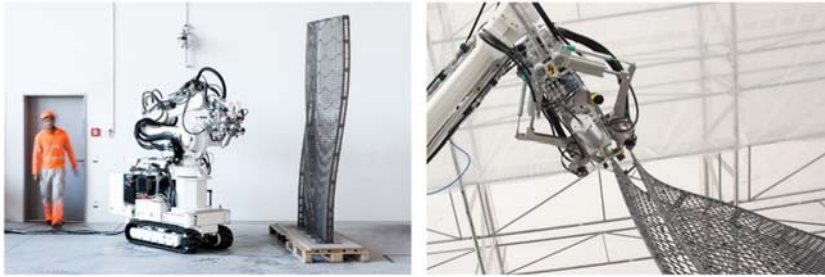


FIGURE 8.7 Mesh Mould and In-situ Fabricator. © Gramazio Kohler Research, ETH Zurich.

Another concrete construction operation that lends itself to robotic automation is positioning and tying of reinforcing bars, which is characterized by repetitiveness and labor strain and is usually prone to accidents as workers walk on irregular mats of rebar. Within these applications, United States-based Advanced Construction Robotics leases TyBot, an autonomous robotic arm rigged to a gantry crane purpose-developed to tie together steel rebar (Sawhney et al., 2020). TyBot is controlled by an AI algorithm that allows it to operate autonomously by recognizing the steel intersections and self-locating the tie modules, without any prior programming. After a set up that takes between 1 and 4 hours, TyBot proceeds to tie up to 230 m² per shift, claiming a 20%–40% productivity boost in man-hours compared to manual labor crews and requiring only one technician to monitor performance, reload the tie wire spool, and ensure the robot does not impede on existing safety protocols. ACR in 2019 introduced IronBot, a rebar placement robot that is designed to lift, carry, and place rebar in horizontal-reinforced concrete applications, a task that is notoriously tedious, labor intensive and with high levels of physical exertion. Similarly to TyBot, IronBot is equipped with machine vision to identify and correct on the go the position and alignment of rebar.

More versatile is the Mesh Mould metal process developed at ETH Zurich, in which a purposed construction robot named In-Situ Digital Fabricator (IF), equipped with tracks, vision sensors, and a customized end effector, can bend and weld metal wires into 3D mesh rebar structures (see Fig. 8.7). As part of the DFAB HOUSE demonstrator prototype, the robot fabricated a 12 m, 100 ton load-bearing curved concrete wall with 335 layers of 6 mm metal wire and over 20,000 welding points (Melenbrink, Werfel, & Menges, 2020; Wangler et al., 2016). The main functional characteristic of the IF is context awareness, as it can provide 1 mm end-effector positioning accuracy with respect to a global reference frame even as the robot moves from one building position to the next, making it particularly suited to construction sites that are typically varied and uncontrolled, allowing to avoid dependence on external reference systems, extensive setup, and tedious calibration routines (Sandy, Giftthaler, Dörfler, Kohler, & Buchli, 2016). Other applications of IF include brick-laying and concrete casting, all with robotic precision, requiring only the switch of the different end-effectors. It was evidenced that IF provides higher productivity over the conventional construction process when complex structures are built, with no additional cost as the complexity of the wall geometry increases. However, the conventional construction method still outperforms the robotic fabrication method for building simpler walls (de Soto et al., 2018).

8.2.1.3 Bricklaying robots

Bricklaying, either for load bearing and nonload bearing walls or for brickwork facades, is a construction activity that is extremely repetitive and physically taxing, as it implies frequent pick-up of heavy objects and may require labor to work on insecure ladders or scaffolding for long stretches of time. At the same time, tasks like splitting bricks and tracing plumb lines require skilled masons. These characteristics make this activity a suitable candidate for on-site automation, and several single task robots have been developed and introduced to the market in the last years.

Australia-based Fastbrick Robotics pioneered Hadrian X, a self-contained robot mounted into a truck to easily transport it for on-site building (see Fig. 8.8). The robot is equipped with a 30 m long telescoping arm to convey tailor made concrete masonry units (CMU), which it then stacks according to a predefined plan, using a quick-setting polymer adhesive. Before application, CMUs must be arranged in the correct order. The machine can also cut blocks into quarters, halves, or three-quarters when needed and stores them for later use. These blocks are then fed into a boom-transport system and conveyed to a layhead, which lays out the blocks based on logic and the pattern programmed into the machine. To ensure the required precision, the robot dynamically stabilizes its arm, counteracting wind, vibration, and inertia. The robot's control system software transforms the CAD model of the wall structure into brick metadata, assigning bricks into a particular nesting pattern and, with the help of an algorithm, determining how to lay out the bricks according to the pattern and other parameters such as the size of the robot's layhead and how it grips the blocks. No human intervention is required.



FIGURE 8.8 Hadrian X bricklaying robot. © 2021 FBR Limited.

United States-based Construction Robotics has developed a bricklaying robot for onsite and prefabricated masonry construction called SAM100 (Semi-Automated Mason), claimed to boost productivity by 3–5 times (Melenbrink et al., 2020). SAM is moveable and guided by a laborer, and is able to lay up to 3000 bricks per day, six times faster than conventional methods. SAM includes a conveyor belt to supply bricks, a metal robotic arm to spread mortar and a laser-guided system to lay the bricks in rows. The robot is designed to work on large, uninterrupted walls, and still requires humans to brick and mortar the first 1.5 m of any area, in addition to corners and areas around windows or doors. Builders can use SAM to build walls offsite, or bring it on-site to get prefab quality while reducing shipping costs even with complex and custom patterns. As part of its control system, SAM captures several data points, including the number, size, and placement of each brick, the date, time, and temperature, the mortar slump, bed gap, and ambient RH, and provides a real-time feed that allows for monitoring of daily progress with detailed analytics. Furthermore, the software automatically corrects for any variation in the as-built dimensions, allowing masons to resolve problems before beginning production.

Another bricklaying robot by Construction Robotics is MULE135 (Material Unit Lift Enhancer), a general purpose lift-assist and precision placement arm that is used for on-site placement of CMUs. This robot is designed to work with human masons, rather than replace them directly, and features a range of attachments designed for other construction applications ensuring greater flexibility than similar products, with better adaption to conventional construction practices. Specifically, MULE is a material handling hoist able to lift, handle, and place in position blocks up to 60 kg via a 3.6 m arm with two pivot points, taking the bulk of the work and leaving agility and precision to the human worker.

Concerning partitions layout, DPR Construction, and Trimble codeveloped Project Lion, an autonomous robot capable of drawing interior layouts on floors. This “laybot,” applies robotic-total-station (RTS) technology (see Section 6.1.3) to help it mark lines on slabs before interior construction with accuracy within 3 mm and speed up to 300 m/h, much quicker than experienced drywallers which average 50 m/h working in pairs with chalk lines and tape measures. The robot is guided by standard DXF or DWG files taken straight from the BIM model that are loaded on its inboard computer. A prism mounted on its top receives signals from the RTS to guide it as it moves.

A similar service is provided by Nextera Oliver, which claims to draw a complete floor layout based on 3D models up to ten times faster than humans, with the possibility of simultaneously adding details about wall types, door styles, and other additional information for other trades (water pipes, wiring, etc.). The robot features a LiDAR mounted 1.5 m high that can rotate 360 degrees and additional scanners at front and rear of the robot to detect landmarks and avoid obstacles for navigation. This allows it to stop and scan multiple locations in the construction site autonomously to compile as-built model for construction quality and progress monitoring.

8.2.1.4 Finishing robots

Among the different activities involved in building construction, finishing tasks such as plastering, painting, or coating application have seen little development in the field of on-site automation in the last years. Although these operations are characterized by high repetitiveness, they require an advanced ability to adapt to different scenarios and to cope with differences or imprecisions that may have developed in previous construction activities (doors and windows



FIGURE 8.9 Okibo wall finishing robot. *Courtesy of Okibo.*

openings, pillars or alcoves, out of square or curved surfaces). As such, viable finishing robots are commonly equipped with advanced 3D scanning cameras to detect their surrounding and execute their actions accordingly. Such is the case of Israel-based Okibo, which pioneered a mobile construction robot tailored for on-site application of wet materials like plaster and paint (see Fig. 8.9). Okibo features with an industrial robotic arm on a wheeled base and is able to apply plaster to walls and ceilings in complete autonomy: after 3D mapping its environment and comparing it with BIM database, the robot identifies the area for application, preplans the working path and applies the material (e.g., premixed compound, gypsum, cement). First, the wet material is sprayed on the surface in the set amount, then the robot arm automatically switches the nozzle with a trowel to even the surface, remove excessive material and recover it for reuse. The robotic arm allows floor to ceiling reach for both plastering and painting applications.

Similar to Okibo, Canvas is semiautonomous robot that combines a mobile base, robot arm, multiple end effectors and computer vision to provide Level 5 finish on drywalls. A human operator is still required to navigate the robot to the specific location on-site and set the parameters of the work to be completed, then Canvas works by spraying drywall compound on walls and ceilings and provides on-board dust collection system and sanding arm to reduce cleanup on-site. The robot has room-level autonomy, figuring out the spray and the sanding patterns, then moving between walls in a room as directed by the operator, who can be supervising multiple machines at once.

8.2.1.5 Overhead drilling robots

Other physically demanding, repetitive installation tasks that are suitable for robotic automation include overhead drilling, particularly if numerous holes are required for mechanical, electrical, and plumbing fixtures. Construction tools maker Hilti introduced in 2020 the Jaibot construction robot, a semiautonomous robot able to effortlessly perform overhead drilling in a dust-controlled manner with absolute precision. Jaibot is equipped with threads and is steered by an operator from one work area to the next, then locates itself accurately via BIM using a total station. Then, the robot is able to drill any hole indicated in the BIM model and vacuum any dust produced in the process with a built-in dust removal system, conversely marking each perforation with a different color according to the specific trade (mechanical, electrical, plumbing, or interior finishing installation work). The robot operates cordlessly for up to 8 hours between charges and, according to the manufacturer, can be controlled intuitively even by unskilled labor. Location, depth, and diameter of each hole are defined by the drilling plan, allowing in fewer errors, greater accuracy, and cleaner holes. When marking and drilling, the Jaibot automatically syncs back to the project management system where the current status of the project can be tracked in real time for documentation.

8.2.2 Biomorphic robots

Biomorphic robots represent an entirely different approach to the automation of the construction site compared to STCRs. Although the final objective is the same, that is, the help or replacement of human labor in various tasks to improve productivity, it is pursued by developing machines that reproduce the human or animal shape to pursue the

maximum operative flexibility, rather than optimizing their configuration to perform a single operation in the most efficient way. Such robots may help construction workers with more general tasks and can be considered to be task-generic (Pan, Linner, Pan, Cheng, & Bock, 2020). A human- or animal-shaped robot, in fact, able to move and maintain its balance autonomously and to interact with common tools and equipment designed for human labor, has the distinct advantage of requiring little, if any, preparation or set up of the construction site as well as minimal or no additional programming. Biomorphic robots may navigate the premises traversing stairs or other obstacles, opening doors, and picking up and operating power tools just like a human worker would, with the benefit of increased safety, reliability, accuracy, and endurance.

Compared to STCRs, even mobile ones equipped with wheels or threads, biomorphic robots are inherently more focused on freedom of movement and commonly feature machine vision cameras or radar/LiDAR sensors in order to trace their surroundings and program their route accordingly; balance is provided by two or four fully articulated legs controlled by gyroscopes and actuators. Object manipulation is instead carried out by means of robotic hands, able to operate common power tools, or, in the case of four legged biomorphic robots, robotic arms with a gripper on their end able to operate door handles, levers, and switches.

Currently, most biomorphic robots are at the prototype stage and are used as testing beds and demonstrators to further develop the mechatronic technology underneath, although the first ones, mainly four legged, have entered the market and taken services within construction contractors and service companies.

Regarding four legged robots, one of the most renowned products is Spot by United States based Boston Dynamics, which has been one of the earliest to enter the market, first as a leasable then as a buyable asset, and has at the moment more than 100 units in the field (see Fig. 8.10). Spot can move for 90 minutes at up to 1.6 m/s speed up slopes of 30° and over 30 cm high steps, and features built-in stereo cameras to provide depth information to produce 3D point clouds, enabling the robot to map its surroundings and avoid obstacles. A modular configuration allows to add panorama and pan-tilt-zoom cameras or LiDAR sensors to provide high-definition, color images or increased range in 3D mapping, with the option to install a robotic arm with six DOFs and a gripper to open doors and cabinets and manipulate objects. Recently, Spot has also been upgraded with 5G technology by Ericsson to allow greater range for specific applications such as airport surveillance.

Similar to Spot, ANYmal C is a four-legged robot developed by ANYbotics, a spin-off of ETH Zurich, compatible with a full array of sensors and able to work on all terrains either teleoperated, under human supervision, or fully autonomously on a predefined set of tasks (see Fig. 8.11). ANYmal C can also be equipped with four hub motor-equipped wheels that are attached to each of its feet, allowing it to move up to 4 m/s on smooth terrain and to selectively control torque in each wheel to brake them and use their grip to allow gait movement. Other four legged robots are in development at the Italian Institute of Technology (IIT), which debuted HyQReal, a heavy-duty hydraulic quadruped capable of

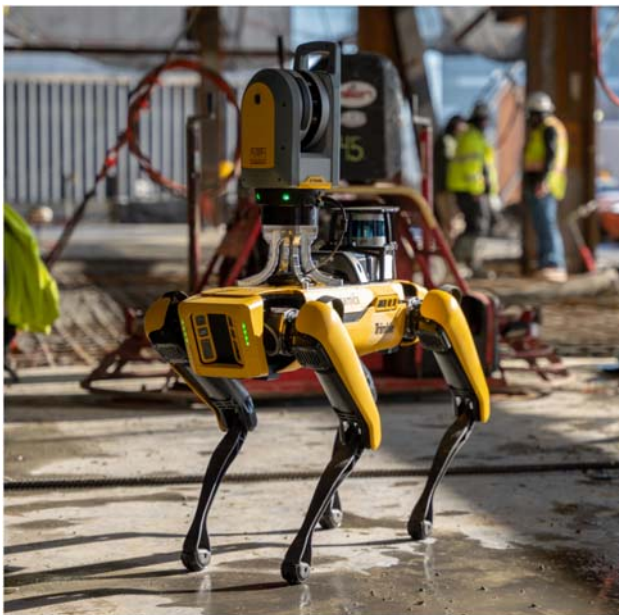


FIGURE 8.10 Spot biomorphic robot. Courtesy of Boston Dynamics.

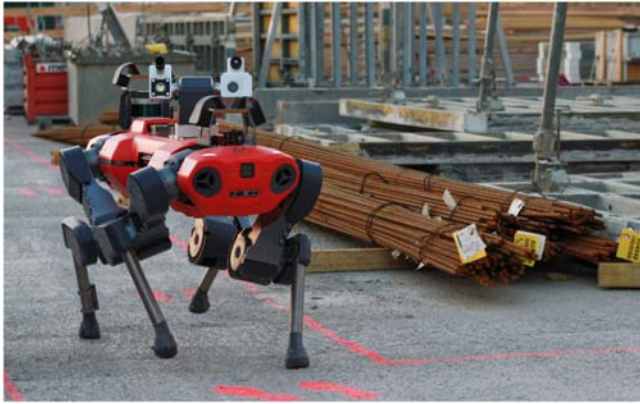


FIGURE 8.11 ANYmal C biomorphic robot. *Courtesy of ANYbotics.*

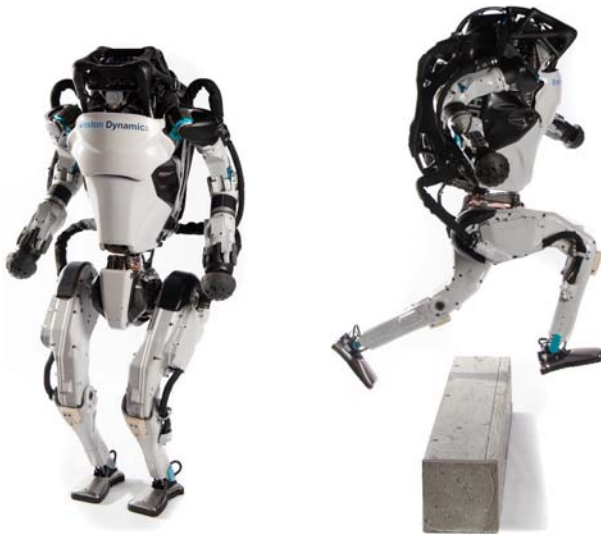


FIGURE 8.12 Atlas biomorphic robot. *Courtesy of Boston Dynamics.*

towing more than 3 tons, and HyQCentaur, equipped with two hydraulically actuated robotic arms, each with 6 DOFs, for added balance and unprecedented manipulation capability.

Main application in construction of quadrupeds like Spot and ANYmal C is the autonomous survey of construction sites to document and manage site progress, either by camera recording, thermal inspection or laser scanning. Routine site scanning is used to create a digital twin of the worksite, update it automatically and identify rework as soon as possible. They are also commonly employed in facility management to perform remote reading of gauges or displays, detect water, steam or gas leaks, and abnormal operating noises from machinery in order to schedule predictive maintenance operations. For instance, Foster + Partners architecture firm tested a Spot biomorphic robot equipped with LiDAR scanners in its Battersea Roof Gardens redevelopment site in London, making it repeatedly follow a premapped route during works to perform sequential scans of the construction site to supervise procurement and logistics and assess progression. Returning to the site on a weekly basis allowed Spot to re-run the same missions, with the process yielding a sequence of highly comparable, consistent models. Spot was also instrumental in constructing a digital twin of the firm's campus in London, autowalking the site and allowing the team to build up a four-dimensional model, showing how the space changes over time.

Two legged biomorphic robots are instead still in the development phase but have the greatest potential in replacing human labor due to their humanoid shape in several tasks, including driving construction vehicles (Bock, 2007). Compared to four legged robots, they require more complex control systems to maintain their balance while walking or performing scheduled tasks, spurring extensive research that culminated in demonstrators such as Atlas by Boston Dynamics, a bipedal robot equipped with 28 hydraulic joints controlled by algorithms that allow it to run at 1.5 m/s and perform leaps and somersaults (see Fig. 8.12) (Ruggiero, Salvo, & St. Laurent, 2016).

Current applications of bipedal robots like Atlas or Digit by Agility Robots are limited to site navigation and materials carrying, as those machines are not equipped with fully articulated hands for tools operation and object manipulation. More focused on construction tasks is HRP-5P by the National Institute of Advanced Industrial Science and Technology (AIST) in Japan, the fifth generation of an ongoing development platform for heavy labor. This humanoid robot has a body with 37 total DOFs, enabling operations more closely resembling human motion. HRP-5P features two robotic hands that allow it to pick up and handle large and relatively heavy objects such as gypsum or plywood panels, and by using head-mounted sensors, it constantly acquires 3D measurements of the surrounding environment, storing, and updating the results in order to execute its walking route even if the field of view is blocked by objects used in work. In a demonstration of construction activity, HRP-5P mapped the workspace, detected objects and autonomously approached the workbench on which gypsum wall boards were stacked. The robot then separated a single board, picked it up and transported it to the designated place, where it was lowered and stood against the wall and finally screwed using a screwdriver recognized and picked up using high precision AR markers (Sawhney et al., 2020).

8.2.3 Human augmentation

The integration of robotics and automation into the construction site activities, with the aim of increasing productivity and reduce time, cost, and safety issues for workers, does not strictly translate to replacing human labor. On the contrary, much of robotics and bio-mechanic science is currently being applied also to ease the working conditions of human labor by directly enhancing their physical capability by means of wearable electro-mechanical devices known as exoskeletons, thus allowing human augmentation of the workforce. Although these exoskeletons may not be considered as a robotic system to all effects, as the human worker is not replaced but simply supported in its tasks, they share much of the same technology and represent an important step of robots, automated systems, and augmented workers working together seamlessly before automated construction sites will be entirely devoid of humans (Delgado et al., 2019).

Generally, the concept of “Human Augmentation” (Raisamo et al., 2019), along with “Augmented Human” and “Human 2.0,” refers to methods and technologies that enhance the human productivity or capability, improving their sensing, action and/or cognitive abilities. This can be achieved through sensing and actuation technologies, fusion and fission of information, as well as with AI methods. In particular, augmented action is achieved by sensing each action of the human worker and mapping it to specific machine actions in local, remote, or even virtual environments.

Exoskeletons (or exosuits) are wearable mechanical devices, passive or powered, that aim to minimize strain and injury by providing lift support, weight distribution, posture correction and other capabilities. Initially conceived for physical rehabilitation, these equipment are being increasingly used by workers in manufacturing, logistic, and recently also in construction. Exoskeletons can help workers by allowing them to lift heavy loads, reduce fatigue, facilitate the use of tools in awkward positions, etc., reducing the impact of each task and improving their productivity (Looze, Bosch, Krause, Stadler, & O’Sullivan, 2015), resulting in a healthier workforce less prone to severe strain, injuries, and permanent disabilities normally associated with repetitive, physically demanding tasks. Exoskeletons can also allow older workers to continue their on-site activities, mitigating the issues associated with the aging of the construction workforce.

Despite these benefits, several challenges are still to be addressed before exoskeletons are more widely adopted. In addition to industry-wide issues that include high costs, energy efficiency, safety, and comfort, the construction sector poses the following barriers to exoskeleton use (Kim et al., 2019):

- health and safety concerns regarding increased risks of catching, snagging and falling, hygiene issues, and a false sense of safety;
- usability concerns regarding the ruggedness expected from exoskeletons to adapt to the harsh conditions of the construction site while remaining comfortable and safe to use;
- integration with other personal protective equipment (PPE);
- high initial costs of adoption;
- possible low acceptance rates by workers.

Concerning their operation, exoskeletons can either be purely mechanical or can operate with a mix of mechanics and electricity. Their frames can be comprised of hard material, like metal and fiber-reinforced plastic, or soft materials, like cloth and textiles, according to their function.

Purely mechanical exoskeletons operate by taking weight from a specific area of the body (like the arms and shoulders) and redistributing it to another (like the core and waist) to reduce strain and fatigue. These exoskeletons use no electricity and show higher longevity in the field since they do not need recharging, nor does the user need to carry a power source.

TABLE 8.3 Main types of exoskeletons used in construction.

Body area	Uses	Benefits	Company and products
Power gloves	Gripping tools and materials	Strengthens grip and improves dexterity	Ironhand by Bioservo
Arm and shoulder support	Overhead activities and lifting	Redistributes weight from shoulders and arms to lessen strain	EksoVest EVO by Ekso Bionics Airframe Exoskeleton by Levitate Technologies shoulderX by SuitX EXO-01 by Hilti Mate by Comau
Back support	Stooping, lifting or reaching	Correct postures and reduces back pressure	V22 ErgoSkeleton by Strong Arm Tech backX by suitX
Standing and crouching support	Tasks that require prolonged standing like drilling	Redistributes weight from legs and knees and locks in place to provide support	Chairless Chair 2.0 by Noonee legX by suitX
Whole-body suits	Lifting and carrying heavy tools or objects	Reduces strain on the majority of the body and enhances the user strength	Guardian XO by Sarcos
Virtual exoskeleton	Remote controlled lifting and carrying heavy tools or objects	Allows the worker to operate from any distance from the activity	Guardian GT by Sarcos

Partial or fully electric exoskeletons, on the other hand, are typically more powerful than mechanical exoskeletons and can handle more weight. They can target more specific areas, like the hand, and increase pressure and strength where needed. However, once depleted, they need either to replace the batteries or to recharge the suits to power them back up. In addition to higher cost, batteries also add weight, potentially impeding mobility, and sometimes need to wait for the suits to cool off before replacement.

Exoskeletons' operation depends on the part of the body they are outfitted for and the way they are powered. Commonly, mechanical exoskeletons aim to reduce continuous strain and increase endurance by shifting loads from one part of the body to other parts, whereas powered exoskeletons aim to enhance the user's strength by detecting the motion via on-board sensors and adding extra force where needed.

There are several types of exoskeletons that specifically assist construction workers (see [Table 8.3](#)). Based on the area of the body they support, they can be classified in: power gloves, arm and shoulder support, back support, standing and crouching support, whole-body suits. In addition to enhancing human abilities, exoskeletons can also be used for remote controlling mobile robots through VR, allowing on site operation without physical presence of the worker (virtual exoskeletons).

8.2.3.1 Power gloves

Power gloves are suitable for grasp intensive work tasks where the hands are exposed to high forces, repetitive or static work. Improved grip is also helpful when carrying heavy hand tools or picking up objects.

An example of power glove is the Ironhand system by Bioservo, which consists of a five fingers glove and a wearable power pack and is able to detect the user's movement. The glove senses when the user is about to grip an object and increases power based on the object's weight. Force, balance between the fingers, sensitivity, locking, and other settings can be adjusted via remote control according to the work situation.

The glove also collects data to assess and identify gripping situations that pose an ergonomic risk to the user of developing strain injuries.

8.2.3.2 Arm and shoulder support

These exosuits support workers who lift heavy tools and materials above their waist and are suited for overhead tasks like drilling, cutting, and grinding. They support both shoulders and arms to lessen the strain of continuously holding heavy tools for an extended period of time.

Shoulder support exoskeletons should be lightweight, breathable, low profile, and not impede mobility. Notable products on the market include Ekso Bionics' EVO that uses swappable gas springs in both arms to give the user lift assistance, Airframe Exoskeleton by Levitate Technologies that uses a pulley system to achieve this task, MATE by Comau, and SuitX's shoulderX that supports the user with springs (see Fig. 8.13). In order to ensure effective and comfortable operation, a firm fit to the user is required, reducing slippage (sagging) between the wearer and the exoskeleton and thus the need to perform micro-adjustments of the device during use. Several exoskeleton models therefore are available in two or more different sizes, others pursue a "one size fits all" approach and some require to be custom fit to the single worker. Shoulder supports are usually mechanical exoskeletons that do not require electricity to operate and employ systems of strings and pulleys to transfer the weight of the arms from the shoulders, neck, and upper back to the outside of the hips, evenly distributing energy to reduce stress, progressively activating as the arm is raised, and gradually releasing as the arm is lowered, resulting in a variable level of support. Most advanced shoulder and arms support systems weight around 3 kg, minimize points of contact to the body to be more comfortable and cooler during operation, and allow full flexibility of a user's torso and waist, including twisting and bending to the site as well as reaching directly overhead, across the body, or even into a back pocket for a phone, and do not interfere with tool belts or safety harnesses.

8.2.3.3 Back support

Back support exoskeletons commonly fit around the shoulders, back, and waist to reduce stress on the back and spine when the wearer is lifting heavy objects, stooping, bending, or reaching. Most advanced devices like backX by SuitX (see Fig. 8.14) are designed for all-day wearing, allowing natural movements and letting the wearer walk, ascend and descend stairs and ladders, drive automobiles, ride bicycles, run, or generally perform any maneuver. Back supports are designed to integrate with standard safety harnesses and tool belts to maintain their functionality and provide no discomfort, and can be comfortably worn under clothing or jackets. Some products even include pouches to hold cooling



FIGURE 8.13 shoulderX support exoskeleton. *Courtesy of SuitX.*



FIGURE 8.14 backX support exoskeleton. *Courtesy of SuitX.*

and heating packs for extreme weather. When worn, the back support reduces the forces and torques on a wearer's lower back region (L5/S1 disks) by an average of 60%, with testing showing that average muscle activities of the thoracic and lumbar erector spinae muscles while maintaining forward bending postures are reduced by 75% for males and 56% for female workers (Kazerooni, Tung, & Pillai, 2019).

In fact, repetitive movements and prolonged periods of time in a bent posture are common experiences in jobs with a high risk of back injury, with the majority of cases occurring when workers were not lifting loads but instead when they were bending down or reaching, causing the weight of their upper body to create large torques in the lower back region. Some back support exoskeletons, such as V22 Ergoskeleton by Strong Arm Tech, aim therefore to correct one's posture when bending or lifting, acting as a "coach" to provide feedback to the user when they are not safely bending. These back supports gently remind the body to remain in proper posture, bending at the knees and pivoting when twisting to help mitigate lower lumbar risk, and ensure the conformance to safe lifting guidelines throughout the course of a worker's shift.

8.2.3.4 Standing and crouching support

Standing and crouching exoskeletons are worn from the waist down and are in some cases integrable with the shoulder and back supports described above. When unlocked, they allow free movement of the legs and waist but can lock in place to distribute weight down to the ground, reducing pressure on knees and legs and decreasing strain on joints and muscles when a standing or crouching position is held for extended periods of time. This gives users the option to effectively sit in place when working instead of squatting, even when chairs are not available or would otherwise impede safety or productivity the work zone. This is a key feature for construction workers who spend lots of time standing or crouching repeatedly during the workday. Products such as Noonee's Chairless Chair or legX by SuitX (see Fig. 8.15) are purely mechanical, recognize when a user is walking, crouching, and standing and adjust accordingly, can be compatible with tool belts and safety harnesses, and provide support to the knee joints and quadriceps muscles that can be adjusted to suit the needs and weight of the user. At over 6 kg, weight is higher than shoulder and back supports; however, it is directly transferred to the ground and is not borne by the user.

8.2.3.5 Whole-body suits

Whole-body exoskeletons provide support throughout the entire body to minimize strain and enhance strength at the same time and can be purely mechanical or electro-mechanical according to their specifications, with the latter providing higher performance with the drawback of additional costs, weight, and downtime related to the need of batteries.

More advanced electrical full body suits, such as Guardian XO by Sarcos (see Fig. 8.16), allow operators to safely lift and manipulate up to 90 kg without fatigue or strain, amplifying human strength over 20 times and dynamically compensating for gravity and inertia, all while offloading 100% of the exoskeleton's weight during use. Whole body exoskeletons provide up to 24 DOFs to allow the operator to move freely and naturally in unstructured environments where larger machinery may be unable to access, and employ control systems with robot-integrated sensors to detect and replicate operator movements with the lowest latency. This highly responsive control system also allows to fluidly execute fall-prevention motions such as stumble-recovery, and as an added safety measure, redundant hardware and software limit-stops enable passive braking to prevent operator injury in the event of sudden power loss. Power required



FIGURE 8.15 legX support exoskeleton. Courtesy of SuitX.

FIGURE 8.16 Guardian XO exoskeleton. *Courtesy of Sarcos.*

is around 400 W for normal operation and a single charge may last up to eight hours, with the possibility of hot-swapping batteries to reduce downtime.

8.2.3.6 Virtual exoskeletons

Finally, the concept of the whole-body suit can be extended to virtual exoskeletons, that is, robotic systems in which a machine placed in a separate location is operated in synchrony with the movements of an operator detected by a sensors-equipped exoskeleton. This type of remote control based on human-robot interaction is especially useful in hazardous operating environments such as factories, construction sites, nuclear power plants, assembly or maintenance in space or the sea, and search and rescue operations (Raisamo et al., 2019). The highest fidelity of operation can be achieved if the user sees from the robot's perspective using a VR headset, and other input methods such as touch, gestures, gaze, and speech can be integrated. Hand controllers, gloves and similar systems are often used in VR to enable virtual limbs that can manipulate objects of any size and weight with a high degree of accuracy.

An example of virtual exoskeleton is the Guardian GT system, a human-controlled, force-multiplying robotic system with one or two highly mobile arms mounted on a track or wheeled base, allowing to perform remotely tasks such as heavy lifting, intricate processes like welding and joining, or even operating switches and levers (see Fig. 8.17).

8.2.4 Autonomous and teleoperated vehicles

In the last decade, autonomous vehicles have seen vast research, development, and application in the fields of mineral extraction and agriculture, where they have already proven a key factor in improving overall productivity. Conversely, the construction sector has seen slower adoption of this technology, although with rising numbers and with more and more products entering the market, either adapted from other applications or purposely developed.



FIGURE 8.17 Guardian GT virtual exoskeleton. *Courtesy of Sarcos.*

In the modern construction site, autonomous or remotely controlled terrestrial and aerial vehicles can be used for several tasks, including:

- automated excavation, demolition, and earth moving;
- surveying and monitoring tasks;
- delivery of materials and tools;
- accessing extreme and dangerous environments, allowing to remove human workers from high-risk areas.

In particular, site preparation and road grading or paving activities are best suited application of autonomous vehicles, as those are usually characterized by larger and more open environments and repetitive or cycling tasks. Established companies like CAT, Volvo, or Komatsu and more innovative startups like Built Robotics have been upgrading conventional vehicles with autonomous guidance systems based on AI algorithms and equipped with the required sensors. Main autonomous vehicles for construction site preparation include:

- compact track loaders (CTL), which are able to perform small size autonomous excavation even in reduced spaces;
- dozers, that can take care of rough and finish grading, spreading, pushing, and track walking of different soil types;
- excavators, that can provide foundation excavation, trenching and truck loading work;
- earth moving trucks which can transport excavated material in-between locations.

These machines are usually equipped with multilayer safety systems that allow them to detect and avoid people, animals, and other manned or unmanned vehicles. Working areas can be geofenced, meaning that vehicles movement is confined to specified zones using GNSS to prevent wandering in unwanted places. More evolved vehicles allow operators to set the site perimeter and input the project plans with tablets or smartphones. In the right conditions, that is, in construction sites structured to allow repetitive and cyclic tasks with little variation, autonomous vehicles make for an efficient and safe environment, needing only an external observer to survey operations and to step in to halt operation remotely in case of immediate danger.

Notable autonomous construction vehicles include Built Robotics automated CLT, dozer and excavators (see Figs. 8.18–8.20), and Volvo TA15 Autonomous Hauler, which brought automated earth mover to the spotlight having been awarded the Red Dot Design Award 2020.

Automated earth moving systems such as Komatsu Autonomous Haulage System (AHS) (Uhlemann, 2015), and CAT Command, though developed for the mining industry, can be fully adapted to large construction sites such as infrastructure ones. Chinese equipment manufacturer XCMG has tested autonomous asphalt compactors and pavers, able to operate within 2–3 cm accuracy, during construction of a new highway in China, coordinated by a remote monitoring data center that submits instructions to the autonomous machines' onboard control system.

In general, the construction industry has lagged behind the mining industry in terms of automating earthmoving equipment, as these vehicles are well suited to the structured environment of the mining site and maintain a precise understanding of the terrain, whereas conditions for conventional construction site preparation are inherently more chaotic and ever-changing (Melenbrink et al., 2020).

The diffusion of autonomous vehicles in the construction industry is more closely dependent on the developments in the fields of consumer driverless cars/trucks and advanced driver assistance systems (ADAS). Differently from industrial (mining or agricultural) autonomous movement, these systems can be certified for use on publicly accessible roadways that, crucially, serve users of vehicles of all classes and driving automation levels (including no driving automation), as well as motorcyclists, pedal cyclists, and pedestrians.



FIGURE 8.18 Built Robotics autonomous excavator. *Courtesy of Build Robotics.*



FIGURE 8.19 Built Robotics autonomous dozer. *Courtesy of Build Robotics.*



FIGURE 8.20 Built Robotics autonomous CLT. *Courtesy of Build Robotics.*

In particular, on-road driving automation systems are classified according to the Society of Automotive Engineers (SAE) International J3016 standard in 6 levels of increasing autonomy (see [Table 8.4](#)):

- Level 0: No automation. System only provides warnings and momentary assistance (e.g., automatic emergency braking).
- Level 1: Driver assistance. System provides either steering or brake/acceleration support (e.g., adaptive cruise control or lane centering).

TABLE 8.4 SAE international's levels of driving automation for on-road vehicles.

SAE level	Name	Narrative definition	Execution of steering and acceleration/ deceleration	Monitoring of driving environment	Fallback performance of <i>dynamic driving task</i>	System capability (<i>driving modes</i>)
<i>Human driver monitors the driving environment</i>						
0	No Automation	The full-time performance by the human driver of all aspects of the <i>dynamic driving task</i> , even when enhanced by warning or intervention systems	Human driver	Human driver	Human driver	n/a
1	Driver Assistance	The <i>driving mode</i> -specific execution by a driver assistance system of either steering or acceleration/deceleration using information about the driving environment and with the expectation that the <i>human driver</i> performs all remaining aspects of the <i>dynamic driving task</i>	Human driver and system	Human driver	Human driver	Some driving modes
2	Partial Automation	The <i>driving mode</i> -specific execution by one or more driver assistance system of both steering and acceleration/ deceleration using information about the driving environment and with the expectation that the <i>human driver</i> performs all remaining aspects of the <i>dynamic driving task</i>	System	Human driver	Human driver	Some driving modes
<i>Automated driving system ("system") monitors the driving environment</i>						
3	Conditional Automation	The <i>driving mode</i> -specific performance by an automated <i>driving system</i> of all aspects of the <i>dynamic driving task</i> with the expectation that the <i>human driver</i> will respond appropriately to a request to <i>intervene</i>	System	System	Human driver	Some driving modes
4	High Automation	The <i>driving mode</i> -specific performance by an automated <i>driving system</i> of all aspects of the <i>dynamic driving task</i> , even if a <i>human driver</i> does not respond appropriately to a request to <i>intervene</i>	System	System	System	Some driving modes
5	Full Automation	The full-time performance by an <i>automated driving system</i> of all aspects of the <i>dynamic driving task</i> under all roadway and environmental conditions that can be managed by a <i>human driver</i>	System	System	System	All driving modes

- Level 2: Partial automation. In given conditions, system provides both steering and brake/acceleration support (e.g., adaptive cruise control and lane centering at the same time).
- Level 3: Conditional automation. The system is capable of fully driving the vehicle in required conditions, but is programmed to request driver assistance when needed (e.g., traffic jam assist).
- Level 4: High automation. The system drives autonomously under certain site conditions without asking the driver for assistance, and pedals and steering wheel are not required (e.g., driverless taxis).
- Level 5: Full automation. The system can drive autonomously anywhere in all site or weather conditions.

It is evident that levels from 0 to 2 require a driver or operator at any time and include only driver support features, whereas actual automated driving is allowed only from level 3 and beyond. For construction vehicles, driverless features are only part of the equation, as automation has to be extended also to the construction activities that currently require a human operator: loading/unloading, grading, excavating, etc.

Autonomous vehicles operate on the basis of the instructions received (even in the form of CAD drawings) and are controlled by their own AI routine with data gathered by a comprehensive on-board sensor suite. Most autonomous vehicles are equipped with LiDAR, radar and cameras to scan the surrounding and generate a map to plan their movements, supported by GNSS receivers. Dozers, haulers, and excavators can be equipped with inertial measurement units (IMU) to help maintain their balance when loading and unloading cargo. Moreover, each vehicle communicates with others and with a fleet coordinator system that analyzes vehicular flows, manages priority at intersections, allows logistic trains and issues warnings to the human supervisors when needed.

In addition to site preparation, another application of autonomous vehicles in the construction site is for tools and materials delivery. Automated vehicles are already an established reality in the logistics sector, with firms like Amazon employing more than 45,000 of those in its warehouses. As with earth moving vehicles, translating their operation from the structured environment of the warehouse, which can be designed to scope and equipped with floor markers, stickers or wires, to the more challenging construction site, requires a more substantial investment in sensors and AI, along with more robust frames and suitable wheels or tracks.

Autonomous transport vehicles such as Effidience can perform both autonomously, ferrying tools and construction materials from storage to set destinations to be loaded and unloaded, or semi-autonomously, by fixing its cameras on a worker and following them with its cargo. Trailers up to 500 kg can be towed. In larger construction sites, autonomous forklifts such as those manufactured by Yale can move skids or pallets of construction materials or demolition debris between unloading and temporary storage areas to working stations and deposits.

Great potential for automation characterizes the tower cranes commonly used in most construction sites. These heavy machines can represent a primary bottleneck of the building process and pose safety concerns when used stand alone or in more units with risks of arms contact, dropped cargo and danger from falling objects. Companies like Insite have equipped tower cranes with ADAS technology and AI-based algorithms for optimal movement, to identify most efficient trajectories and providing safety alerts when necessary. The AutoSite100 crane features a high-resolution camera installed on the trolley, and the system allows real-time detection of all objects on the worksite, both fixed and moving (including humans), determining the safest operational trajectories for the crane and reducing jobsite collisions and accidents. Visual data are processed using AI trained with machine learning for object detection and classification. The computer controlling the crane determines where the trolley and crane arm are by recognizing which part of the construction site the terrain below matches, and how far away it is (for altitude) (Jackson, 2020). The vantage point provides a complete site map and crane activity dashboard, allowing real-time insights on the construction process across all areas of the worksite.

Eventually, the increasing autonomy of individual construction equipment and vehicles will allow in the next future to automate the entire jobsite, planning and coordinating movement and operation of the entire fleet by exploiting image recognition, cognitive/control technologies, autonomous driving systems, 5G remote control, 3D drone surveys, accurate workload estimation, and assignment and failure prediction technologies. Korean manufacturer Doosan Infracore already demonstrated its own integrated control solution, named Concept-X, that promises to survey worksite topography via 3D drone scanning, to establish operational plans based on the topographical data, to operate construction equipment without human intervention, and to enable real-time monitoring of work progress from any remote control center.

Notwithstanding the growing diffusion of autonomous vehicles in the construction site, remote teleoperation of equipment is another approach that is finding increasing application, in particular in sites characterized by harsh climate, bad weather conditions or dangerous situations as it allows machines to work without the operator being inside the vehicle itself. For instance, Chinese construction vehicles manufacturer Sany debuted in 2019 its VR unmanned

control package. Compatible with excavators and cranes, it allows the machine to be operated remotely and is targeted toward works in unstable geology, in the presence of hazardous materials, in high altitudes or in atmospheric extremes of cold and heat, which would prove challenging for the operator to get to and from the machine and might require special air conditioning, heating, or in-cab oxygen supplies. The operator wears VR glasses reproducing a full view of the working area, hears any sounds from site as well as audible warnings, and uses the same controls as on the actual machine ensuring the experience is almost the same as sitting in the vehicle's cab, even if they are working hundreds of kilometers away. The system would also allow machines to be used by different operators working in shifts (even in different time zones), permitting 24/7 operation for maximum productivity.

Another Chinese company, China Molybdenum Co. Ltd, has recently introduced a teleoperated excavator for mining operations, equipped with a camera able to take 360-degree pictures with no dead angles and controlled by an operator 1 km away. An ultra-high bandwidth, low latency 5G telecommunication system allows the operator to control the excavator using a cockpit that is an exact replica of the real one.

5G network is also at the center of the systems for remote control of construction and mining equipment by Volvo, able to operate vehicles up to 400 m below ground and successfully tested in cross-national remote control from Spain to Sweden, and by Doosan, which demonstrated an excavator in South Korea controlled from 8500 km away in Germany over mobile network.

By far, the most widespread autonomous vehicles used in industry are the aerial ones, commonly called UAVs or drones. In particular, UAVs are already widely used in the real estate, agriculture and mining sectors, but the construction industry is the fastest growing commercial adopter evidencing +239% growth of drone usage on-site from 2017 to 2018 ([DroneDeploy, 2018](#)).

Drones in fact constitute a quick and inexpensive solution to survey at a glance the construction site, identify safety issues, provide accurate maps and layouts and track work progress and quantity assessment. Fixed wing drones are especially suited for large-scale surveying, as required with large infrastructure projects, and rotating blades drones are more adapted to smaller construction yards. Currently, remote sensing with UAVs usually requires manually piloting the drone while also operating the sensor/camera, often with a secondary operator. However, the need for manual piloting partially voids the efficiency of UAVs compared to traditional methods, making fully autonomous drone operation a main requirement towards a comprehensive inspection concept. Solutions available can take advantage of BIM data to automatically generate collision-free flight paths toward the desired point of interest ([Freimuth & König, 2018](#)).

UAVs can be integrated in the construction workflow in every stage of the building process. During site preparation, UAVs can scan construction sites to produce accurate 3D models to feed to autonomous earth moving vehicles and then track their operation in real time, allowing greater precision, productivity, and economy without needing to interrupt any activity. When earthworks are complete, a final site scan can assess the consistency with planning instructions before moving to the next phases of construction ([Zhou & Gheisari, 2018](#)). In 2018, Komatsu and Skycatch partnered in providing an integrated solution for on-premise data processing and aerial analytics, scoped for the automation of most earth-moving activities.

Once human labor takes over, UAVs make for efficient solution for instant communication between project management and workers: equipped with cameras and voice transmitters, drones allow direct interaction at any distance and instant feedback or advice, minimizing errors by miscommunication or misinterpretation.

UAVs are particularly suited for enforcing security surveillance of the construction site, both during active and inactive hours. Compared to human security guards or CCTV, drones are much cheaper and can cover a wide area in their patrols. Limited battery life can be addressed using wired power supply or, in case of two or more security vehicles, coordinated recharging or battery swap. Motion detectors and IR cameras can be particularly effective to prevent theft or trespassing at nighttime, in addition to the deterrent effect of a highly visible patrolling UAV.

Regarding health and safety of the construction site, UAVs have been proven as an effective solution to improve the well-being of workers and reduce accidents ([Dastgheibifard & Asnafi, 2018](#)). On the one hand, drones can directly replace human workers for inspections, maintenance or manual measurements in hazardous places such as unsteady heights, as falls account for 42% of construction-related fatalities ([Sue Dong, Largay, Wang, Trahan Cain, & Romano, 2017](#)). On the other hand, drones can survey every angle of the construction site to check for safety concerns, ensuring equipment and scaffolding are well fixed and, with the help of thermal scanners, detecting heat surges or electrical issues. Labor activity can also be monitored, with AI-based software determining whether workers are wearing PPE or identify workers' actions. In case of PPE violation, site safety officer can be notified in real time, and infringements can be registered with corresponding video footage.

In addition to these contributions to on-site management, UAVs can be directly involved in the construction activity, either by ferrying tools and materials or by performing actual finishing or even assembly operations. Concerning site

transportation, UAVs can replace heavy lifting machinery such as cranes for lighter tasks such as moving tools or equipment to different working areas without any geometrical boundary, as they can move around or even into buildings without any limitation by rough terrain, traffic or inaccessibility with the only drawback of a carrying capacity usually around 2 kg, although heavier duty drones are available on the market (Sawhney et al., 2020).

In the UK, the Universities of Leeds, Birmingham, Southampton, and University College London are developing a combined technology for the concept of “self-repairing cities,” consisting in drones equipped with 3D scanning and 3D printing capabilities. These UAVs would prevent the formation of potholes by identifying cracks in the asphalt and print asphalt into these cracks to seal them. The objective is to make road construction works completely autonomous and possible to perform at night, to eliminate traffic jams and road closures, achieving zero street works in cities by 2050 (ECSSO, 2019).

Regarding UAVs use for finishing operations, several companies have developed custom drones for coating and painting of indoor or outdoor surfaces. This operation lends itself well to UAVs, as these materials are sprayed with minimum thickness and large areas can be covered with small containers suitable with drones’ size and weight limitations. Moreover, painting UAVs remove the need for scaffolding altogether, itself a major expense for higher surfaces, and eliminate the risk of falling injuries. Painting drones, like Worker Bee developed by Apellix and AzkoNobel, are equipped with a spray nozzle and can be either untethered, allowing maximum range in height but requiring frequent recharging of the paint tank and the battery, or tethered to a base station via an umbilical cord to provide paint material and electric power, enabling continuous operation at the expense of a reduced range. PaintCopter, a tethered painting UAV developed by Disney Research and ETH Zurich, has been optimized for painting on 3D surfaces with a specific workflow: the target surface is scanned first, then the user can specify a desired surface design on the acquired 3D model which is automatically translated to waypoints and target spray points to instruct the drone. During the painting session, the UAV uses the stored 3D model to relocalize itself against the target surface, follows the trajectory defined by the waypoints, and directs the spray gun according to the target spray points on the surface (Vempati et al., 2018). Additionally, more drones can be coordinated by a centralized control system to work together on the same surface. Such is the case of “Paint by Drone,” a portable system demonstrated by design firm Carlo Ratti Associati (CRA) in 2017 in Turin, Italy, that employed an array of four quadcopters, each loaded with a spray-paint tank able to create CMYK-colored designs. A central control system instructed each UAV as to what it should be doing, with a visual monitoring system tracking their position in relation to each another. Over the course of two days, a 14 by 12 m graffiti mural was completed from a crowdsourced design.

The final step of UAVs integration in construction is their application in the actual building assembly, having autonomous flying vehicles that lift building elements and position them according to a precise BIM or CAD model, alongside or in replacement of traditional scaffolding or crane solutions. Dubbed Aerial Robotic Construction (ARC), this new approach to building has the potential to overcome the constraints of ground-based construction, either performed by human labor or robots, and open up entirely new possibilities related to the unprecedented freedom of positioning building components in space. Advantages of aerial construction are multiple: as aerial robots fly and mount construction parts directly to their required position, no scaffolding is required and height and bottom-up accessibility are no longer a constraint, and structures can be built according to highly complex designs. Finally, work capacity is easily scalable: while conventional machines are limited to operating on a small component of a traditional structure, many aerial robots can operate on an ARC structure at the same time, either individually or cooperatively (Willmann et al., 2012).

Researchers at ETH Zurich have demonstrated two prototypes of construction entirely performed by drones. The first is Flight Assembled Architecture, a structurally stable, 6 m tall, 1500 polystyrene blocks tower first designed by algorithmic optimization of modules overlap, then assembled by 50 flying robots controlled by a real-time camera system to avoid collisions and identify best-case paths for pickup and subsequent nonstandard placement of each individual, preglued module (see Fig. 8.21) (Augugliaro et al., 2014).

The second is the rope bridge able of supporting the crossing of a person above a 7.4 m gap, consisting in 9 segments of ultra-light dyneema rope for a total length of 120 m including knots, links and braids, laid by UAVs equipped with a motorized spool to control tension acting on the rope during deployment (see Fig. 8.22) (Mirjan, Gramazio, Kohler, Augugliaro, & D’Andrea, 2013).

A further application of ARC foresees the combination of drones and additive manufacturing, with the objective of miniaturizing 3D printers and provide them with aerial capabilities in order to manufacture complex building structures using parallel production by a multitude of UAVs. Research projects such as Aerial ABM are pursuing this goal, overcoming the current limitations consisting in short flight time, reserve of printable material constrained to 50 mL, and on-site printing accuracy still limited to 10–15 cm (Hunt, Mitzalis, Alhinai, Hooper, & Kovac, 2014).



FIGURE 8.21 Flight Assembled Architecture. © Gramazio Kohler Architects.



FIGURE 8.22 Aerial construction. © Institute for Dynamic Systems and Control and Gramazio Kohler Research, ETH Zurich.

8.2.5 Robotic on-site factories

Robotic on-site factories represent the ultimate development for automation of the construction site, in which most if not all operations are scheduled and performed by robots in a work environment that is much more similar to a factory than to a conventional construction yard. In fact, the piecemeal integration of single robots and robotic aids in the construction site, as described in the chapters above, can certainly increase productivity of single works but at the same time may generate other challenges such as the need for additional health and safety requirements, the difficulty to parallelize and to integrate with human workers tasks, and the lack of integration with downstream and upstream activities (Delgado et al., 2019). In an efficient robotic on-site factory, instead, standalone robots are integrated into controlled, structured environments that enable the implementation of more complex robot systems, that provide for instance the collaboration among various robots in an automated manner resembling a conventional manufacturing production line.

In order to accomplish this result, the traditional construction site has to be reinvented and restructured with automation at the forefront, removing any disruptive or chaotic condition and controlling humans and robots interactions to fully take advantage of the speed and workmanship of optimized operations.

The deployment of an on-site factory is a time and cost-consuming task that can take weeks to months, and is not suitable for smaller structures or sites that do not readily support such extensive structuring. Indeed, on site factories are best suited for buildings with limited footprint and sufficient repetition of operations such as high-rises and skyscrapers; hence, they are therefore known as “sky factories” as well. The technique of vertically mobile sky factories involves lifting the entire factory up by one level after construction of the prior level is complete, and is particularly relevant to high-rise construction in dense urban environments (Melenbrink et al., 2020). These integrated high-rise construction systems saw considerable initial development in Japan in the 1970s and 1980s, with several instances brought on by companies like Obayashi Corporation with its Automated Building Construction System (ABCS) and Big Canopy system, and Shimizu with its SMART modular on-site factory (Bock & Linner, 2015).

Generally speaking, on-site factories, especially those adapted to high-rise construction, require the following elements:

- a covered working platform, where material manipulators and automated construction systems can operate protected from adverse weather and with reduced impact on the surroundings, built on hydraulic jacks to raise alongside the building each time a floor is completed;
- just-in-time delivery of structural members and subassembled components, identified by barcodes or RFID tags, which are automatically transported from an unloading area at the ground level to the working platform, either to a substorage area or directly to their final position;
- an automated material handling system, that orientates and positions subassemblies and structural members according to the defined work plan;
- a centralized on-site integrated control center that monitors and coordinates the construction process, maintaining a real-time inventory of components, drawings, scheduling, and progress (Taylor, Wamuziri, & Smith, 2003).

A key component of any on-site factory is the overhead crane that allows to speed up and automate materials and components delivery all over the construction site. Specifically, gantry systems are a logical choice for on-site factory environments, as they are relatively simple to control and are capable of efficiently carrying heavy loads, and their high initial cost for set-up is soon overridden in larger projects. A cheaper, more agile alternative is represented by cable-driven parallel robots (CDPR) which, compared to conventional gantries, are relatively lightweight and therefore easier to transport and deploy in an on-site factory.

Renowned examples of on-site factory construction include Tokyo Sky Tree tower, which was built by Obayashi Corporation using its ABCS, automating on-site assembly operations to a high degree by installing a mobile working platform with automated logistics, column and beam positioning, welding, and real-time process control (Rauch, Dallasega, & Matt, 2015). Recently, UK based Mace Group employed “jump factories” in the construction of two residential towers in Stratford, London: each on-site factory was six story high, weighed 510 tons and created an indoor construction environment that rose alongside with the building—improving noise control, reducing safety risks, and preventing delays due to weather. Each factory featured an overhead gantry and spaces dedicated to materials delivery, façade installation, and subassemblies construction. This optimal work environment, along with extensive prefabrication of building elements, allowed to reduce the project’s transportation by 40% and its waste by 75%, and enabled construction as quick as 18 floors in 18 weeks (East Village No. 8: One big leap for construction).

Overall, the extensive site automation allowed by on-site factories permits to reduce construction costs and time for towers with sufficient height and geometrical conformity, by effectively moving tasks that would otherwise be conducted in offsite prefabrication facilities directly onto the construction site, without any decrease in quality as the construction tasks and corresponding robotic manipulators are the same used in controlled factory environments, and with important benefits in terms of materials procurement and transportation. Concerning construction time, higher buildings amortize better the assembly and disassembly period of the on-site factory: for instance, Obayashi Corporation claims that its ABCS can reduce the construction schedule for a 30-story structure by 3 months and the schedule for a 40-story structure by 6 months (Taylor et al., 2003).

Besides high-rises, infrastructures are another field that is suitable for deployment of mobile on-site factories with considerable benefits in view of their large scale and repetitive nature. In particular, bridges and viaducts are characterized by long spans of steel or prestressed concrete assemblies with constant section and are commonly located in places where environmental hazards (wind, vibrations, risk of falls, etc.) tend to slow and hinder construction. Although nowadays it is common to assemble suspended structures from large prefabricated elements constructed off-site, transported to destination and positioned in place by crane or winches, there are situations in which this process is not possible due to roads or topography limitations and an on-site factory allows, again, to combine safety and quality of off-site prefabrication with the agility of on-site construction.

A notable case of bridge construction with on-site factories is constituted by the renowned Millau viaduct in France, a multicable-stayed structure 2460 m long consisting in eight spans suspended up to 245 m over the valley bottom (see Fig. 8.23). The high complexity of the site and the steepness of the slopes limited the number of piers and their position, and prevented the installation of ground-based cranes or hoists to jack the bridge spans in place. The solution devised was to set-up two on-site factories on the platforms behind each abutment, each over 500 m long and complete with all necessary equipment (cranes, 90-ton material handling gantries, welding shops, paint shops) to fully assemble the bridge deck beside the valley slopes, from joining the prefabricated steel elements to painting and installing windscreens and guard rails. The bridge deck was then put in position by launching consecutive sections, each 171 m long, as they were ready, sliding them over the piers by means of hydraulic wedges at a rate of 10 m/h (Buonomo et al., 2004).



FIGURE 8.23 Millau viaduct. *Credit: Richard Leeming.*

By far, the most advanced application of automated on-site factories is in tunnel construction, which has been revolutionized with the introduction of tunnel boring machines (TBM), large and complex mobile construction sites capable of excavating the soil, extracting it to the surface and at the same time building the tunnel lining around them, leaving behind a fully finished tunnel ready to be equipped for the desired use (road, rail, aqueduct, etc.). Specifically, a TBM is a fully enclosed mobile construction site able to work underground, consisting in a rotating cutting wheel, a main bearing, a thrust system to advance the cutting head, and trailing support mechanisms to evacuate excavated soil and supply the prefabricated concrete lining elements that a robotic arm puts in place. Each time a concrete ring is complete, the hydraulic jacks push the cutting head forward and the whole machine advances. Large TBMs are often outfitted with laser guidance systems and hundreds of sensors, and normally operate autonomously, but remain dependent on human operators (or teleoperators) to make control decisions (Melenbrink et al., 2020). Compared to traditional tunnel excavating techniques, the approach of setting up automated/robotic on-site factories such as TBMs is capable of achieving a 10-fold performance multiplication, with the added benefit of minimized interference with the external environment (Bock & Linner, 2016).

8.3 Additive manufacturing in construction

The term additive manufacturing (AM) indicates “the process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies” such as machining, cutting and drilling (ISO/ASTM52921-1 “Standard Terminology for Additive Manufacturing-Coordinate Systems and Test Methodologies”). As a synonym, in the media and in the world of makers and personal manufacture the term “3D printing” is often used, which is more specifically defined by the American Society for Testing and Materials (ASTM) as “the fabrication of objects through the deposition of a material using a print head, nozzle, or another printer technology” (ISO/ASTM52921).

Invented at the end of the 1980s for the rapid production of prototypes, 3D printing has subsequently extended its application to the creation of molds and other industrial tooling, and has arrived to the production of end-use industrial components, objects d’art and final consumer products (direct digital manufacturing, DDM), fully qualifying as an industrial manufacturing process alternative to traditional formative and subtractive methods (see Fig. 8.24).

Compared to the latter, AM has numerous advantages in terms of freedom of design and possibility of creating highly complex geometries, of mass customization and of waste minimization, making it particularly cost-effective in rapid prototyping and in all cases of one-off or low-run productions where a few hundred or less units are required (see Table 8.5 and Fig. 8.25).

For high volume production of parts (> 1000), formative manufacturing is certainly unrivaled in cost per unit. The main limitation of formative manufacturing is, however, the need to prepare a tool (mold or die) to form the part, which is often expensive and complicated to produce, increasing lead times and delaying the delivery of the product. This large upfront investment is why formative manufacturing is generally only cost effective at high volumes. Parts that are produced via formative manufacturing also have specific design requirements to aid in the forming process, such as draft angles and uniform wall thickness.

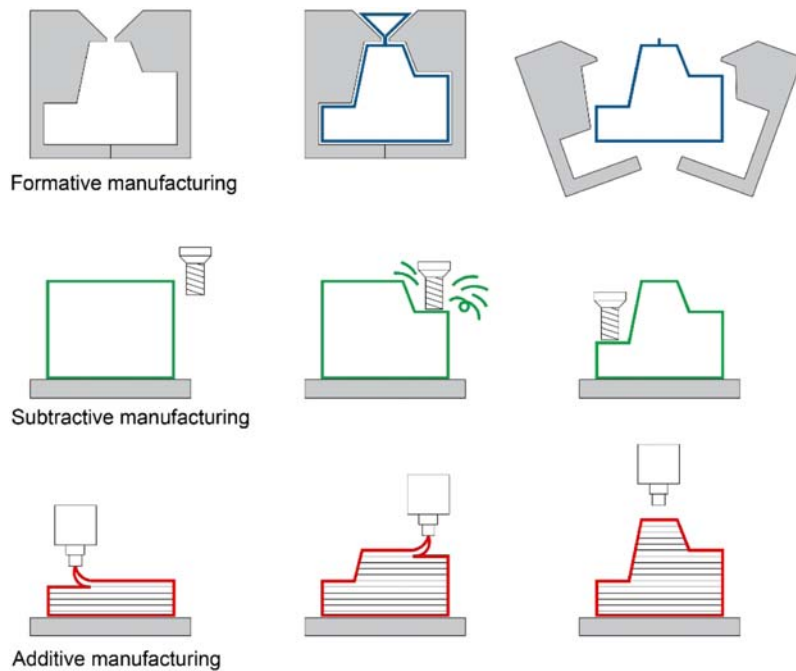


FIGURE 8.24 Formative, Subtractive and Additive manufacturing methods. Redrawn from: (Redwood et al., 2017).

TABLE 8.5 Recommended process reference table.

No. of parts	1's	10's	100's	1000's
Plastic	3D printing	3D Printing (consider: CNC)	CNC (consider: injection molding)	Injection molding
Metal	3D printing & CNC ^a	CNC (consider: 3D printing)	CNC (consider: investment casting)	Investment or die casting

^aHighly dependent on part geometry.

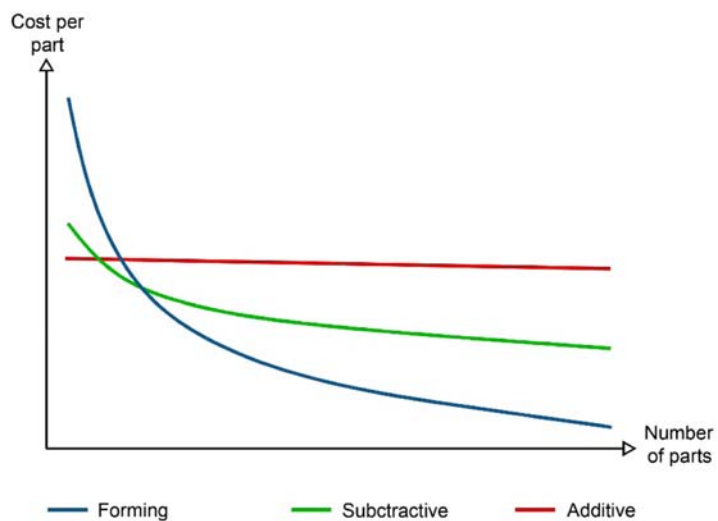


FIGURE 8.25 Cost comparison between different manufacturing methods. Redrawn from: (Redwood et al., 2017).

In contrast, in AM the number or shape/geometric complexity of items yield virtually no cost difference as there are no tooling costs and few if any learning curves for production workers. Whenever a few hundred or less components are required, 3D printing is therefore already the most convenient manufacturing method, and often the only cost-effective option. For this reason, 3D printing has gained a high level of adoption in rapid prototyping. 3D printers can produce concept models and functional prototypes in a few days or even a few hours for a fraction of the price of traditional methods, greatly accelerating the design cycle (design, test, improve, redesign). Furthermore, 3D printers are finding increasing application also in the production of molds, jigs, fixtures and other production tooling in formative manufacturing techniques (rapid tooling), as the preparation of these tools is also complex itself, with the need for mold features like spurs or runners to assist in the formation of parts.

In case of small one-off jobs or medium to high volume production (less than 250–500 parts) with relatively simple geometries, subtractive methods such as CNC are the most popular methods used in manufacturing, as they offer excellent repeatability, high accuracy and a wide range of materials and surface finishes.

However, there are several limitations that must be considered when designing parts for CNC machining, including tool access and clearances, hold or mount points, as well as the inability to machine square corners due to tool geometry. Some geometries are impossible to CNC machine (even with 5-axis CNC systems) as the tool cannot access all the surfaces of a component, and most require the rotation of the part to access the different sides, adding to the processing and labor time and requiring custom jigs and fixtures that affect the final price. On the contrary, 3D printing has very few geometry restrictions compared to CNC and has the ability to produce highly complex geometries. For particular geometries, a hybrid approach (print first, CNC machine afterwards) is also a viable option. When considering metals, CNC can be price competitive even for low quantities, but geometry limitations still apply.

3D printing is also preferable to CNC whenever fast turn-around time is critical, low-cost is essential (for small volumes, 3D printing is generally cheaper than CNC), there is a small number of identical parts required (less than 10), or when materials required cannot be easily machined, like metal super alloys or flexible thermoplastic polyurethane (TPU).

Subtractive manufacturing is also generally considered a wasteful process, due to the large amounts of material that is often removed to produce the final part geometry. 3D printing is instead an additive activity that starts with nothing and adds only the material that the final part requires, allowing substantial raw material savings. Furthermore, 3D printed products can feature internal structures that are optimized to consume the minimum of materials. 3D printed plastic or metal parts can, for example, be fabricated with internal air gaps or open lattice work that cannot be prepared inside an object produced using many traditional production techniques. This again can result in material savings, as well as the creation of lighter parts. Moreover, AM can reduce the production of spare parts that may be never used and end up as scrap. More broadly, 3D printing may turn out to be the cornerstone of a future transition toward “local digital manufacturing,” that is, making parts at or near the point of use rather than at a central facility thus reducing freight costs as well as the carbon footprint associated with transporting the part from the factory or warehouse to the field.

Well consolidated in industrial sectors such as aviation, automotive, biomedical engineering, art and jewelry or fashion, AM has already been widely implemented in the construction industry as well, in particular for architecture (design and physical modeling), and engineering (design, development and prototyping) activities. The next step is its wider adoption also for the fabrication phase, which today represents only 3% of the total AM industry (Wohlers Report, 2018).

Several studies and applied examples clearly outline the advantages in terms of cost-effectiveness and efficiency that derive from implementing automated and digital additive construction practices for the production of building components, up to entire buildings, both in new constructions and in renovation and restoration interventions, in a field which has until now remained tied to highly inefficient, labor-intensive approaches.

These advantages concern in particular the reduction of construction time and waste production, the possibility of creating products with superior mechanical properties, greater lightness or unique forms, the reduction of transportation costs, the improvement of management, maintenance and restoration of buildings through overcoming of the concept of obsolescence of equipment and the possibility to have at any time ad hoc printed substitutional elements at disposal, along with the possibility of using recovered or recycled materials with a consequent reduction of the impacts on the environment, up to the ability to print objects able to independently reach their final form at a later time (4D printing) (Shuaib, Haleem, Kumar, & Javaid, 2021).

Despite the benefits of additive manufacturing, there are drawbacks that would require further research and development to adopt this technology in various industries. One is the void formation between subsequent layers of materials that results in additional porosity during the manufacturing process and may reduce mechanical performance due to a reduction in interfacial bonding between printed layers. Anisotropic behavior is another common challenge of AM,

which results in different mechanical behavior under vertical tension or compression compared to that of the horizontal direction. Also, transferring CAD into a 3D-printed part often results in inaccuracies and defects, especially in curved surfaces due to the tessellation concept of CAD which inherently approximates the design. Moreover, the layer-by-layer appearance of AM in some applications such as buildings and aerospace is not preferable. Ongoing research and development of materials and methods have helped to circumvent some of these challenges but there is still room for improvement. Despite being a revolutionary method for customized products and niche applications, 3D printing needs more development in order to compete with traditional methods in the mass production of ordinary goods because of its higher cost and lower speed.

8.3.1 3D printing processes and technologies

8.3.1.1 Additive manufacturing process

The AM process involves several steps, from the design of the object to be printed to the postprinting activities required for the intended final use (Gebhardt, Kessler, & Thurn, 2019; Karakurt & Lin, 2020). These steps can be summarized as follows:

- creation of a digital model through 3D/BIM modeling software or 3D scanning;
- conversion of the 3D model file into a format which is understandable by the 3D printer;
- transfer of the document to the 3D printer and adjustment of the print file by the operator (object orientation, resolution, etc.);
- 3D printing of the object layer by layer;
- extraction of the object from the printing chamber;
- object postproduction, which can include curing, sandpapering, polishing, application of coatings, etc., depending on the material and 3D printing techniques employed.

Concerning the 3D modeling of the object, it must be carried out with a thorough understanding of the possibilities, and the limitations, associated with 3D printing. On the one hand, in fact, AM allows to generate parts with geometries virtually independent from the “design for manufacturing” constraints of conventional production techniques, including atypical geometric features such as trabecular, foam-like, or honeycomb structures, which neither traditional design nor most modeling tools can handle efficiently. On the other hand, the actual 3D printing phase is a critical step that may pose unexpected challenges, often unrelated to the foreseen use of the object, which require a thorough awareness of cavities, cantilever or orphan parts (which may not be connected to the main body during printing), thickness and size of components and their compatibility with the intended material and printing technique.

The printing process takes place layer by layer, either from the bottom of the model to the top or the other way round according to the technique employed, hence gravity takes an important role in the object creation. For instance, a bottom-top printing technique requires the object to lay on the print plane, thus an object with a large base is advised to prevent it from falling over during deposition. A top-down approach, on the other hand, works best with the model suspended on few supporting arms, designed to be eliminated after the printing phase is over. Model stability during printing can also be ensured by checking the barycenter position and, if necessary, altering it by differentiating the filling of the model with material according to shape and weight.

Once the 3D model, generated using a CAD system (either as a solid or surface model), is finished, it must be converted in a format compatible with the AM system. Commonly, the model is tessellated and converted into the standard Stereo Lithography Language (STL) format, which slices it in multiple cross-sections that are sent to the 3D printer (Craveiro, Duarte, Bartolo, & Bartolo, 2019).

An industry standard since the mid-80s, the STL conversion consists of slicing the part volume and transforming resulting slices in planar triangular facets, which size dictates the layer thickness and therefore the resolution (accuracy) of the printed geometry and the size of the STL file. The STL format, however, has the limitation of only containing information about a surface mesh, with no provisions for representing color, texture, material, substructure, and other properties of the fabricated target object. Today, AM technology allows instead to fabricate heterogeneous structures with varying materials or densities (functionally graded structures) in full color. Print resolution is approaching the micron scale, which would require an enormous number of triangles.

Alternatives to STL include directly slicing CAD, IGES and STEP formats. Recently, a file format called Additive Manufacturing File (AMF) was developed by ASTM using a mesh of curved triangles, rather than planar ones, with the support of embedded features, like different colors, materials, and build orientations. Contrary to the STL file, however,

AMF has no industrial standard for slicing data, and proposed methods include the Common Layer Interface (CLI), Layer Exchange ASCII Format, and SliCe format (SLC). The SLC is a key element as it generates the numerical control information to control the AM system which can either be based on vectors (movements in straight lines; curves approximated to segments) or raster (individual dots, like a monotone bitmap).

Once a STL file has been generated, the file is imported into a slicer program, which slices the design into the layers that will be used to build up the part. The slicer program takes the STL file and converts it into G-code. G-code is a numerical control programming language used in CAM to control automated machines like CNC machines and 3D printers. The slicer program also allows the 3D printer operator to define the 3D printer build parameters by specifying support location, layer height, and part orientation. Slicer programs are often proprietary to each brand of 3D printer, although some universal slicer software are available (Redwood et al., 2017).

The operator shall always verify the integrity of the STL or AMF file to correct eventual errors generated by the conversion, such as missing faces or inverted normals. The resolution can be tweaked according to the object's intended use and the potential of the printer. Lastly, the model's position in the generation chamber can be rotated for an easier manufacturing.

The actual printing phase varies greatly according to the specific technique employed and is investigated in Section 8.3.1.2.

Once the object has been printed, it must be removed for the printing chamber. For some 3D printing technologies, removal of the print is as simple as separating the printed part from the build platform. For other, more industrial 3D printing methods, the removal of a print is a highly technical process involving precise extraction of the print while it is still encased in the build material or attached to the build plate. These methods generally also require strict removal procedures and highly skilled machine operators along with safety equipment and controlled environments (Redwood et al., 2017).

Finally, postprocessing is a key part of the 3D printing process, especially as the additive manufacturing market moves from prototyping to production of end-use products geared to consumer markets, since it can greatly influence the look and feel of the 3D-printed object. Indeed, most parts manufactured with 3D printing technologies usually require some degree of postproduction treatment, which refers to any process or task that needs to be performed on a printed part, or any technique used to further enhance the object, including removing support or excess material, washing and curing, sanding or polishing a model, painting or coloring. When done manually, postprocessing is labor intensive and its cost can amount to 27% of the total costs of producing a model, which include the costs of part breakage (Wohlers Report, 2018). As a result, various postprocessing systems are being developed with the objective of automating the task of finishing 3D-printed parts, either as separated machines or seamlessly integrated with the AM system.

Overall, postprocessing usually involves the following five tasks, although not all these are always required: cleaning, fixing, curing or hardening, surface finishing, coloring or coating.

Concerning cleaning, this includes removing of material which is undesired in the finished product, such as support structures added to hold up overhanging parts, or powder or resin that may cling or remain in the model holes or most intricate parts. In single-material 3D-printed objects, support removal is carried out by hand using knives or pliers, whereas multimaterial models allow to employ soluble supports that can be dissolved in water or with chemical agents. Powder removal is obtained by vibrating and rotating the model and can be automated in the printing process. Objects printed by photopolymerization on the other hand may retain some liquid resin, that can be washed away with isopropyl alcohol.

Model fixing is usually done by hand and includes attaching parts that were printed separately, usually to overcome the size limits of the generation chamber of the printer, as well as small repairs to fill holes or cracks that may have developed during printing. Parts can be glued or welded back together depending on their materials, with fillers and hardeners employed to repair imperfections.

Curing is instead employed in 3D-printed objects obtained by photopolymerization and requires baking the model in an UV oven to complete polymerization and bring it to its final mechanical properties. This postprocessing technique can be integrated in the printing process line-up.

Surface finishing is required to overcome the rough aspect of some 3D-printed objects, which display unpleasant layer lines and visible touch points where support was removed. These can be removed by careful sanding of the model or smoothening the surface by melting the outer shell with vapor or chemical agents, giving the model a glossy look.

Finally, the finished object can be painted or coated as required for its final use. Although objects can be directly printed with materials of the desired color, coloring during the postprocessing phase allows for greater freedom, and is usually performed on objects printed in white and with a layer of primer applied. Painting can be done manually using a brush, or automated with spray coloring. Metal coating can be applied by electroplating on objects of any material,

provided the surface is sufficiently smooth as the metal film is extremely thin and not sufficient for hiding coarse parts. For plastic objects, metal coating has the added benefit of protecting and strengthening the parts, broadening their potential applications.

8.3.1.2 Additive manufacturing techniques

Additive manufacturing can be carried out using different processes and techniques in relation to both the material to be used and the characteristics, dimensions, and applications of the object to be printed (Barnatt, 2016; Gebhardt et al., 2019; Karakurt & Lin, 2020; Redwood et al., 2017). The different techniques refer to four main approaches: the deposition of a viscous material through a print nozzle, the solidification of a liquid material, the binding of powdered material and the joining of sheets or foils material. According to the ISO/ASTM 52900:2015 standard, these AM processes or techniques can be divided in the following seven main categories, each including several technologies and different registered terms (see Table 8.6).

Material extrusion

Material extrusion (ME) process forms objects by outputting a molten or otherwise semiliquid material from a print head nozzle and depositing it layer-by-layer onto a substrate (see Fig. 8.26). The process, firstly invented by Crump and commercialized by Stratasys as Fused Deposition Modeling (FDM) in 1989 for thermoplastic 3D printing, is now used for AM of a large variety of materials including construction materials such as metals and concrete, often with the FDM or FFF (fused filament fabrication) acronyms (Daminabo, Goel, Grammatikos, Nezhad, & Thakur, 2020; Gebhardt et al., 2019). ME is the most common and versatile 3D printing technique, used by the majority of consumer 3D printers. Common postprocessing options for FDM include support removal, sanding, gap filling, cold welding, polishing, priming and painting, metal plating, vapor smoothing, and epoxy coating.

ME 3D printers can have many setups, the most popular being cartesian and delta in which the toolhead moves linearly in the X, Y, and Z planes and the deposition is made only in the top-down direction. These setups have limitations with respect to which geometries are possible to produce, and they usually require support structures for overhangs or cantilever parts. More complex and intricate geometries can be created with 5-axis ME setups that enable the nozzle to rotate on two axes in addition to 3D movement. This allows the complete elimination of support structures and the production of dynamic, nonplanar surfaces with higher quality surface finish, more design flexibility, and greater part strength. By printing from different directions, in fact, the part can come out much sturdier than by simply stacking layers in the Z direction. However, 5-axis ME printers are much more complicated than 3D ones, and most slicing programs assume layers are built up in a single direction, requiring tool paths to be manually computed in more complex CAM software, especially in the case of 3D printing a nonplanar surface.

Overall, benefits of ME include low cost, high speed, and simplicity of the process. On the other hand, drawbacks include weak mechanical properties (which may be improved via fiber-reinforced FDM), layered appearance with poor surface quality and a limited number of suitable thermoplastic materials.

Vat photopolymerization

In vat photopolymerization processes, a laser or other light source solidifies successive layers on the surface or base of a vat of liquid photopolymer, with the energy of the light source and exposure as the main factors controlling the thickness of each layer. The two main technologies of vat photopolymerization are stereolithography (stereolithography apparatus, SLA), that was the first commercial 3D printing process in 1986, and digital light processing (DLP) (Gebhardt et al., 2019; Quan et al., 2020). SLA uses a computer-controlled UV laser beam to build a 3D object point by point within a vat (or tank) filled with photocurable liquid resin (photopolymer resin), producing very accurate samples at a resolution as low as 10 μm (see Fig. 8.26). Unlike objects created using material extrusion, those produced with SLA have a smooth surface. DLP replaces the laser with a projector that is often positioned below the build platform and solidifies each object layer at once, with a higher print speed compared to SLA. A variant of DLP is continuous direct light processing (CDLP) technology (also known as continuous liquid interface production or CLIP) which provides the continuous motion of the build plate in the Z direction (upwards) allowing for faster build times respect to DLP as the printer is not required to stop and separate the part from the build plate after each layer is produced. Vat technologies are commonly used for rapid prototyping and mold casting employing photocurable plastics, wax based polymers, metal-resin composites, and also nanocomposites. Vat polymerization processes are excellent at producing parts with fine details and give a smooth surface finish. This makes them ideal for jewelry, low-run injection molding, many dental and medical applications, and the production of complex architectural models with a very high level of

TABLE 8.6 AM techniques.

Approach	Technique	Technology	Materials
Deposition of viscous material	<i>Material extrusion</i> : A process that form objects by outputting a molten or otherwise semiliquid material from a print head nozzle and depositing it layer-by-layer onto a substrate	Fused deposition modeling (FDM) or FFF	Thermoplastics, metals, concrete, ceramic, composite, continuous fiber
Solidification of a liquid material	<i>Vat photopolymerization</i> : A process that solidifies by a laser or other light source successive layers on the surface or base of a vat of liquid photopolymer	<i>Cured with laser</i> : stereolithography apparatus (SLA)	Thermosets, wax-based polymers and metal-resin composites.
		<i>Cured with projector</i> : digital light processing (DLP)	
		<i>Cured with LED and oxygen</i> : continuous digital light processing (CDLP)	
	<i>Material jetting</i> : A 3D printing technique which inkjet printheads spray a liquid build material on the build platform of the 3D printer, which then cools and solidifies to form a 3D object layer by layer	<i>Cured with UV light</i> : multiJet printing (MJP), photopolymer jetting (Polyjet),	Thermosets
		<i>Cured with heat</i> : nanoparticle jetting	Stainless steel, ceramics
		<i>Milled to form</i> : wax deposition modeling (WDM), drop on demand (DOD)	Wax
Binding of powdered material	<i>Binder jetting</i> : A process consisting in a print head that selectively sprays a binder onto successive layers of powder	<i>Binder jetting (BJ)</i>	Metals, ceramic, glass, gypsum, sand
	<i>Powder bed fusion</i> : A process of selectively fusing a powdered material using thermal energy, typically in the form of a laser or electron beam, layer by layer on a powder bed	<i>Fused with laser (plastic)</i> : selective laser sintering technology (SLS)	Nylon, TPU, alumide, glass-filled nylon, carbon fiber nylon
		<i>Fused with laser (metal)</i> : direct metal laser sintering (DMLS), selective laser melting (SLM)	Metals and alloys
		<i>Fused with electron beam</i> : electron beam melting (EBM)	Titanium, cobalt-chrome
		<i>Fused with agent and energy</i> : multi jet fusion (MJF)	Nylon
	<i>Direct energy deposition</i> : A process that fuses a powdered material with focused thermal energy as it is being deposited.	<i>Fused with laser</i> : laser engineering net shape (LENS)	Metal
		<i>Fused with electron beam</i> : electron beam additive manufacturing (EBAM)	
Joining of sheets or foils material	<i>Sheet lamination</i> : A process consisting of shaping and sticking together sheets of material to form an object	Laminated object manufacturing (LOM)	Paper, composite

detail. The main limitation of vat polymerization is the brittleness of the produced parts and the price of photopolymers which is far higher than that of the build materials used in thermoplastic extrusion. For example, a liter of resin for SLA printers costs between \$149 and \$399, depending on the material.

Material jetting

The material jetting technique employs inkjet printheads to spray a liquid build material on the platform of the 3D printer, which then cools and solidifies to form a 3D object layer by layer (Gebhardt et al., 2019). In photopolymer

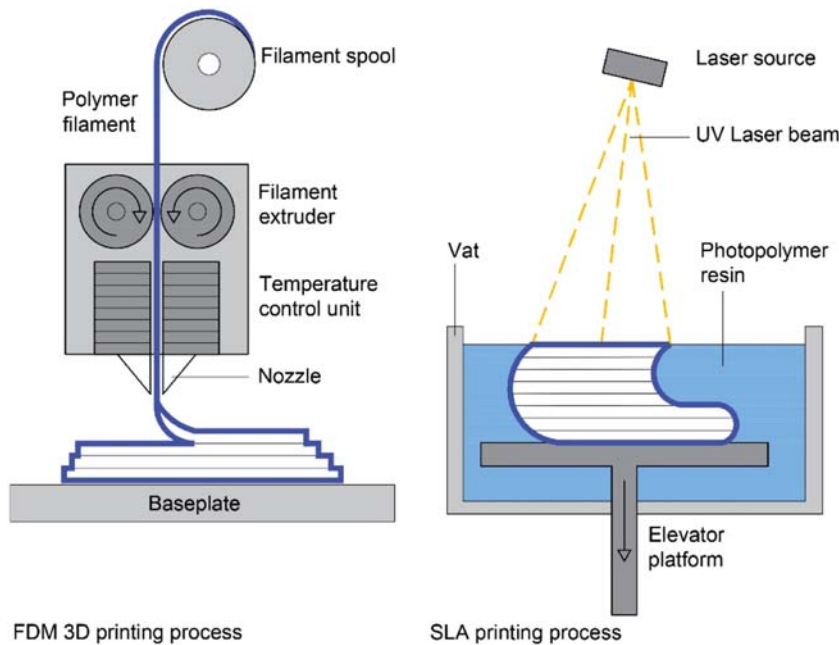


FIGURE 8.26 FDM and SLA printing processes.

jetting 3D printing, the print heads jet a liquid photopolymer material (sensitive to light) on the print bed, which is then directly cured by a UV lamp attached to the print head, to form the solid object. Several materials can be jetted together to create multimaterials or multicolor objects. Wax deposition modeling (WDM) technology creates objects in special wax-like plastics by jetting a melted build material that solidifies naturally as it rapidly cools on the print bed. The most recent material jetting technology is nanoparticle jetting (NPJ), developed by XJet, for high-resolution 3D-printed metal parts. Each object layer is formed from droplets sprayed from a print head constituted by solid metal nanoparticles in a liquid suspension. Heat is then used to bind the nanoparticles together.

Material jetting is ideal for realistic prototypes, providing excellent details, high accuracy, and smooth surface finish. Material jetting allows a designer to print in multiple colors and multiple materials in a single print. The main drawbacks of material jetting technologies are the high cost and the brittle mechanical properties of the UV activated photopolymers.

Binder jetting

Binder jetting (BJ) technique consists in a print head that selectively sprays a binder onto successive layers of powder (Gebhardt et al., 2019; Mostafaei et al., 2021). First, a layer of powder is laid on a build platform creating the “powder bed,” on which a multinozzle inkjet printhead selectively jets a binder solution in the shape of each print layer. Then another layer of powder is laid down and a subsequent layer of binder is jetted onto it. When a complete object has been printed, it remains encased in a block of loose powder and needs to be transferred to a “depowdering chamber” to be cleaned. Main characteristics of BJ include no need of support structures, as the loose powder that surrounds an object supports overhangs or orphan parts while they are printed; high printing speed; low cost of printed objects; and the possibility to print fully colored objects. To 3D print in color, BJ sprays colored inks as well as a binder solution onto each layer of powder. BJ can print objects from gypsum, plastic, sand, metal, ceramic or glass powder, obtaining samples fragile and porous that commonly need to be postprocessed by infiltration or thermal treatment. Ceramic-based BJ is ideally suited for applications that showcase esthetics and form: architectural models, packaging, ergonomic verification etc. It is not suitable though for functional prototypes, as the parts are very brittle. Ceramic-based BJ can also be used to create molds for sand casting. Metal BJ parts can be used as functional components and are more cost-effective than metal parts printed with powder bed fusion techniques, but have poorer mechanical properties.

Powder bed fusion

In powder bed fusion (PBF), a powdered material is selectively fused using thermal energy, typically in the form of a laser or electron beam, layer by layer on a powder bed (Gebhardt et al., 2019). PBF prints objects from plastic, ceramic,

sand, wax, and metal by selective laser sintering (SLS) technology, in which a laser beam is used to partially melt the particles and fuse them together. Direct metal laser sintering (DMLS), selective laser melting (SLM), and electron beam melting (EBM) technologies are instead used only with metal powders, and completely melt them together obtaining higher mechanical resistance and purer samples suitable for manufacturing end-use metal parts. Polymer-based PBF technologies offer a lot of design freedom, as there is no need for support, allowing the fabrication of complex geometries.

Both metal and plastic PBF parts typically have very high strength and stiffness and mechanical properties that are comparable (or sometimes even better) than the bulk material. There is a large range of postprocessing methods available, meaning that PBF parts can achieve a very smooth finish and, for this reason, they are often used to manufacture end products. The limitations of PBF often center around surface roughness and internal porosity of the as-printed parts, shrinkage or distortion during processing, and the challenges associated with powder handling and disposal.

Fine resolution and high quality of printing are the main advantages of PBF, which make it suitable for printing complex structures. This method is widely used in various industries for advanced applications such as scaffolds for tissue engineering, lattices, aerospace, and electronics. The main advantage of this method is that the powder bed is used as the support, which overcomes difficulties in removing supporting material. Main drawbacks of PBF include slow production, high costs, and high porosity when the powder is fused with a binder.

Directed energy deposition

Directed energy deposition (DED) technique fuses the printing material with focused thermal energy as it is being deposited (Gebhardt et al., 2019). In particular, DED uses a source of energy (usually a laser, plasma arc, or electron beam, although electromagnetic induction is also used) which is directly focused on a small region of the substrate and is also used to melt a feedstock material (powder or wire) simultaneously. The molten material is deposited and fused into the melted substrate, and solidifies after the laser beam moves away. The difference between DED and SLM methods is that no powder bed is used in DED and the feedstock is melted before deposition in a layer-by-layer fashion similar to FDM but with an extremely higher amount of energy for melting metals. The core benefit of this process is that it is capable of being conducted mostly or entirely from the print head, leading to applications at the large scale. Moreover, unlike all other current 3D printing technologies, DED is not limited to building objects from a progression of successive flat layers, thanks to the use of a nozzle mounted on a multiaxis arm that can move in multiple directions, allowing to deposit the material from any angle and therefore being able to repair existing objects as well as fabricating new ones. Therefore, it can be helpful for filling cracks and retrofitting manufactured parts for which the application of the powder-bed method is limited. This method allows for deposition of multiple materials at the same time. Moreover, DED can be combined easily with conventional subtractive processes to complete machining. DED technique has been used for manufacturing high-performance super-alloys and is commonly applied with titanium, Inconel, stainless steel, aluminum, and the related alloys for aerospace applications. DED method is also known as laser engineered net shaping (LENS), laser solid forming (LSF), directed light fabrication (DLF), direct metal deposition (DMD), electron beam AM (EBAM), wire + arc AM (WAAM) (see Fig. 8.27), or rapid induction printing (RIP). In general, DED is characterized by good speed (from 0.5 kg/h for LENS to 10 kg/h for WAAM) and very large printable areas (up to $6\text{ m} \times 1.4\text{ m} \times 1.4\text{ m}$ for commercial printers). However, it has a lower accuracy (0.25 mm), lower surface quality, and



FIGURE 8.27 WAAM DED printing of metal wires. Courtesy of MX3D, photo by Oliver de Gruijter.

can manufacture less complex parts than SLS or SLM. Furthermore, the high energy input creates a large heat affected zone around the melt pool, which is subjected to large thermal gradients that cause residual stresses and may lead to object distortion and affect the grain structure and strength of the printed metal. Therefore, DED is commonly used for large components with low complexity and also for repairing larger components. DED can reduce the manufacturing time and cost and provides excellent mechanical properties, controlled microstructure and accurate composition control.

Sheet lamination

The sheet lamination process consists of shaping and sticking together sheets of material to form an object (laminated object manufacture, LOM) (Gebhardt et al., 2019). The layered material is rolled on the building platform, on which successive layers are cut precisely using a mechanical cutter or laser and are then bonded together (form-then-bond) or vice versa (bond-then-form). The excess materials after cutting are left as support, and after completion of the process can be removed and recycled. As with most powder-based 3D printing technologies, objects created via sheet lamination do not require support structures, as the unused build material that surrounds them holds everything in place. LOM can be used for a variety of materials such as polymer composites, ceramics, paper, and metal-filled tapes. Postprocessing such as high-temperature treatment may be required depending on the type of materials and desired properties. LOM can result in a reduction of tooling cost and manufacturing time and is one of the best additive manufacturing methods for larger structures. However, LOM has low surface quality (without postprocessing) and its dimensional accuracy is inferior to powder-bed methods. Also, removing the excess parts of laminates after formation of the object is time-consuming compared to the powder-bed methods. Therefore, it is not recommended for complex shapes.

A new subclass of LOM is ultrasonic additive manufacturing (UAM), a hybrid technique which combines ultrasonic welding to bond thin metal foils in a layer-by-layer fashion and periodic CNC machining to create the desired 3D shape (Bournias-Varotsis, Friel, Harris, & Engström, 2018). UAM is the only additive manufacturing method that is capable of fabricating metal structures at low temperature and has been used in various industries such as foundry industries, electronics as well as smart structures, that is, structures (which can be multitasking) with a number of sensors and processors embedded. Unlike conventional methods, UAM can specify cavities in the structure based on the integrated computer design for embedded electronic devices, sensors, pipes, and other features. Electronic circuits can be printed within the same UAM process using direct write technologies.

8.3.1.3 3D printers

The 3D printer market has grown significantly over the past 5 years. At the end of 2020, there are over 2000 models of 3D printers on the market, produced by over 600 companies from over 30 countries around the world, equally distributed between the United States, Asia (China, Japan, India), and Europe (Germany, Italy, France, UK, Poland, the Netherlands). Among printer models on the market, 42% are intended for the professional sector (professional 3D printers), 37% for the industrial sector (Industrial 3D printers), and the remaining 21% are aimed at the consumer market (consumer, desktop, or home 3D printers). Nowadays, 3D printers are able to achieve dimensional accuracy, surface roughness, and improved mechanical properties well suitable for end-use products. In addition, major advancements in materials have transformed 3D printing technology into a platform for material science which allows scientists and researchers to customize material deposition, anisotropic behavior and active sensing based on surrounding environments (Bertram et al., 2019; Thai et al., 2020).

Starting from the first models released in the late nineties, significant progression in 3D printing technology from the viewpoint of both printing devices and materials has been made (see Fig. 8.28). Main differences between the 3D printers on the market concern the type of additive manufacturing technique and the need of support structures, the materials that can be used for printing (including multimaterial printing), colors that can be obtained, the size of the generation chamber and thus of printed objects (build size), as well as print time, dimensional accuracy, layer height, and the intended applications of printed objects (conceptual model, functional prototype, end-use product, etc.) (see Table 8.7).

Dimensional accuracy is connected to the level of detail each process can achieve and the built quality of each 3D printer. Processes that offer higher accuracy can usually create parts with finer features. Industrial grade machines have higher accuracy and repeatability than desktop printers. Layer height determines the smoothness of the as-printed surface and the minimum feature size a printer can produce in the z-direction. Using a smaller layer height also makes the stair stepping effect less prominent and helps produce more accurate curved surfaces. The build size determines the maximum dimensions of a part that a printer can produce. For components that exceed the maximum build size, the part can be split into multiple components that can be assembled later. Finally, the need of support structures determines the level of design freedom. Processes that allow no support, like SLS, or dissolvable support, like material

FIGURE 8.28 Commercial 3D printers. *Courtesy of WASP.***TABLE 8.7** Performance of main 3D printing techniques.

Technology	Dimensional accuracy	Typical layer thickness	Typical build size	Support
CNC	± 0.025 – 0.125 mm	0.75 mm	Milling: $2000 \times 800 \times 1000$ mm Lathe: $\varnothing 500$ mm	Not required
FDM	$\pm 0.5\%$ (lower limit ± 0.5 mm)—desktop $\pm 0.15\%$ (lower limit ± 0.2 mm)—industrial	50–400 μm (most common: 200 μm)	200 $\times$ 200 $\times$ 200 mm for desktop printers Up to 900 $\times$ 600 $\times$ 900 mm for industrial printers	Not always required (dissolvable available)
SLA/DLP	$\pm 0.5\%$ (lower limit: ± 0.10 mm)—desktop $\pm 0.15\%$ (lower limit ± 0.05 mm)—industrial	25–100 μm (most common: 50 μm)	145 $\times$ 145 $\times$ 175 mm for desktop Up to 1500 $\times$ 750 $\times$ 500 mm for industrial printers	Always required
SLS	$\pm 0.3\%$ (lower limit: ± 0.3 mm)	80–120 μm (most common: 100 μm)	300 $\times$ 300 $\times$ 300 mm (up to 750 $\times$ 550 $\times$ 550 mm)	Not required
Material jetting	$\pm 0.1\%$ (lower limit of ± 0.05 mm)	16–30 μm (most common: 16 μm)	380 $\times$ 250 $\times$ 200 mm (up to 1000 $\times$ 800 $\times$ 500 mm)	Always required (always dissolvable)
Binder jetting	± 0.2 mm (± 0.3 mm for sand printing)	100 μm	400 $\times$ 250 $\times$ 250 mm (up to 1800 $\times$ 1000 $\times$ 700 mm)	Not required
DMLS/SLM	± 0.1 mm	30–50 μm	250 $\times$ 150 $\times$ 150 mm (up to up to 500 $\times$ 280 $\times$ 360 mm)	Always required

jetting or dual-extrusion FDM (industrial or desktop), have fewer limitations and can produce free-form structures with greater ease.

As regards 3D printers prices, these vary on average from a range between \$70 and \$1000 for consumer printers, between \$500 and \$10,000 for professional machines, and from \$50,000 to upwards of \$1,000,000 for large industrial printers.

8.3.1.4 3D printable materials

3D printing can be carried out using numerous types of materials with the aim of creating models, molds or end-use objects (DDM). 3D printing feedstock can come in filaments, wire, powder, resin, paste, ink, or sheets form depending

on the 3D printing processes used (Gebhardt et al., 2019; Karakurt & Lin, 2020; Singh, Kumar, & Sehgal, 2020). According to ISO/ASTM 52900, materials for AM can be categorized as polymer, metallic, ceramic, and composite, with composite materials defined as any combination of the other material categories.

Polymers

Polymers for 3D printing include both thermoplastic and thermosetting polymers. For functional polymer parts, thermoplastics (SLS or FDM) are preferred over thermosets, whereas for visual appearance and esthetics, thermosets (SLA/DLP or material jetting) are the best option.

Thermoplastics, in the form of filament or powder, range from standard thermoplastics such as polylactic acid (PLA) and acrylonitrile butadiene styrene (ABS), to engineering materials such as polyamide (PA), TPU, and polyethylene terephthalate glycol-modified (PETG), up to high-performance thermoplastics such as acrylic styrene acrylonitrile (ASA), high impact polystyrene (HIPS), polyether ether ketone (PEEK), and polyetherimide (PEI). They are best suited for functional applications, including manufacturing of functional prototypes and end-use parts for industrial applications.

Thermoplastics have good mechanical properties and high impact, abrasion, and chemical resistance. As a general rule, better engineering properties translate to higher melting temperatures and therefore to a more difficult print. Higher printing temperatures, however, increase the likelihood of warping or distortion during the printing process, as parts cool at an increased rate, generating more intense internal stresses. ABS and PLA are generally considered easy to print with, while thermoplastics like PEEK and PEI offer excellent engineering properties but are generally printed using industrial machines that provide greater control over the print environment. Polyphenylsulfone (PPSF) is used to fabricate end-use objects that must possess a very high temperature and chemical resistance and requires high-end industrial printers. Translucent objects can be printed using transparent thermoplastic polymers like polymethylmethacrylate (PMMA) or ABSi. These can also be sterilized with gamma radiation or ethylene oxide, allowing plastic parts to be 3D printed for use in the food industry or for medical applications. PC-ISO (polycarbonate-ISO) can also be sterilized with gamma radiation or ethylene oxide and offers good biocompatibility for the fabrication of 3D-printed medical devices. Lastly, thermoplastic elastomers (TPE), commonly TPU or TPE-U, are employed whenever flexible, rubber-like components need to be 3D printed.

Thermoplastics can be printed with FDM or SLS techniques. SLS parts have better mechanical and physical properties and higher dimensional accuracy, but FDM is more economical and has shorter lead times. FDM printing makes use of thermoplastics in the form of filament on spools, typically 1.75 mm or 3 mm in diameter. FDM filaments come in a large range of colors and are some of the lowest cost materials used in 3D printing (\$20–\$40 per 1 kg spool) although high-performance filaments like PEEK can cost upwards of \$500/kg (Redwood et al., 2017).

Regarding thermoset polymers, they typically start as a viscous fluid (resin) and are cured to become solid. Curing can occur via heat, light exposure or by mixing with a catalyst. Thermosets are better suited for applications where esthetics are important, as they can produce parts with smooth injection-like surfaces and fine details. Generally, they have high stiffness but are more brittle than thermoplastics, so they are not suitable for functional applications. Specialty resins are available, that are designed for engineering applications (mimicking the properties of ABS and polypropylene) or dental inserts and implants. Thermosets can be printed with material jetting or SLA/DLP techniques. Material jetting produces parts with superior dimensional accuracy and generally smoother surfaces, but at a higher cost than SLA/DLP. Both processes use similar photocurable acrylic-based resins.

Today a far wider variety of stereolithographic photopolymers have been developed. These include rubber-like plastics, many substitutes for ABS and other thermoplastics, flame retardant plastics, totally clear resins, and special photopolymers for dental modeling and jewelry design.

Polymer composites

Thermoplastics can be integrated with additives such as carbon, glass, wood, or others to enhance their physical properties or impart new ones, and over the past few years several composite plastics have been developed.

One of the first composite materials released was Laywood, a composite of wood sawdust and a thermoplastic, which allowed to 3D print objects with wood-like feel and smell, followed by other wood/polymer composite (WPC) filaments. All of these are made from 70% to 80% PLA mixed with a wood additive. Printed parts can be sanded and worked on like any wood composite object such as medium density fiberboard. Other composite filaments include Laybrick from Parthy (a stone-additive material intended for architectural models), and corkFill from colourFabb.

Commercial metal-thermoplastic composites are obtained by mixing PLA and polyhydroxyalkanoate (PHA) with fine powders of bronze, copper, brass, or steel. The first metal composite filament was bronzeFill, a bronze—plastic composite, about three times heavier than a pure thermoplastic, with a matte finish that can be made glossy with careful sanding and polishing.

To increase the strength and durability of final objects, thermoplastics can be integrated with glass fibers or, more commonly, strands of carbon fiber. Products available on the market include “Proto-Pasta Carbon Fiber,” made from PLA compounded 15 wt.% with very short-chopped carbon fibers, or XT-CF20 from colorFabb. Printouts made with carbon fiber reinforced polymer are stiffer and resist bending far more than standard thermoplastic parts, have a solid feel and a slightly metallic shimmer in direct light.

Higher strength objects can be fabricated by extruding nylon parts embedded with continuous strands of carbon, fiberglass, or aramid. These reinforcing materials are laced into the object during printout (rather than being chopped into microfibers and premixed into an extruded filament) in a process termed continuous fiber 3D printing. Continuous fiber 3D printing can be implemented in combination with FFF extrusion, relying on two separate toolheads to deposit the different materials: one extrudes a thermoplastic matrix just like a normal 3D printer and the other lays down strands of fiber in select areas to increase tensile strength, resulting in fiber reinforced nylon objects that are stiffer than aluminum. Another approach employs a photopolymer to coat the strand of fiber as it is deposited, then immediately cures it with an UV light, allowing to embed every single line with fiber and also to bridge long gaps without the need of supports. The latter method is compatible with functional wires such as optical and metal fibers as well, which enables to print embedded sensors and circuits.

To impart electrostatic discharge protection, required for the production of electronic components, ABS or PETG can be mixed with carbon nanotubes, whereas electrically conductive filaments are obtainable with graphene additives.

Metals

A growing number of metals and metal alloys can today be 3D printed and are available in form of powder, wire, filaments, metal 3D printing resin as well as metal sheets, catering to different metal 3D printing methods ([Gadagi & Lekurwale, 2021](#)). Main 3D-printed metals and metal alloys include aluminum, titanium, nickel, Inconel, copper, bronze, cobalt, cobalt-chrome, steel as well as precious metals such as gold, silver, and platinum. Expensive metals such as titanium benefit greatly from waste reduction associated to AM compared to traditional methods.

Main types of 3D metal printing technologies are metal PBF (SLM, DMLS, EBM), metal BJ, and DED, with minor applications in metal filament extrusion (FFF, FDM) and material jetting (NPJ). There are also some niche resin-based metal 3D printers, and metal sheet lamination 3D printers. Different acronyms and names are used for similar technologies as each brand markets their own, proprietary methods. Some manufacturers are specialized in hybrid metal manufacturing systems that combine both subtractive and additive manufacturing methods, often with robotic arms that are able to move on more than three axes.

Depending on the AM techniques used and the conditions in which they are printed, metal 3D-printed parts can be as strong (or even stronger) as metal parts created with traditional manufacturing processes such as die casting. DMLS and SLM techniques produce high performance, end-use metal 3D-printed parts suitable for industrial applications in aerospace, automotive and medical sectors. BJ costs significantly less (by several orders of magnitude) than PBF and allows for very large parts (e.g., die casts) to be printed, but with poorer mechanical properties and dimensional tolerances. DED technologies are used exclusively in metal additive manufacturing and are ideally suited for repairing or adding material to existing components (such as turbine blades). The reliance on dense support structures makes DED not ideally suited for producing parts from scratch.

Ceramics

Concerning ceramic materials, it is possible to 3D print objects in ceramic, glass, concrete, or sandstone. Ceramics are mainly 3D printed in the form of powders or ink, and the main printing techniques are inkjet (suspension), BJ, PBF, material extrusion, and stereolithography.

In particular, inkjet printing is widely used for fabricating complex and advanced ceramic structures for applications such as scaffolds for tissue engineering. In this method, a stable ceramic suspension, for example, zirconium oxide powder in water, is pumped and deposited onto the substrate via the injection nozzle in the form of droplets which solidify to sufficient strength in order to hold subsequent layers of printed material. Two main types of ceramic inks are wax-based inks and liquid suspensions. Wax-based inks are melted and deposited on a cold substrate in order to solidify. On the other hand, liquid suspensions are solidified by liquid evaporation. Final quality of inkjet-printed ceramic parts

depends on the particle size distribution of ceramics, viscosity of the ink and solid content, as well as the extrusion rate, nozzle size and speed of printing.

Particle-bed 3D printing techniques such as BJ and PBF impose almost no limitations on the design of ceramic structures as they require no support and are particularly suitable for large-scale objects. In fact, BJ 3D printers such as DShape allow for production of full sized elements with a width up to 6.0 m, using ceramic powders such as sand or marble dust bound with an inorganic adhesive to form a stone-like material (Labonnote, Rønnquist, Manum, & Rüther, 2016).

Concrete is a ceramic printing material with great potential, especially for large-scale structural applications that allow mass-customization, no required formwork and total automation. Extrusion is the main method used for the additive manufacturing of concrete, although the powder-bed method has been also explored.

Lastly, ceramic stereolithography involves the photopolymerization of ceramic suspensions, constituted by inorganic powder mixed in a monomer, which are solidified by a UV laser or other light source (SLA or DLP techniques). This allows to fabricate ceramic parts and products with more accurate, complex geometries, and smooth surfaces, with the drawback or high brittleness of the object that requires additional postprocessing work, such as high-temperature sintering.

8.3.1.5 4D printing

AM of objects capable, once printed, of modifying their physical characteristics is defined as “4D printing.” The number 4 indicates the temporal dimension that is added to the 3 dimensions of the printed object. Through 4D printing (first applied in 2013 by Skylar Tibbits), the 3D-printed structure becomes changeable in terms of its shape, property, or functions over time, allowing to impart self-assembly, self-repair, or multifunctional capabilities. Objects that conventionally have fixed characteristics can gain additional time-dependent, predictable, reprogrammable properties. This dynamic function depends on the integration in the 3D printing of smart materials such as smart nanocomposites, shape memory alloys, and shape memory polymers (see Section 7.3.1), as the only printable material or as a component in multimaterial printing. Most AM techniques are compatible with 4D printing, including FDM, stereolithography, EBM, inkjet printing, and SLM, with some modifications to ensure, for instance, that shape memory polymers are deposited at the right temperature (Joshi et al., 2020).

Possibilities opened by 4D printing are various. For instance, an object printed in a light-responsive smart materials can be normally inert but deform under UV rays or sunlight and may find application in packaging, aerospace, photovoltaic, or biomedical devices (Mu et al., 2015). At the same time, an object printed with shape memory polymers can be programmed to deform, self-assemble or self-fold when subjected to an external heat or electricity stimulus: at the microscale, this can allow to develop microrobots and microactuators for medical and engineering applications, and on bigger scales can help reduce printing and logistics costs, as the folded/compacted object can be compatible also with 3D printers with smaller printable area and takes up less space during storage and transportation. Objects printed with smart materials sensible to electricity (piezoelectric), heat (pyroelectric), or magnetic fields (magnetostrictive) can allow to incorporate effortlessly sensors into smart structures of various types.

8.3.2 3D printing of building components

3D printing is finding interesting and increasingly widespread applications in the construction industry supply chain, not only for rapid prototyping and rapid tooling, but also for DDM of final components in concrete, metal or plastic, both off-site and on-site, with dimensions up to the scale of whole buildings or other infrastructures (Al Rashid, Alim Khan, Al-Ghamdi, & Koç, 2020; Wu, Wang, & Wang, 2016). In fact, construction 3D printing market is expected to grow significantly in the next years, from USD 0.04 billion in 2016 to almost USD 40 billion in 2027 (ECSO, 2019).

The most promising applications of DDM of final products in construction concern:

- fabrication of unique pieces in metal, plastic, concrete or ceramic, with a structural or esthetic function, not achievable with traditional methods, capable not only of obtaining particular shapes, but also of optimizing the material/performance ratio;
- reproduction of technical or ornamental elements, obtained through 3D scanning, to be applied in the maintenance, restoration, and refurbishment of buildings;
- off-site fabrication of walls, floors, pillars, façade elements up to building modules;
- on-site construction of formwork for reinforced concrete;
- on-site construction of walls, pillars or of the entire building structure.

Below are explained main techniques, examples, and advantages in using AM both off-site and on-site for printing metal, concrete, or composite building components.

8.3.2.1 Metal 3D printing

Metal 3D printing became possible in the 1990s with the development of DMLS technology. However, 3D metal printing only started to gain traction and public interest around 2010 onward. Many unique technical capabilities such as tool-less, design-driven, on-site manufacturing of customized parts and building highly complex components in one step soon after conceptualization provide unprecedented business and technical advantages for AM (Buchanan & Gardner, 2019; DebRoy et al., 2018). However, metal additive manufacturing is not necessarily beneficial for every single metal part. When moving to larger scales such as those required in the construction industry, factors such as printing time and cost may limit the advantages of large-scale AM applications of metals. Although some metal 3D printing systems have a relative capacity for serial production, it is generally cheaper to keep using traditional methods for simpler parts.

For cases where complex geometries, rapid prototyping, and mass customization are required, metal AM is instead convenient and efficient. One of the main advantages of 3D printing metal parts is in fact the possibility to produce lighter, hollow components with the same mechanical properties, making benefits of metal 3D printing particularly significant in case of building up structures or components with complex geometries designed to optimize weight and material use that would be difficult, if not infeasible, to manufacture using conventional techniques (Delgado Camacho et al., 2018).

In addition to costs, other barriers to a more widespread adoption of metal 3D printing in construction include the specific operating environments with controlled temperatures or hygrometry required by some 3D printers to operate, as well as the need to postprocess printed samples (i.e., debinding and sintering or finishing touches for surface quality), which also limit an effective on-site deployment of metal AM.

One of the most promising applications of metal 3D printing in construction involves the realization of load-bearing building elements, such as nodes, beams, or columns, with unprecedented freedom in terms of architectural and structural design. In fact, the possibility of precisely adding material only where it is effectively needed, regardless of constraints related to predetermined shapes or mold geometry requirements, allows to optimize at best the material/performance ratio of each component without any additional cost compared to a simpler 3D-printed shape. This approach, known as topology optimization, emphasizes the design of material as a function of form instead of designing form as a function of material (Craveiro et al., 2019). This type of structural optimization can be considered a biomimetic evolutionary optimization process, as it follows the principle of “just enough” that characterizes natural structures. Expected loads and constraints are applied in a 3D simulation model, and material placement is optimized based on the simulation—putting more material in regions of high stress and less in regions with lower loads (see Fig. 8.29). Repeated cycles of simulation and material placement optimization results in a structure optimized for the loads expected, with minimal material use (du Plessis et al., 2021).

A renowned example of topology optimization are the steel nodes designed by Arup for lightweight structures characterized by a complex shape and customized design dictated by iterative studies of effective loads (see Fig. 8.30). Each of the 14-cm-tall prototypes was produced from stainless steel using DMLS, at just under half the size of the real nodes, and put through preliminary material tests (Paoletti, 2017). The new design was derived by enforcing a maximum von Mises stress constraint on the node to prevent yielding, then using different software applications to generate the finite element model, to perform the topology optimization, and to modify the resulting shape in order to obtain a smoother geometry and to take production requirements into consideration. Compared to the existing tensegrity

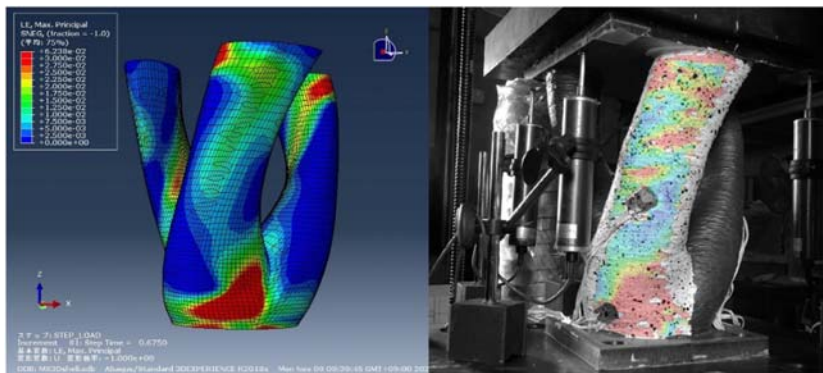


FIGURE 8.29 Simulation and lab testing of stress loads in a 3D-printed metal connector. Courtesy of MX3D.



FIGURE 8.30 Mass reduction of structural nodes via topology optimization. *Courtesy of Arup.*



FIGURE 8.31 3D-printed steel bridge. *Courtesy of MX3D, photos by Adriaan de Groot (top) and Oliver de Grujter (bottom).*

structure on which it was based, produced with conventional metallurgy processes, costs were higher but weight was 75% lighter, which may result in a less expensive, less material-intensive, and more sustainable overall structure with tensile strength and ductility comparable to those resulting from conventional manufacturing methods (Paolini, Kollmannsberger, & Rank, 2019).

Netherlands based MX3D firm instead specializes in metal construction elements 3D printed with WAAM technique, a form of DED which consists of a gas metal arc welding machine and a 6-axis industrial robot able to manufacture metal rods which connect to each other in a self-supporting manner. WAAM allows the realization of light, mesh-like structures as well as massive 3D objects that are printed by continuously stacking welds on top of each other as a deposition process. MX3D manufactured a 12 m long pedestrian bridge entirely made of 3D-printed sections created by 4 multiaxis industrial robots using around 6000 kg of 3D printed stainless steel wire (see Fig. 8.31). Topology



FIGURE 8.32 3D-printed steel connector. *Courtesy of MX3D.*

optimization was employed to design structures and nodes that feature increased performance/weight ratios. The bridge was successfully installed over one of Amsterdam's oldest canals, in the red light district, in July 2021.

Another example is their multimaterial structural semihollow steel connector, which was first printed in duplex stainless steel wire, an alloy renowned for its good mechanical properties and excellent corrosion resistance, by a WAAM robotic 3D printer, then casted with concrete by a second industrial robot (see Fig. 8.32). Generative design allowed the geometry of the connector to make use of both the advantages of steel and concrete, with a net weight of 40 kg reaching up to 45 kg after its hollow core was filled with approximately 2.5 L of mortar. Using stainless steel wire as printing material is particularly suitable for large metal elements such as those required in the construction sector, as it is faster and as much as 10 times less expensive compared to the SLM powders used in the metal sintering equipment (Craveiro et al., 2019).

Nonetheless, the application of 3D printing for manufacturing load-bearing building elements requires some further understanding of how the processing of the material may influence its structure and ultimately its mechanical properties, which may differ from those of the same material processed with more conventional methods. AM metallurgy has in fact its own set of processing–structure–property relationships, with many aspects involving powder and welding metallurgy as well. Processing can impact the metal microstructure (size, shape, and orientation of grains or crystals), which will alter the mechanical properties of the metal alloy, that in turn also alter how the material can be further processed. At the same time, certain alloying additions that make an alloy too brittle for rolling, forging or other wrought processing make AM the only way to produce certain highly alloyed materials.

Concerning AM techniques for metal printing, EBM tends to generate lower residual stress levels and less cracking compared to LM and DED, most likely due to slower cooling and in situ aging. Powder or wire fed DED processes can in turn be used to deposit multimaterials, which could enable parts with tougher cores and wear-resistant surface layers, and can be employed also to rebuilt or repair existing metal structures. Most of the processes that employ melting rapidly solidify the metal deposits, which reduces elemental segregation and can aid in developing refined or unique microstructures but can cause gas entrapment, delamination, retain undesirable metastable phases and increase residual stress levels. Finally, BJ deposits are not prone to delamination, but freshly printed samples can be delicate and have high porosities until sintered or fired.

As successive layers are deposited during 3D printing, heat builds-up within a printed part could lead to grain or microstructure coarsening: for instance, metal objects printed with EBM technique can take 5–80 hours to cool below 100°C, hence may experience a significant amount of annealing and recrystallization within the printer chamber.

Additionally, heating certain metal powders or parts in normal atmosphere may result in oxidation or oxide scale formation; therefore, 3D printing processes based on metal melting—LM, EBM, DED—use inert or vacuum atmospheres within the metal deposition chamber.

Lastly, 3D-printed elements tend to have rough surfaces, resulting in a reduced fatigue strength compared to polished samples obtained via conventional processes. This can be addressed in postprocessing by machining, grinding, honing, or polishing the printed parts, with isotropic superfinishing processes allowing surface finish improvements

without alterations to the geometry, and extrusion honing or abrasive flow machining to refine the surfaces of internal channels or hollows. Internal pores may be closed by hot isostatic pressing (HIP) after the printing process (DebRoy et al., 2018).

8.3.2.2 Concrete 3D printing

The introduction of digital manufacturing techniques, such as 3D printing applied to cementitious materials, opens new perspectives on the way in which buildings are designed (Sanjayan, Nazari, & Nematollahisanjayan, 2019).

Research on this theme is thriving, and there is a high rate of innovation related to concrete. At the same time, the first life-size constructions made from printed concrete are currently being erected. Indeed, concrete 3D printing allows to construct medium to large structures with much greater freedom in geometrical shape, whereas conventional construction methods (with concrete, as well as with wood or masonry) struggle with round forms and curves. Therefore, shape can be optimized with several strategies, including the fabrication of forms inspired by nature (biomimicry). For instance, the elimination of sharp tips and corners reduces stress concentrations under loading conditions, and curved walls have several structural advantages, do not require buttresses and, due to the curvature, are stronger against lateral forces, thus requiring less material compared to an equivalent-strength straight wall (du Plessis et al., 2021). Processes of topology optimization, as described in Section 8.3.2.1, are viable as well, in particular for the fabrication of large scale cellular and lattice structures which are typically used either for infill patterns in surface-closed beams and walls, or for creating open-porous structures (see Fig. 8.33). Some advantages of cellular designs are the faster build rates, less material use, thermal insulation when using infill patterns in walls (closed porous spaces) or airflow for passive cooling when using open cellular designs, itself a biomimetic strategy inspired by termite mounds (du Plessis et al., 2021).

Nonetheless, actual commercial deployment is still slowed down by the high price commanded by the required machinery—about USD 500,000 to USD 2,000,000 for a mainstream on-site concrete printer (ECSO, 2019).

Concrete 3D printing is particularly promising because its build material is already ubiquitous in construction for its low cost and its suitable and reliable mechanical properties, backed by decades of research, development, and experimentation. As a semiliquid material that gains strength as it naturally dries after pouring, concrete lends itself well to extrusion-based AM techniques, with the added benefit that cementitious materials can already be extruded in conventional construction using concrete pumps (Delgado Camacho et al., 2018). In particular, concrete 3D printers are basically scaled-up versions of conventional FDM or FFF set-ups, with an extrusion nozzle, either mounted on a gantry, a robotic arm or a CDPR (Delta system), a back-up system to mix the cement, aggregates, and additives, and a distribution system to deliver the viscous cement mix to the nozzle for deposition. As with other extruded materials, the dimension of the nozzle and therefore of the deposited concrete filament dictates the resolution and other key parameters of the printing process (see Fig. 8.34). Concrete extrusion techniques can be divided into three types, depending on the filament size:

- deposition of fine filaments less than 1 cm in diameter. An example of this type is 3D concrete printing (3DCP);
- deposition of medium-fine filaments with cross-sectional dimensions up to several cm. Examples include both contour crafting (CC) and 3DCP;
- deposition of coarse filaments in the range of several dm. This category includes, for instance, CONPrint3D technology (Paolini et al., 2019).



FIGURE 8.33 3D-printed cellular structure. Courtesy of WASP.



FIGURE 8.34 Delta cement printer. *Courtesy of WASP.*

Finer filaments translate to higher printing resolution, allowing for greater precision and geometric complexity and are better suited for off-site prefabrication of detailed or complex building components. On the other hand, printing a filament with larger cross section enables a much quicker building speed and higher productivity, is compatible with coarser-grained concrete, resulting in a reduced need for cement, lower cost and less shrinkage, and is therefore more adapt for on-site 3D printing of large building components (walls, columns, whole building envelopes).

In addition to material and extrusion characteristics, different architectural arrangements of layers also affect the mechanical properties of hardened concrete. In addition to conventional unidirectional layers (0°), other patterns such as cross-ply (90°), quasi-isotropic ($0/45/90^\circ$), and helicoidal patterns (with pitch angles of 10, 20, and 30°) can be used to create unidirectional, bidirectional, and multidirectional layers in printed objects. These techniques entail considerable improvements on compressive and flexural strengths, which have a promising potential for being applied in highly complex or self-supporting concrete architectures (Pham, Lu, & Tran, 2021).

3D concrete printing

3DCP technique has high printing system control and printing resolution, due to the small to medium diameter of the nozzle employed, and is capable of resolving details as low as 4–6 mm (Zhang, Wang, Dong, Yu, & Han, 2019). Concrete is deposited in a layer by layer process, with the potential of incorporating functional voids into the structure and achieving complex internal and external geometries. Printed elements display the characteristic ribbed finish of objects manufactured via FFF or FDM, thus whenever a smooth finish is required either the wet paste is troweled during printing or the printed finish is ground or rendered manually. Differently from conventionally poured concrete, the layered structure obtained by 3DCP is usually anisotropic due to the void formation between filaments, deteriorating the final performance of the printed component (Hamidi & Aslani, 2019).

In 3DCP, the extrusion nozzle can be fixed to a gantry system to move along the cartesian grid and on the z-axis (three DOFs), or to a multiaxis robotic arm to obtain up to 6 DOF, allowing the deposition of the build material also in a nonperpendicular direction. This allows tangential continuity method (TCM), an extrusion technology better suited for large-scale AM in which the building paths are actually 3-dimensional, that is, made of nonplanar layers with locally varying thicknesses (Gosselin et al., 2016). TCM allows to keep contact surfaces constant between two layers even when they are not perfectly superimposed, as in overhangs or sloped sections, hence avoiding the geometrical gaps which often limit the possibilities of AM processes. As an additional development, researchers at TU Eindhoven integrated their own 3DCP technology with a specific nozzle to deliver a reinforcement cable together with the extruded concrete, and used it to manufacture a functional cycling bridge with a span of 6.5 m, composed of six elements printed off-site and pressed together by posttensioned prestressing tendons (Salet, Ahmed, Bos, & Laagland, 2018). The bridge was built by Royal BAM Group contractor and materials company Saint-Gobain Weber Beamix, which after this pilot project established in 2019 Europe's first industrial and commercial 3D printing factory for concrete elements.

Contour crafting

CC technology was developed at University of Southern California in 2005 with the objective of quickly printing buildings on site in a single, self-contained manufacturing process, and is based on the extrusion of a cement-based paste with a nozzle equipped with one or two trowels, resulting in smooth surface finish. The nozzle is carried by a gantry

system to be installed at the construction site and deposits the thick concrete ink one layer at a time: after being partially cured, the hardened lower layers are able to support the fresh cement layer above. As in 3DCP, the layer-by-layer construction technique in CC allows to build utility conduits within walls and to mechanize the installation of plumbing and electrical services. With CC, it is possible to fabricate vertical elements with high compressive strength, but whenever a door or window needs to be installed, a lintel would be incorporated to place the wall above as it is not possible to produce overhangs without on-site support (Hamidi & Aslani, 2019).

In addition to concrete, CC is compatible with other cementitious materials such as raw earth or clay, which can be sourced locally at the construction site to further reduce costs associated with transport. Wall or column sections are commonly hollow with few connecting segments to increase rigidity and mechanical resistance. These cavities may host systems or be filled with insulating materials, to improve the element's thermal resistance, or with conventional concrete to form a composite structure with superior mechanical performance. In this case, CC creates 3D-printed permanent formworks, which will be part of the final printed structure (Lu et al., 2019).

CONPrint3D

CONPrint3D technology was developed by researchers at TU Dresden with the primary objective of overcoming the traditional issues of high cost and slow deposition associated with little and medium sized filament technologies such as 3DCP and CC. This was addressed by focusing on the deposition of larger quantities of concrete and on the optimization for simpler geometries such as those required by conventional, utilitarian construction. In particular, the use of large-size filaments would enable high productivity and use of concrete with coarse aggregates, instead of costly UHPC employed in other concrete AM, reducing the quantity of binder and shrinkage, all in accordance with valid national and international norms. The system is based on a large print-head designed to print monolithic wall profiles with a cross section of 150×50 mm for layer, at speeds of up to 10 m/min using concrete with an aggregate size of up to 10 mm (Mechtcherine et al., 2019). Although the system is currently being tested mounted on a gantry, its final development is envisaged as a truck mounted solution integrated with the concrete pump, with the print-head position driven by optimized drive components, control algorithms, and control systems implemented to reduce the oscillation amplitude of the pump mast and provide the accuracy needed for precise wall-laying.

Characteristics of 3D printing concrete

Notwithstanding the technology used for 3D printing, there are challenges associated with ensuring concrete is pumpable, extrudable, able to maintain its shape after deposition and capable of rapidly providing enough mechanical resistance to support its self-weight post-extrusion. These main characteristics can be identified as “flowability, extrudability, buildability, and open time” (Li et al., 2020). Flowability, also called pumpability, indicates the ease of transporting the fresh concrete mix from the pump to the extrusion nozzle ensuring no particle segregation occurs in the hose. This in fact may lead to blockages and printing downtime, which decrease productivity and may lead toward forming of cold joints between subsequent layers owing to the pauses in the build process. Extrudability is in turn the capability of the material to pass through the nozzles at the printing head as a continuous and intact filament and is dictated by size and shape of aggregate particles present in the cement mix compared to the diameter of the nozzle. Buildability, instead, indicates whether a printed filament can retain its extruded shape under the loads from itself, subsequently deposited layers, and extrusion pressure, and is a key requirement for preventing collapse during printing. Finally, open time describes how rapidly the concrete hydrates and hardens and is an indicator of its capacity of maintaining of both the viscosity and yield stress of the mix. These factors shall be carefully balanced in designing the concrete mix, as the cementitious paste is expected to be soft enough to be transported in the printing system and extruded through the printing nozzle, but at the same time it must be stiff and have sufficient buildability to maintain its shape right after extrusion. Additionally, a long open time is beneficial to continuous extrusion, as well as good interlayer bonding, but it is detrimental to shape stability of printed objects with respect to buildability.

Cementitious materials employed in 3D printing, like portland cement, are characterized by a high thixotropy, that is, can provide high yield stress and low viscosity, leading to smooth extrusion of material, and retaining the final shape of the printed component after deposition (Hamidi & Aslani, 2019). Additives commonly employed to improve the concrete performance in relation to 3D printing requirements include reinforcing fibers, accelerating agents, superplasticizers and fine mineral additives and chemical admixtures to achieve the required rheological, mechanical, and/or durability characteristics. Concerning accelerating agents, these are fundamental to reduce the time gap between the lower yield stress and plastic viscosity required before and during deposition and the higher yield stress and plastic viscosity required after extrusion to support the layers above. For instance, cement manufacturer Sika developed a printing

mortar mixed with a range of additives allowing the cure in seconds, while ensuring a correct bonding with the previous layer (Craveiro et al., 2019). XtreeE researchers devised a 3D concrete system with two separate pumps, one for the premix and another for the accelerating agent: firstly, a mortar premix with an appropriate rheological behavior is prepared and kept in a shearing mixer, then the premix is pumped to the print head and accelerating additives are simultaneously dispersed in the mix to accelerate the setting of mechanical properties after extrusion (Gosselin et al., 2016).

In addition to cement AM, concrete structural construction can benefit from 3D printing by taking advantage of the possibility of producing printed formworks with unparalleled geometrical freedom. Complex molds, to be filled with concrete and later removed or kept, can be produced with sandstone to produce prefabricated large-scale building components with highly detailed and complex geometry, that are easily removable with pressured water after the concrete set. On the other hand, the FreeFAB Wax process produces wax molds for concrete by 3D printing, that can be melt off and recycled after concrete has hardened (Craveiro et al., 2019). Lost formwork can be 3D printed with insulating foams and be retained in the final construction to improve the thermal characteristics of the concrete element. Researchers from ETH Zurich demonstrated a 78 m² prestressed concrete slab discretized into eleven 7.4-m-long segments, each cast in a unique formwork modeled with computational design and fabricated with both BJ and FFF. Another demonstration of the potential of concrete and 3D formwork is the Future Tree canopy in Esslingen (see Fig. 8.35) by Gramazio Kohler Research. The stem is a structurally optimized concrete column made using a 1.5 mm thin thermoplastic formwork, printed using a robotic arm, combined with fast-hardening concrete and conventional reinforcing bars (see Fig. 8.36), whereas the timber elements of the canopy were cut to size and assembled by a robotic arm.

The ability to 3D print complex, loadbearing cement components can have positive effects on buildings' energy performance: on the one hand, the cement mix can incorporate insulating materials to forego the need for thermal insulation layers and provide a more performing envelope, on the other hand the geometric freedom allows to explore novel forms of biomimicry to improve thermal performance. For instance, fast-setting, insulating 3D printing material can be obtained with aerogel granules, a phosphate-based cement and fly ash, with thermal conductivity as low as 0.04 W/mK (Baghban, 2019). The incorporation of air bubbles in the cementitious mixture results in the improvement of its thermal insulation and acoustic absorption, with conductivity values of 0.125 W/mK for extrudable foamed concrete slabs and 0.153 W/mK for aerated autoclaved concrete, at the same wet density of 550 kg/m³. Lightweight expanded clay aggregates (maximum size 10 mm) can be added to the mixture without affecting the extrusion capacity for a replacement of up to 30% of the volume, resulting in improved thermal insulation as well as increased strength and elastic modulus of the concrete (Rahul & Santhanam, 2020). The incorporation of biomimicry can be seen, for example, in the use of cellular or lattice structures, which generally not only present optimized stiffness and lightness properties, but also have good thermal and acoustical characteristics, and the internal spaces of the printed element allow to reduce thermal bridging, install thermal insulation, and minimize load (Pessoa, Guimaraes, Lucas, & Simoes, 2021).

Lastly, concrete 3D printing has remarkable potential in cultural preservation and reproduction of buildings and building elements (Ngo, Kashani, Imbalzano, Nguyen, & Hui, 2018). In fact, each component of a historic structure can be 3D scanned on site with a streamlined approach already established in heritage and archeology research, quickly and effortlessly acquiring an accurate 3D model. This can then be faithfully reproduced by transferring the model to the concrete printer, with the possibility of improving its mechanical characteristics or integrating features without altering

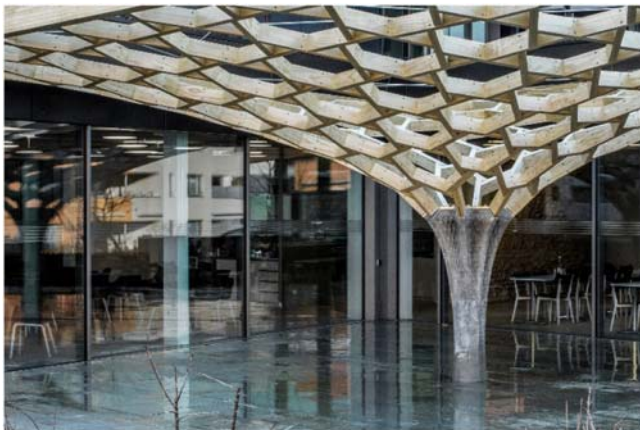


FIGURE 8.35 Future Tree canopy. © Gramazio Kohler Research, ETH Zurich.

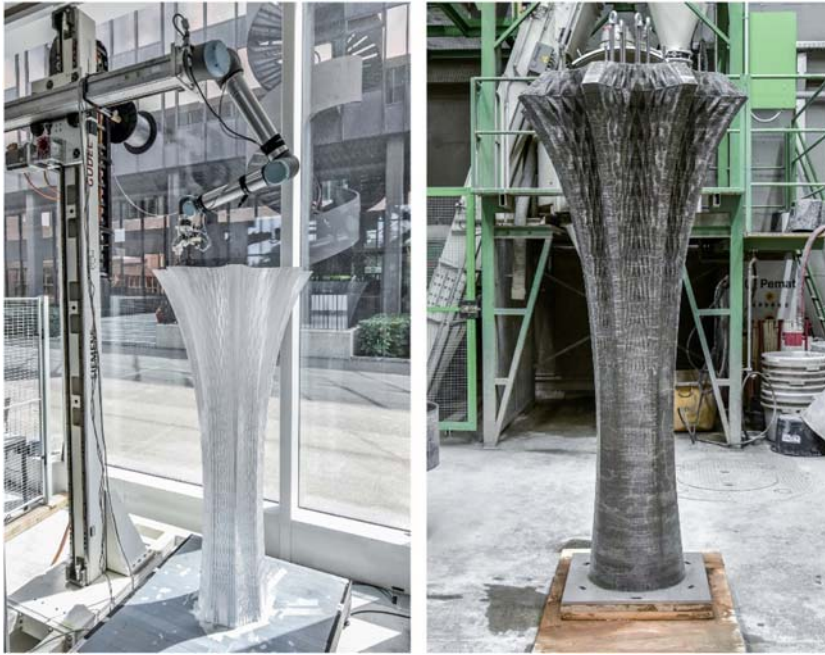


FIGURE 8.36 3D-printed formwork and cast column of Future Tree canopy. © Gramazio Kohler Research, ETH Zurich.

the esthetic appearance of the building. This way it becomes possible to replicate or replace elements such as decorative tiles, capitals, window frames or even load bearing components like caryatids, resulting in cost-effective and labor-efficient construction as compared to traditional restoration methods.

8.3.2.3 Polymers and composites 3D printing

Polymers and composite printing materials can be used for AM in construction, although in more limited and niche applications compared to 3D-printed metals and concrete due to their inherent lower mechanical resistance, stiffness, and durability, which hinder pure polymer products as fully functional and load-bearing components (Ghaffar, Corker, & Fan, 2018). As such, polymers can be used in construction for esthetic elements or in light structural applications, if combined with other strength-enhancing materials (polymer composites).

Concerning building components with a purely esthetic function, in 2013 Skanska contractor employed 3D-printed polymers to fabricate complex cladding elements for structural connections at 6 Bevis Marks Office in London, which would have been much more expensive and difficult to produce with traditional methods, such as cast steel nodes. In this case, nylon PA12 high-performance polymers were printed with SLS technique to obtain unique objects that could be resistant to rain, sunlight, and heat and cover the unsightly structural nodes below (Paolini et al., 2019).

Composites build materials promise improved mechanical characteristics compared to pure polymers, and usually come in the form of fiber-reinforced plastics tailored for application in AM. In particular, short fibers including glass and carbon can be added to ABS or PLA base materials to be printed with FDM technique, with content restricted to around 40 wt.% due to possible nozzle clogging issues. As an alternative, direct wire deposition employs a single carbon fiber filament that is deposited continuously along with the polymer and allows higher mechanical performance if properly cross-layered. An example of large scale, mechanically sound elements printed with carbon fiber reinforced polymers is the Additive Manufacturing Integrated Energy (AMIE) building described in Section 8.3.3.

Polymers can find application in the production of formwork for concrete structures: complex sections with topology optimized geometry can be obtained using polymer binders processed with sand in BJ techniques, whereas foamed polymers, namely, two-component fast-curing PU foams, can be sprayed by a printing head connected to a robotic arm to create freeform shapes that act as a lost formwork with thermal insulation properties.

Regarding thermoset photopolymer resins, commonly associated with vat photopolymerization AM techniques such as SLA or DLP, these are instead unsuitable for extended application in construction. In addition to their inherent brittleness and low mechanical resistance, additional drawbacks include the typical material degradation over time of these polymers, in particular when exposed to UV light, and the considerable amount of liquid light-activated resins that

would be required to manufacture medium to large building components, along with the large size and costly equipment needed (Sawhney et al., 2020).

8.3.3 Building scale 3D printing

Full building and infrastructure construction with 3D printing has been a reality from several years, and nowadays there are already several buildings around the world, both demonstration prototypes and fully operational structures, that have been fabricated with AM technologies, either by assembling 3D printed parts manufactured off-site, or by installing the 3D printer on location and fabricating the structure entirely on-site.

Concerning 3D printed buildings prefabricated off-site, Chinese contractor Winsun has gained notoriety with several projects in the last few years, starting from successfully printing a group of 200 m² houses in China in 2014 with a large gantry system (150 × 10 × 6.6 m), then manufacturing villas and multistory apartments in the following years, with a proprietary technology akin to CC using a mix of glass fiber, steel, high-grade cement, hardening agents and recycled construction waste materials (Craveiro et al., 2019). A more recent project is the HQ of the Dubai Futures Foundation, a 250 m² office building designed by Gensler and Thornton Tomasetti. Winsun printed all building components in Shanghai in 17 days, then shipped them to Dubai where on-site installation took only 2 more days, claiming reduced labor costs by 50%–80% and construction waste by 30%–60% (Sepasgozar, Shi, Yang, Shirowzhan, & Edwards, 2020).

Another example of building 3D printed off-site, is AMIE, a solar powered housing prototype developed by SOM and researchers from Oak Ridge National Laboratory (ORNL), which complex, organic geometries were optimized to reduce localized stress and mitigate turbulent exterior air flow. The 11.6 × 3.6 × 4 m home was constructed assembling C-shaped elements printed in ORNL laboratory over 225 hours using big area additive manufacturing (BAAM), an extrusion technique capable of producing large scale carbon fiber-reinforced polymer elements (Paolini et al., 2019).

Netherland based DUS architects developed their own in-house FDM 3D printer, able to fabricate building sections as large as 1.6 × 1.6 × 4.5 m with bio-based plastic, and used it for research and demonstrative projects in Amsterdam such as the Canal House, a 700 m² structure with 3D-printed façade elements, the Europe Building, a 300 m² façade with integrated 3D-printed benches, and the Urban Cabin, an 8 m² urban retreat entirely made with 3D-printed elements.

3D printing at building scale was also experimented in pedestrian concrete bridges. The first 3D-printed bridge was inaugurated in Madrid in 2016 at the Castilla-La Mancha urban park in Alcobenda. The footbridge is 3D printed with micro-reinforced concrete material, measuring a total of 12 m in length and 1.75 m in width. The world's longest 3D-printed concrete pedestrian bridge has been completed in Wisdom Bay pond, Shanghai, in 2019. Designed by researchers from the Tsinghua University, the single-arch 26.3-m-long bridge consists of 44 hollowed-out 3D-printed concrete units, while the handrails are divided into 68 units. The bridge's components have been printed off-site from composite materials, containing polyethylene fiber concrete to match the structural performance of conventional materials.

Regarding on-site 3D-printed buildings, these employ dedicated 3D printers optimized for outdoor operations on a large scale (see Fig. 8.37), which are mostly based on gantry or cable-suspended systems with some employing robotic arms (see Table 8.8).

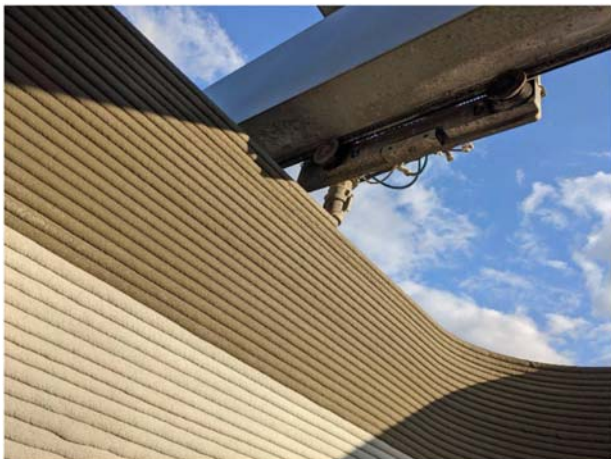


FIGURE 8.37 Building scale 3D printing. Courtesy of ICON.

TABLE 8.8 Main 3D printers for on-site building construction.

Manufacturer	3D printer	System	Printable dimensions (m)	Country
Apis Cor	3D printer	Robotic arm	$8.5 \times 1.6 \times 1.5$ m	US
Batiprint3D	3D printer	Robotic arm	Up to 7 m high	France
COBOD	BOD2	Gantry—modular	$14.6 \times 8.1 \times \infty$	Netherlands
Cybe	3D printer	Robotic arm	n.d.	Netherlands
ICON	Vulcan II	Gantry	$8.5 \times 2.6 \times \infty$	US
SQ4D	ARCS	Gantry	$9.1 \times 4.4 \times \infty$	US
WASP	Crane Wasp	Delta—modular	$\varnothing 6.3 \times 3$ each module	Italy

Gantry systems are the most labor-intensive to set up on site because of their weight and size, which must be larger than the element under construction (Delgado Camacho et al., 2018). Once assembled, gantry systems usually need no repositioning during construction and can proceed in printing several buildings in a row, such as semidetached houses or independent cabins, if provided with a suitable rail platform. An alternative to gantry systems are cable-suspended platforms, which are cheaper, easier to transport and set-up, and able to provide larger workspaces. Also known as delta systems, these consist of a nozzle attached from below and above to an external frame using multiple cables which are extended or retracted automatically to move it in the three directions (Labonnote et al., 2016). An example of large scale delta 3D printer is the 12 m high Big Delta developed by Italy based WASP, considered to be the biggest 3D printer available. The experience gathered with Big Delta was reinvested in developing the Crane WASP modular printing system, which can be assembled in different configurations according to the printing area, and is able to print single modules up to 6.6 m in diameter and 3 m in height (see Fig. 8.38). Crane WASP was used to fabricate Gaia, a sustainable housing unit built using a mix of 25% earth from the construction site, 40% rice chaff, 25% rice husk and 10% hydraulic lime. The house features a 3D-printed foundation layer and a 40 cm thick engineered envelope that integrates ventilation chambers, housings for systems, and thermal insulation that was printed over 10 days totaling 22 km of extruded filament (Chiusoli, 2018).

The concept of sustainable 3D printing was further developed in the TECLA (Technology and Clay) project, the first eco-sustainable housing model 3D printed entirely from local raw earth, jointly designed by WASP and MCA architecture firm. TECLA used two synchronized printer arms simultaneously, each with a 50 m² printing areas, thanks to software capable of optimizing movements, avoiding collisions and ensuring streamlined operation (see Fig. 8.38). With an area of about 60 m², it comprises a living zone with a kitchen and a night zone which includes services and furnishings partly printed in local earth and integrated into the raw-earth structure, combining vernacular construction practices and bioclimatic principles. The building was delivered with 200 hours of printing, 7000 machine codes (G-code), 350 layers each 12 mm thick, 150 km of extrusion, 60 m³ of natural materials for an average power use of less than 6 kW.

A similar concept is used by Apis Cor, a United States based 3D printing service that employs a robotic arm pivoting around a central support, capable of constructing up to $8.5 \times 1.6 \times 1.5$ m volume at a time. Apis Cor printed a single module, 38 m² house on-site in Stupino, Russia, in 2016, but gained attention in 2019 with the two-story 640 m² office fabricated in Dubai, UAE, that resulted at the time the world's largest 3D-printed building (see Fig. 8.39). To cover such a large area, the stationary 3D printer was moved to different positions within the construction site by crane. A gypsum-based mixture was used to print free-form walls and formworks for columns that were manually filled with rebar and heavy concrete, while floor slabs were conventional precast elements. Total printing time was about 500 hours, 8 hours per day, with breaks to allow the general contractor to integrate fittings, electronics and ceilings.

United States-based ICON developed a complete 3D printing system for on-site building construction, constituted by a large scale printer called Vulcan II, a proprietary portland cement-based mix called Lavacrete, that can be customized according to climate and location, and a dedicated material delivery system dubbed Magma (see Fig. 8.40). The Vulcan II 3D printer is gantry-based, comes preassembled in a container, and is characterized by a print size 8.5 m wide and 2.6 m high, with a theoretically infinite printing length and a printing speed of 25 cm/s. After a proof of concept home fabricated in 2018, which was the first fully permitted 3D-printed house in the United States, the firm partnered with nonprofit organizations to deliver 3D-printed homes to distressed communities: their community of 47 m²



FIGURE 8.38 Crane WASP modular 3D printer building TECLA house. *Courtesy of WASP.*



FIGURE 8.39 Building in Dubai 3D printed with Apis Cor. *Credit: Apis Cor.*





FIGURE 8.40 Vulcan II 3D printer. *Courtesy of ICON.*



FIGURE 8.41 3D-printed buildings by ICON: first permitted house (top left), community housing in Austin (top right) and Mexico (bottom left), mixed tech house in Austin (bottom right). *Courtesy of ICON.*

individual houses in Tabasco, Mexico, withstood a 7.4 magnitude earthquake in June 2020 with no visible damage, and the "Community First! Village" in Austin, Texas, for formerly homeless was unharmed during Texas' particularly harsh storms at the start of 2021. A real estate development of four residences, between 95 and 190 m², was also built in Austin in 2021, two of which sold within days of their unveiling in march, with the ground floor entirely 3D printed and the upper floor erected with traditional wood frames (see Fig. 8.41).

Denmark-based COBOD International manufactured the first code-compliant 3D-printed building in Europe, the BOD (Building On Demand), an office hotel of less than 50 m² located in Copenhagen's Nordhavn (see Fig. 8.42). The building demonstrated the versatility of COBOD's own 3D printer by not containing any straight walls, the only straight elements being the windows and doors, and featuring foundation partly realized with AM.

COBOD'S 3D printer, called BOD2, is gantry-based and characterized by a modular design to adapt to the size of the building to be printed, with a print area of minimum 1.9 × 2.1 × 1.5 m and maximum of 14.6 × 8.1 m with theoretically infinite length according to the number of X, Y, and Z axis modules employed (see Figs. 8.43 and 8.44). Different nozzles allow various layer width (30–100 mm) and height (10–30 mm) compatible with mortars and concrete with aggregates up to 10 mm diameter. Printing speed is up to 100 cm/s, equivalent to an output of almost 10 tons/h.

The BOD2 printer has been already employed in several applications worldwide, including: the 8 m high and 90 m² 3DPO building in Westerlo, Belgium, which was the first two-story building in Europe with the entire building envelope printed on-site in one piece; a 3D-printed apartment building in Bavaria, Germany, which three floors and 380 m² of floor space were printed in just 6 weeks (see Fig. 8.45); and a 70 m² storage unit in Florida, which was the first 3D-



FIGURE 8.42 Building On Demand (BOD) 3D-printed house. *Courtesy of COBOD.*



FIGURE 8.43 BOD2 3D printer and nozzle. *Courtesy of COBOD.*



FIGURE 8.44 BOD2 3D printer in operation. *Credit: PERI.*

printed building in that State. Other buildings were also printed in Malawi (see Fig. 8.46) and India. COBOD also partnered with GE Renewable Energy to 3D print the larger base segments of wind towers on site before installing the upper, prefabricated steel sections. Such solution would allow wind towers as high as 200 m.

United States-based SQ4D completed in 2020 a 180 m² 3D-printed home in 48 hours of print time, over an 8-day period. Its own gantry-based system robotically built foundations, exterior walls, interior walls, and utility conduits, with a claimed reduction in labor to as little as three people and using less than \$6000 in materials. Their following project, a 130 m² home with a 65 m² garage, became the first 3D-printed house listed for sale in the United States and included a 50-year limited warranty on the 3D-printed structures.

Netherlands based Cybe developed a 3D printer system based on a robotic arm, available both on a fixed support, suitable for off-site prefabrication of building components, and on a mobile platform recommended for on-site



FIGURE 8.45 3D-printed house in Bavaria. *Credit: PERI.*



FIGURE 8.46 3D-printed house in Malawi with BOD. *Credit: 14trees.*

fabrication at the construction site. A custom mortar optimized for 3D printing sets in 3 minutes and achieves structural strength in 1 hour with reduced shrinkage. Constructed buildings include the R&Drone Laboratory in Dubai, UAE, printed on-site in 46 hours over 3 weeks, and a 80 m² house printed in the Saudi Arabian desert, consisting of 27 walls and 21 parapets all printed within 1 week.

Another approach is that patented by the University of Nantes, France, with its Batiprint process. A laser guided robotic arm sprays an expandable polyurethane foam layer by layer, fabricating on-site an insulating, self-supporting lost formwork for all walls in which windows, doors, lintels and rebars are fixed before pouring the concrete inside. This way it is possible to rapidly fabricate a three-layer, thermally insulated and load bearing building envelope which just needs interior and exterior finishing. The polymer polyurethane foam (density 35 kg/m³, thermal conductivity 0.027 W/mK) is obtained by mixing together isocyanate and polyol and directly depositing it onto the surface of the building slab: it takes only three seconds for the material to expand and about 45 seconds for the foam to obtain sufficient stiffness to support a new layer of foam. This system was demonstrated in 2017 in Nantes by fabricating the Yhnova house, a 95 m² five-rooms home which took 54 hours of printing time over 4 months for final delivery, and is now inhabited by a family assigned through regular social housing listing. The printed envelope assembly (80 mm PU, 150 mm concrete, 80 mm PU) achieved a total thermal resistance of 6.75 m² K/W (Furet, Poullain, & Garnier, 2019).

In the city of Eindhoven (NL), Project Milestone, a mini district of five 3D-printed concrete houses, is under construction by a partnership with Eindhoven University of Technology and the Vesteda housing corporation. The first building, a 94 m² detached home characterized by a boulder-like free shape, was delivered to the first inhabitants in spring 2021, with each subsequently printed house leveraging the lessons learned in the prior works.

Finally, United States-based Mighty Buildings company is developing a community in California of 15 zero energy homes. Rather than printed on site, in this case the buildings are made with prefabricated panels 3D printed at the contractor's facility and assembled with steel frames, insulation materials, air/moisture/fire barriers and interior and exterior finishes, with a claimed 99% reduction of the typical waste and 95% reduction of on-site labor.

Another promising application of AM in construction concerns the development of ways to create 3D-printed infrastructure for living on other astronomical objects such as Mars or the Moon, using materials found on their surface. In 2017 British firm Foster + Partners unveiled a proposal to 3D print buildings on the Moon. In 2020 BIG and ICON have revealed they are working on NASA funded “Project Olympus,” which aims to develop additive manufacturing in construction for the Moon settlements. The United States Space agency also ran the 3D-printed Habitat Challenge, which tasked architects and designers to conceive 3D-printed homes for deep space.

8.4 Conclusions and future trends

The increase in labor costs and labor shortages, stricter regulations on the sustainability and safety in the construction site, higher requirements on environmental performance of the life cycle of buildings, along with ever growing costs and time constraints and evolving sophistication and needs of customers and owners, are pushing the construction industry towards a radical transformation of the processes, techniques and tools for the construction of buildings and infrastructure.

Consequently, many innovative advanced building construction methods have been emerging in the last 10 years, such as advanced prefabrication and modular construction, and off-site and on-site construction automation, robotics and additive manufacturing, offering disruptive solutions for systemic changes in AEC industry.

The main accelerators of this transition include the digitalization of the design and production processes, the advancement of automation and robotics, new advanced materials, and the evolution in supply chain management.

As for prefabrication, the goal is to move the production of the building from the construction site to the more controlled and structured environment of the factory through the fabrication of increasingly complete and complex components, up to the preparation of entire modules to be assembled on site in reduced times and costs, with operations simple and safe to perform by unskilled labor or robots. The transition to efficient off-site manufacturing involves the integration of automated production systems, essentially making construction more like automotive manufacturing. Through close collaboration with designers or integrated R&D departments, prefabrication companies will build more standardized libraries of subsystems that allow mass customization.

A further innovative element of the construction process concerns the automation and the use of robots on the construction site, alongside or in place of human labor, for carrying out repetitive, burdensome, dangerous operations, or those which require a high quality of execution in order to reduce construction times and costs, limit risks of accidents ensuring the best construction results. The technology in this field is moving toward the development of single task robots optimized for single processes, self-driving drones and construction vehicles, as well as exoskeletons and assistant robots. At the vanguard of this revolution is the large-scale application of additive manufacturing on construction site to fabricate building elements such as walls and pillars up to the entire building or infrastructure.

The key to exploiting at best all possibilities offered by these advanced construction methods and tools resides in an integrated approach that takes into account the logistic and construction aspects since the early stages of the design phase (design for assembly and manufacturing) in an effort to minimize the information gap between each project stakeholder and contributor, which is responsible for most setbacks that hinder every project. Today, digital design tools such as BIM can streamline the information flow between designers and constructors by establishing a shared, master building model in which all interferences and inconsistencies can be identified and addressed collectively, and promote the development of digital fabrication, automation, and modular construction.

To promote a wider and smoother diffusion of these innovative technologies in AEC, including modular construction, additive manufacturing, robotics, intelligent control systems, and new technologies for workers, these must be assessed also in terms of safety and security by the development of new procedures, legislation, certification, standards, building codes, and testing to address their uniqueness. Considering the rapid evolution of new technologies and the importance of their full uptake by the construction sector, constant and effective communication between policy makers, companies, and innovators is paramount to eliminate the barriers to innovation.

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Advanced site management tools and methods

9.1 Digital construction management

The actual stage of the construction works of a building is a particularly important and delicate phase for achieving the compliance with regulatory requirements, project objectives, and expected times and costs, as well as protection of the environment, health of the occupants, and safety of workers. In practice, the management of the construction site involves, in addition to the explicit construction work, numerous other activities and the interaction with multiple different subjects, both public and private, who are involved in various role in achieving the project objectives (see [Table 9.1](#)). Moreover, projects often have numerous subcontractors and workers on-site who may have never worked together before.

Executing construction projects is therefore a major managerial challenge and indeed the industry usually struggles to deliver projects on budget and on time. The current approach to managing work on-site results often in unnecessary costs, wrong use of cash flows, suboptimal schedule duration, risk of incidents, and quality and operability issues ([McKinsey, 2017](#)).

To improve productivity and quality of work, control time-to-market effectively and optimize revenue, efficient connected workflows must be defined to coordinate tasks between teams and keep information and systems in sync, by adopting lean and modern methods of construction and using a common data environment to give teams access to real-time information ([Autodesk, 2016](#); [Boston Consulting Group, 2016](#); [ECSO, 2021](#); [JRC, 2019](#); [Roland Berger, 2016](#); [Roland Berger, 2017](#); [Roland Berger, 2018](#)).

Construction management (CM) can benefit from adopting a production-system engineering perspective, in which work processes are more defined and standardized, material inventories are optimized and better controlled, and labor is more effectively allocated. However, this requires a shift in how to approach construction site management, as well as an effective framework for understanding throughput, variability, inventory, and capacity factors ([Autodesk, 2021](#); [McKinsey, 2018](#)).

In the construction industry, budgeting and scheduling are particularly delicate challenges, in terms both of accuracy and updating. Reliable plans are a prerequisite for effective execution on any site. Data managing and menial processes shall be automated as much as possible, and multiple systems shall be connected to each other. Projects commonly suffer disproportionate disruption because planners did not take into account uncertainties such as bad weather and realities such as holidays, customs clearances, and difficult logistics, or more often because the plan is not flexible or easy to update enough to cope with those. Too often, plans lack sufficient detail to enable construction managers to steer activities on-site effectively, and supervisors have to rely on past experience and intuition instead of shared practices and references. In fact, best practices indicate that approximately 25% of the cost of a project should be spent on planning. Equally important in any construction project is managing and tracking construction assets, as the availability of moveable equipment, building materials, and other assets on time and in the right place will ensure that the necessary components are installed, and projects are delivered successfully.

Overall, construction works suffer not only from the frequent deviations from the estimated costs and schedule but also from the late detection of these deviations. Menial reasons such as unexpected soil conditions or scope changes agreed on a lower operational level may turn out to have major implications, as this late awareness limits the companies' ability to take timely mitigation measures or to revise the contract, often with severe financial and reputational consequences.

The management of the construction site, especially when large and complex, therefore requires adequate IT support through dedicated software capable of managing, even remotely, all aspects related to the construction works, from setting up the yard to its final delivery to the client. Today, these programs must also ensure the ability to easily manage project variations during execution and allow collaborative workspaces.

TABLE 9.1 Main activities and subjects in construction management.

Construction management activities	Subjects involved
Permission and authorization management	Client
Management of relations with public administration and control bodies	General contractor
Management of relations with the local community	Project manager
Logistics (transport and storage of materials)	Works supervisor
Construction site waste management	Labor
Vehicles maintenance	Tradesmen
Procurement / supplier management	H&S supervisor
Management of subcontractors	Subcontractors
Personnel management	Suppliers
Accounting	Designer
Activity scheduling	Local communities
Production	Public authority
Relations with the client / design group	Utility companies
Worker H&S management	Control bodies
Connections and utilities of the construction yard	Technical tester
Surveillance	Energy certifier
Documents management	

Indeed, traditional CM methods are now growing inadequate to contemporary objectives of productivity, as they are marred by human error vulnerability and overall inefficiency. And because they are manually run, they require more time and manpower resources to operate, diverting a bigger portion of the budget on accomplishing tasks that could otherwise be automated.

Currently, project monitoring in the construction industry often consists of little more than post hoc documenting of the cost overruns and construction delays. Instead, supervision should be real-time and forward-looking, in order to provide timely data that can immediately be translated into action to mitigate or anticipate incoming problems.

Each of the disciplines on-site should be monitored by specific Key Performance Indicators (KPIs), that cover safety, schedule, cost, and quality and are maintained in a central shared repository where they can be clearly consulted. This way, outcomes can be visible in a timely manner and with an appropriate level of detail, enabling to establish “plan-do-check-act” processes. For each discipline, regular meetings should take place in which engineers and supervisors analyze KPIs and discuss where change is needed ([Stanitsas, Kirytopoulos, & Leopoulos, 2021](#)).

Building information modeling (BIM) can play an essential part in structuring CM activities, as it comprises the graphical model of the asset as well as information on construction sequences over time (4D BIM) and information on costs (5D BIM), which provide the baseline for works programming and monitoring ([Demirkesen and Ozorhon, 2017](#); [Souad and Lalimi, 2021](#)).

Furthermore, digital measuring and monitoring devices allow companies to track construction processes and activities more rigorously and safely. Regular LiDAR scanning and 3D photo reconstruction can be performed manually or automated with drones and robots to compare as-built structures to the as-designed model, identify any deviations in a timely manner and minimize corrective reworks. Drones and remote cameras can survey construction sites, while IoT systems transmit data on multiple machine parameters, such as fuel consumption, for optimized fleet management, or on workers to monitor their safety and activities. By exploiting 5 G mobile connectivity and augmented reality (AR), companies can engage in real-time communication with on-site workers to provide information and instructions and retrieve progress updates.

Finally, advanced analytics can be applied to these data to optimize the assignment of construction staff and equipment, to further enhance decision making, identify and eliminate waste, and to predict where bottlenecks and other issues are more likely to occur.

9.1.1 Construction management software

Available CM software tools were developed with the purpose of simplifying the crucial aspects involved in accomplishing construction projects, such as time and delivery, project cost, and quality of service via process automation.

Created specifically for contractors and construction companies, these programs are designed to control every stage and constraints of the construction works—planning, project cost estimation, field service management, decision making, conflict resolution, risk analysis, etc. They take the role of automating traditionally manual tasks, including monitoring the progress of a project, creating a centralized communication and collaboration space for the members of the team, resource planning, keeping track of client requests, etc. (Okudan et al., 2021).

From an operative point of view, CM programs can create a single window of visibility for all stakeholders, from field workers up through CEOs, making it easier to track project expenditures, address critical issues when they occur, and mitigate work delays due to unforeseen errors. Managers can assign projects and tasks to workers seamlessly, letting everyone know their daily tasks in advance and eliminating the possibility of confusion, and can be also automatically notified when a milestone is unmet or a task is not completed by the set deadline.

Currently, there are over 200 applications of this type, with many equipped with additional functions such as customer and portfolio management and accounting features, and more and more construction businesses and professionals are now gradually recognizing their benefits.

CM solutions are mainly cloud-based, which enhances the accessibility of their features and improves overall project visibility. This is particularly helpful when operating in an on-site environment. With this type of technology, construction professionals can have easier access to and control of the different aspects of a project, such as orders and purchases, equipment and other resources, documentations, job costing, project timeline, and more. Contractors, builders, and construction business owners can log in to check various job sites without having to travel to each one, looking at the financials and seeing photos and video feeds of the progress of each site. They can communicate with clients on the software and show them real-time progress reports.

Cloud-based collaboration in the context of project management for construction has great potential. Benefits include the elimination of latency and the provision of real-time information from the site to the head office, the prevention of data entry duplicates leading to significant productivity loss, as well as the ability to collate information across projects to provide data-driven analytics on various KPIs, overall improving the reliability of project delivery within time and budget.

Specific features of different CM software may vary, but they normally include some of the following core features:

- project management;
- scheduling tools including staff and production calendars;
- quality and safety management;
- accounting and financial tools;
- workforce management;
- budget tracking and job cost accounting;
- inventory and equipment management;
- real-time progress reports;
- project performance dashboard;
- document management and progress photo capture;
- real-time communication for employees;
- bid management and capital planning;
- contract management.

Main CM software on the market include AccuLynx, BIM 360, Bluebeam, Buildertrend, BuildPro, CMIC, CoConstruct, ComputerEase, ConstructionOnline, Contractor Foreman, e-Builder Enterprise, eSUB Subcontractor Software, FOUNDATION, HCSS Heavy Job, JobNimbus, Knowify, PlanGrid, Plexxis, Procore, ProjectSight, Projul, Prolog, Quick Base, RAKEN, RedTeam, Sage 300 Construction and Real Estate, VPO, ViewPoint Team, and many others. Each of these tools usually focuses on a specific area, and often offers integration with other relevant applications; therefore, finding a single program that provides all required features may be difficult.

Following the digital progress that is evolving the construction sector, CM software is expanding its functionality towards the following main converging directions:

- *Interoperability*: ability of tools to communicate with different software using standardized interfaces and processes;
- *BIM integration*: integration with project CAD drawings and 3D BIM models for virtual inspection, design review and quantity take-off;
- *Virtual design and construction*: making use of the virtual information and metrics that are generated both in the BIM model and in the production processes for real-time simulation and visualization of construction schedule (4D) and costs (5D);

- *Real time data collection*: direct real-time connection with imaging tools and IoT devices for the collection of data from the construction site and the automatic measurement of the construction progress using 4D BIM associated with remote sensing and 3D point clouds;
- *AI and augmented analytics*: exploitation of artificial intelligence (AI) and machine learning (ML) for advanced analytics, management optimization and improved forecasting (AI, Big Data and augmented analytics).

In particular, AI-based software is greatly augmenting latest CM tools, and most advanced systems already integrate advanced data analytics and AI capabilities to not only collect data from multiple sources in real time, but also provide valuable business insights. Built-in ML and AI capabilities help top-level managers understand issues in their process, look for better approaches, and improve tasks such as manpower logs, project billing, and job estimation.

Another turnkey innovation in CM is constituted by wearable devices, which are seeing increasing adoption by more and more contractors. These wearables (e.g., smart glasses, jackets, and sensors attached to worker suits) help collect data on workers' activity and status, which is shared with CM software in real time to analyze working conditions and measure staff performance to minimize downtime, check equipment availability, avoid risky workflows, ensure worker safety, and more.

9.1.2 Virtual design and construction

The most useful innovation of latest CM software (Autodesk BIM 360, TeamSystem Construction Project Management, Procore BIM, Trimble ProjectSight, Nadhi nPulse, Bentley Synchro) is represented by their integration with the BIM model of the project to allow virtual inspection, design review, quantity take off, planning and management of the sequence of processes, execution times (4D), as well as construction costs and proceeds (5D).

This integration allows to apply what is called Virtual Design and Construction approach (VDC), in which all the virtual information and metrics that are generated both in the BIM model and in the construction works can converge in the decision-making process (Aslam, Ga, & Smith, 2021).

VDC concept, first developed by Stanford University's Center for integrated Facility Engineering (CIFE) in 2001, allows several multidisciplinary parties to collaborate in a virtual environment, providing everyone with the most up-to-date design information and enhancing off-site coordination allowing architects, engineers, and contractors to analyze construction plans from start to finish before breaking ground. VDC takes place in integrated concurrent engineering sessions, in which the different teams carry out simultaneous design work aided by collaborative real-time display technology. Participants use projectors and large touch screens to share BIM models and project data on which to analyze problems and discuss solutions on the spot.

VDC technology uses 3D BIM models and other information to digitally plan out all aspects of a construction project—from estimating costs to scheduling and risk management—allowing to build a project virtually then track construction progress, optimize processes, minimize waste, and validate installations on that benchmark.

When applied properly, VDC can help reduce costs and time of construction, from delivering more accurate preconstruction cost analysis to optimized detailing for more accurate bids and estimates. Preconstruction modeling and visualization helps allocating proper funding to important construction aspects and eliminating field errors, as well as identifying and assessing safety concerns to timely reduce hazards.

In order to implement VDC, a BIM model with a level of development (LOD) of 400 is required, so-called 4D-ready or Ready for Construction model. At this LOD, models include specific system information, and all building elements are modeled with the necessary level of detail and accuracy for their fabrication (see Section 4.2.2). The model contains graphic and nongraphic information that will guide the fabrication, assembly, and installation processes. Prefabrication sheets and cutting lists can be derived from the model and components can be ordered. A model at this LOD level is ready for construction and fabrication. LOD 400 is typically relevant to the work of facade detailers, quantity surveyors, purchasing and cost control accountants, project managers, crane suppliers, site safety consultants, steel detailers, roofing contractors, quality controllers, erection teams, project schedulers, carpenters, formwork contractors, concrete contractors, window manufacturers, MEP manufacturers and installers, and lighting suppliers.

9.1.2.1 Model-based design construction review and remote site observation

The integration of BIM in CM allows access at any time and from any place to the project documents for consultation and verification of information, to perform measurements on drawings or models to support quantification and constructability, to communicate with the team by adding photos, graphic or text markups to sheets and models, and to create and assign tickets and requests for information (RFI) to resolve project errors or omissions. In particular, RFI management is recognized as an important factor of a project's turnout, with more successful projects usually

characterized by the right prioritization of closing more critical RFIs faster. By using systems like BIM360, Procore, Structionsite, Holobuilder, and Openspace, actionable building observations can be shared across devices.

Advanced functionalities such as RFI Risk Factor Card in BIM360 leverage ML to analyze and identify RFIs and classify root causes in categories such as High-risk RFIs that pose the greatest risks to costs or schedule, MEP and Structural RFIs, or RFIs with a root cause in design coordination, in documentation errors or in code compliance. An effective RFI management tool allows to prioritize which RFIs need action, catching design issues and risks earlier and preventing downstream rework, safety issues, and permit hurdles. Additional benefits can be found when leveraging RFI Risk Factor Cards across multiple projects: based on observed trends, project managers can make decisions proactively and lower the number of RFIs on future projects even before the problems arise.

Advanced project management software also allow virtual walk-throughs that can be annotated with observations that can be tagged to existing or new RFIs, eliminating the need to walk the site, take photos, label them manually, create a report referring to RFIs and meeting notes in separate documents, and send it to all stakeholders, with the risk of losing the possibility to track down problems if any part of this process falls through.

Holobuilder, Structionsite and Openspace tools allow to create and share 360° views of the building over time passively via hardhat-attached hardware, documenting construction progress in easily viewable photos and creating as-built conditions for project handoff. They can be integrated with BIM 360 for remote side-by-side comparisons between the digital model and as-built conditions through the same cloud interface (see [Figs. 9.1, 9.2 and 9.3](#)).

9.1.2.2 Quantity take-off

The integration with BIM also enables the automated extraction from the as-planned and as-built models of the quantities of the different materials, divided by type, for the rapid processing of highly accurate metric estimates at any stage



FIGURE 9.1 Tool-assisted 360° survey of construction site. *Courtesy of Structionsite.*

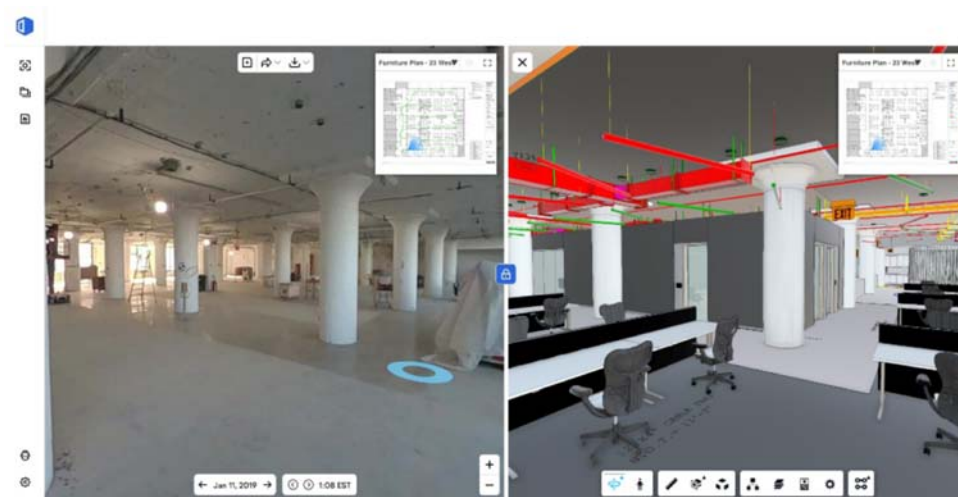


FIGURE 9.2 Comparison between 360° photo from site and BIM design model. *Credit: Openspace.*



FIGURE 9.3 Multidevice system for progress tracking. *Courtesy of Holobuilder.*

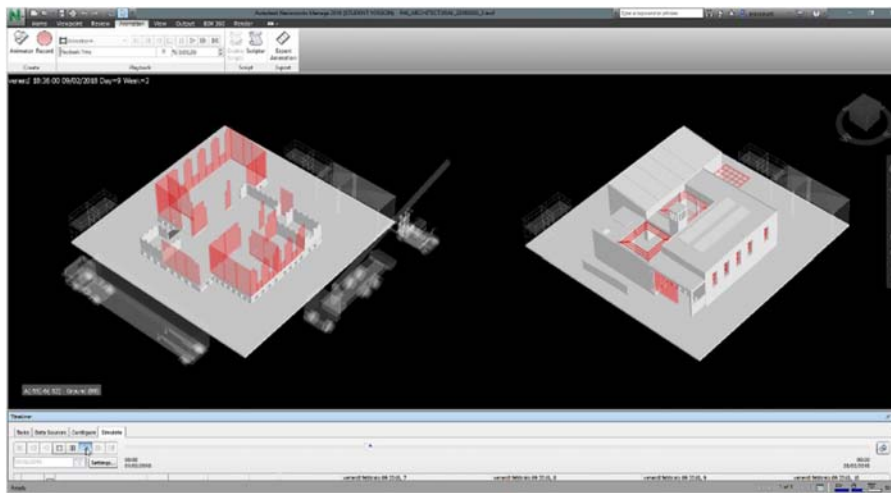


FIGURE 9.4 4D scheduling of assembly with Navisworks. *Image by the author.*

of processing (quantity take-off). This allows to determine precise measurements for each article of metric, directly calculated from the quantitative properties of objects drawn in the architectural, structural, and plant models of a project. This way, metrics are certain as they derive directly from the BIM design and, in case of drawing revisions, they can be automatically updated with the new measurements. It is also possible to set computation rules based on categories and object families to optimize metric metering. By linking pricelists to object families, it is possible to determine at the same time the value of each element of the project, in addition to the whole work.

9.1.2.3 4D simulations

4D work scheduling modules such as Navisworks (see Fig. 9.4), Synchro Pro and Fuzor (see Fig. 9.5), allow to animate and interact with objects to show project's assembly, operation, disassembly, and link these simulations to the construction schedule. It is possible to create a 3D animation of the construction work and visualize its completion status moment by moment highlighting the objects created or still under construction, checking each operation and moving back and forth in time. At each moment of the animation, it is also possible to select a specific activity or Work-Breakdown Structure (WBS) of the Gantt and view the respective objects in the 3D model, or in turn select one or more objects from the model and view the related activities or WBS, adding or reducing resources or quickly making changes to optimize the schedule. The module also provides integration with the most common project management software (Microsoft Project, Oracle Primavera P6) as well as the ability to export a Gantt chart in a interoperable format.

The 4D model helps identifying errors and missing information in the plan and optimizing the construction schedule. Works animation allows to identify in advance any interference between moving objects. For example, a crane that passes through a building while turning, a truck that collides with a work group, and other potential hazards (clash detection) (see Fig. 9.6) (Li, Xu, & Zhang, 2017).

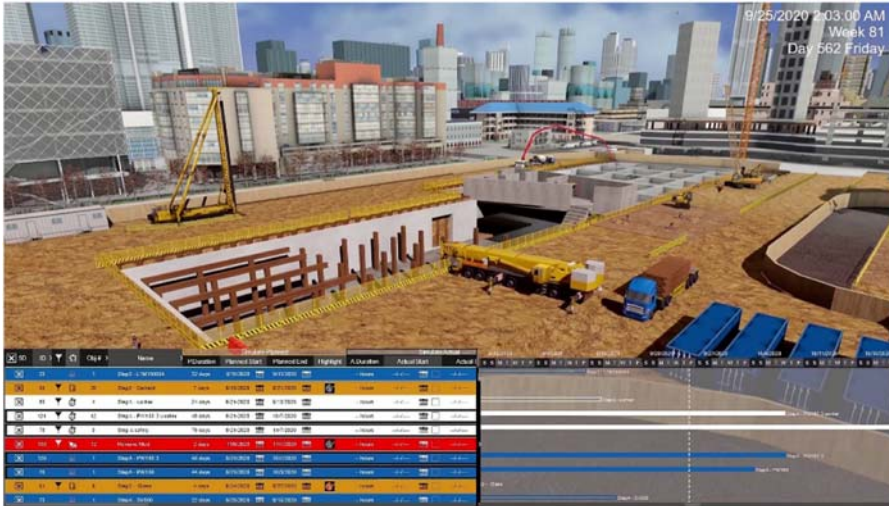


FIGURE 9.5 4D simulation of construction site with Fuzor. *Courtesy of Kallos Studios, Inc.*



FIGURE 9.6 Simulation of construction activities with Fuzor. *Courtesy of Kallos Studios, Inc.*

It also improves the communication of the plan to the entire construction team. Overall, main advantages of 4D modeling include improved visualization and mental interpretation of the schedule; identification of potential conflicts of space and time during construction; support in placing equipment, construction site elements and resources for planning analysis; support in the sequencing and optimization of work rates; visualization of possible disruption caused by changes in planning; improved integration and communication between all project stakeholders (Brito and Ferreira, 2015; Jupp, 2017; Tak, Taghaddos, Mousaei, Bolourani, & Hermann, 2021).

9.1.2.4 5D simulations

The 5D CM modules, along with works animations and the Gantt chart of the project, allow a contextual display of the cost and revenue curves of the project, allowing to manage and track all relevant technical and economic information in both predictions and final reports (Jiang Xu, 2017).

Through price and cost analysis, it is possible to generate interactive budget views for the project's WBSs and create advanced business intelligence reports.

Project and costs (5D) monitoring therefore allows the so-called operational control from a management point of view, to define works timing, budget, financial performance, and the list of requirements for supplying (Smith, 2016).

Through a 5D BIM management software, it is possible to quickly assess needs based on product categories, planned quantities, costs, times and quantities ordered, and submit purchase requests directly from administrative management. Through the concept of earned value management, 5D digital models can calculate and visualize performance metrics such as the schedule performance index and the cost performance index, allowing managers to understand why and where they are spending too much or where they are behind schedule. In terms of times, other "earned" based methods can also be used such the "earned scheduled" concept, which make it possible to keep delays under control in a more precise manner.

Moreover, 5D allows to optimize productivity by efficiently managing employee schedules and properly allocating them across different tasks, forecasting labor requirements and make adjustments accordingly. Furthermore, it is possible to check equipment availability and keep track of which equipment is needed and deployed to different work sites, also taking care of scheduling periodic equipment checks for maintenance purposes.

Works' execution can also benefit from advanced CM techniques such as the lean construction (LC) paradigm, which can help to optimize the replanning carried out "just in time" (week by week) through the LPS (last planner system) or to facilitate, for example, the lay-in of semfinished products in several points of the same structure on the same day relying on the LBS (location-based system). By leveraging AI analytics, finally, is possible to predict and prevent costly design issues relating to code compliance, building components, or document errors as well as view any overdue RFIs or reviews.

9.1.3 BIM and lean construction

The concept of lean production, or lean manufacturing was originally applied in the automotive industry starting from the middle of the last century as a management approach aimed at eliminating waste and diseconomies, identified in particular in a series of critical issues, including activities that do not produce value, logistical inefficiencies, excess waste and rework, downtime, and excess of stock and production. In this context, the solution was identified in five guiding principles: definition of value for the customer, elimination of waste, uninterrupted flow of activities, execution of activities only when required by the process and continuous improvement of processes and products.

As the construction and manufacturing industries became more closely integrated, these lean paradigms began to make their way into construction operations, processes, and projects as well. LC is defined as a "respect-and-relationship-oriented production management-based approach to project delivery—a new and transformational way to design and build capital facilities" (Seed, 2017). After determining a substantial leap forward in manufacturing design, supply, and assembly, lean production management, applied to building or infrastructure design, supply, and construction, is currently changing how work is done throughout the project-delivery process.

The LC approach has proven able to increase projects successfully delivered on time and in budget, as well as stakeholder satisfaction and the construction firm's reputation, due to higher productivity rates and employee engagement. By involving employees in the project right from the start, they can better understand their contribution to its success and can also define the environment that allows them to work in a more productive way.

Although benefits achievable from LC methodology vary based on application, current state of operations, company size, and even location, the most notable include: higher quality of output and operations, enhanced safety and reduced risks, greater cost control, improved planning and scheduling and higher customer and employee satisfaction (see table 9.2). Furthermore, lean concepts such as using less resources, improving quality and reducing rework, waste, energy/water consumption and pollution costs constitute a basis for improving sustainability as well, and conversely most sustainable practices already support a variety of lean transformation objectives (Aslam et al., 2021).

Standardizing building processes following LC techniques allows to increase productivity and create cost savings through collaboration. Studies show that collaborative contractual relationships result in up to 9% improvement in

TABLE 9.2 Main benefits achievable from LC methodology (Autodesk, 2021).

Quality • Reduced rework during construction • Reduced disputes between stakeholders • Reduced number of design issues onsite	Schedule • Reduced delays • Improved plan to actual ratio for fewer scheduling conflicts • Improved schedule control • Improved resource planning and coordination
Safety • Reduced total number of workers onsite that could experience an accident • Reduced incident frequency rate by minimizing mistakes through both automated and manual review	Winning more work • Increased number of successful projects • Improved stakeholder engagement at all levels
Cost • Improved plan to actual ratios to reduce wasted labor and materials • Improved cost control for higher profit margins	Environment • Reduce wastes • Resource conservation

productivity and a up to 7% improvement in cost savings (when compared to more traditional contractual structures) (McKinsey, 2017).

LC methods empower teams to monitor progress, identify potential risks, and mitigate them as quickly as possible, thereby reducing overall business risks by involving decision-makers to address any issue quickly before it has lasting effects on the project. Both manual and automated review techniques are also leveraged to reduce incident frequency rates. The reduction in waste increases project efficiency and entails higher profit margins. Moreover, downtime waiting for materials, equipment and information can be reduced by purging inefficiencies from processes. A solution to prevent material waste and maximize the use of all materials is a higher emphasis on prefabrication.

Such methodology is based on collaboration and accountability. In an industry where adversarial relationships between owners, designers and contractors are routine, LC requires all stakeholders to align with goals and objectives, place great trust in each other and engage in a cooperative relationship. In LC, the whole project team uses collaborative processes, tools, and technology to uncover ways to add value, continuously improve, and eliminate waste.

Indeed, communications between construction crews and contractors often take place late in the building process and end up less effective than they could have been at an earlier date. LC addresses this challenge by selecting contractors by the insights and feedback they can provide during the combined design-build stages, rather than just on a cost basis.

Currently, only about half of global contractors had a moderate or better familiarity with this LC process (Autodesk, 2021). Typically, planning processes in the construction industry are linear: they start with design and preconstruction and adjust timeframes continuously as issues develop during the process. Such planning method, although popular in the industry, has significant downsides and often leads to reworks, poor profit margins, obstacles, employee burnout, and low productivity.

In particular, one of the biggest causes of productivity loss is the inefficient scheduling of workers. Employees often end up working in a congested area where they cannot perform tasks efficiently or in a space that is not available. Such conflicts can be addressed by employing pull-planning practices, that is, having every key stakeholder on a project collaboratively start with the end goal and work backward milestone by milestone toward the start date. As schedules are planned backward to meet the final deadline, potential problems can be identified and solved ahead of time. Project team members begin by defining the final deadline for the project, then they work backward to set key milestones, deadlines, project phases, and handoffs. This allows to prioritize critical tasks and uncover any dependencies between tasks. Weekly planning sessions and meetings are schedule to monitor deadlines and discover any potential risks for going over schedules and budgets.

The objective of LC is to remove all nonvalue adding processes in the system. Time is one of the scarcest and most valuable resources; therefore, time wastages should be among the first subject of optimization. At large, any activity in the chain which adds no value can at that point be considered as a time-wasting activity. To achieve cost reductions without affecting quality, construction companies shall reduce the overall amount of time spent on site. Main sources where time wastages normally occur include:

- overproduction of more goods than can be utilized or required;
- waiting for required resources that are not available at the moment;
- construction defects that require reworks;
- inappropriate processing, use of inadequate techniques or lack of clarity;
- excessive transportation and unnecessary motion, for example, placing material storage far away from work stations;
- unnecessary inventory that requires additional space and handling.

Optimization of these time-wasting activities should start with the early design and planning stage, all through construction and until project handover. Lean principles in construction entail that each tasks is assigned the required resources with no under or over utilization issues.

Different LC techniques can be applied to the production system flow, for example, looking to ensure simplification of the systems, using parallel processing whereby more than one task can be carried out simultaneously, and using reliable technology. Common LC methodologies include: Just in time (JIT) approach, concurrent engineering, and LPS.

The JIT approach ensures availability of resources on construction sites at the right time for application or usage, instead of arriving prior to the required time or later, with the objective of removing wait times in construction. For instance, JIT delivery for precast concrete on site is often critical in the saving of time on a project and thus should be implemented well in the planning of the construction process. A method to achieve JIT and maintain the flow in construction with no need of inventory is the Kanban system. In this system, when materials are need on site from an away location, the need is transmitted through a signal that tells a supplier to produce and deliver a new shipment. This signal

is tracked through the replenishment cycle via RFID and barcode readers, bringing visibility to the supplier, consumer, and buyer. JIT and Kanban systems are particularly convenient in cases where the material is made off site and therefore prefabricated and then delivered to site.

Concurrent engineering seeks to shorten the cycle times of delivering the project through a thorough understanding of the client's needs, forming capable teams that can carry out parallel design of the required assignment with adequate communication between them. On site, working in parallel reduces the total time needed in the construction.

Another major application of LC into the construction industry, LPS has proven to form a well-coordinated organization of the flow of tasks throughout the whole process all before the actual work starts, also spelling out how the system will be controlled in case of distractions in the flow (Uusitalo, Seppänen, Lappalainen, Peltokorpi, & Olivieri, 2019).

In LPS, the calculation of the duration of the activities to be carried out is based on the ability of the teams (the last planner) to carry out that job. Therefore, instead of having the site manager deciding how long an activity should last, it is the team leader of each specific team who communicates how long it takes to perform that specific activity. LPS aims to optimize resources available to perform a specific task in response to the needs of the resources themselves. LPS is commonly based on the following 4 planning levels:

- the master pull schedule, which represents the general view of the work plan, with the main work phases and milestones, and defines what should be done in that time frame;
- the look-ahead schedule, which based on a duration of 4–5 weeks and is used to control how the workflow is progressing and defines what can actually be done;
- the weekly work planning (WWP), which defines what will be carried out the following week and is updated weekly on the basis of the meetings between the project manager and contractors and tradesmen;
- the daily plan (if necessary), useful for projects that use a lot of prefabricated material of which it is necessary to know precisely when this must be supplied and therefore also manufactured.

LPS also includes a monitoring phase to identify eventual planning issues and initiate a continuous improvement process. The percent plan complete (PPC) indicator, computed as the ratio between the number of activities completed and the number of activities scheduled in a specific week, is used to track how many assignments have been 100% completed. Teams can review PPC trends, progress, and risks during weekly work planning sessions to reduce delays, wasted resources, and missed deadlines. Whenever a scheduled task is not completed, a reason for noncompletion should be provided, which is analyzed by the foremen involved to understand its causes and to apply improvement actions (root cause analysis—RCA).

Main characteristics that define LPS include:

- reliability of production, as day-to-day production is linked to expected delivery;
- improved collaboration between different teams and disciplines part of the project;
- the use of pull scheduling to provide workers with right information at right time when they are ready to be done, for example, starting ceilings works after the necessary systems works have been completed;
- tasks made ready, to identify when the teams can start the task without any constraint;
- PPC to track progress on what was planned;
- RCA to determine the cause of the deviation from planned and eliminate root cause so it is not repeated;
- different levels of schedule that is master schedule, look ahead plan, and WWP.

Considering all the above, it is quite clear that the principles and processes underlying LC are not only compatible with the use of BIM, but BIM is the most valid and effective tool to pursue them. Indeed, BIM has proven to support project and construction processes by eliminating conflicts and reducing rework, visualizing, and coordinating different disciplines, avoiding errors and omissions, improving productivity, supporting scheduling, safety, costs and quality management. Due to its parametric and automated nature, BIM also supports more complex components and calculation, thereby easing sustainable assessment processes and enabling a more consistent decision-making process at early stages.

Integrating BIM processes in construction ensure that information is passed on thoroughly from the designers to the constructors, and to owners and operators afterwards, and facilitates participation of all the actors since the early design phase to ensure better collaboration between the different stakeholders and an integrated project delivery. BIM ensures the availability of all information to the required team members, including any information about changes that may be made, eliminating the possibility of reworks caused by misinformation. 3D BIM visualizations of the possible design solutions provide the entire team with a clear understanding in the design, including those without technical background

but still part of the project team, such as clients and future operators, allowing them to communicate with each other in a clear way with less chances of misunderstandings (Heigermoser, de Soto, Abbott, & Chua, 2019).

In addition to the established advantages of using BIM in the design phase, the integration of BIM model with CM software during the construction phase allows a VDC, eventually powered by extended reality technologies, which allows virtual inspection, design review, quantity take off, planning and management of the sequence of processes and times (4D BIM), as well as construction costs and proceeds (5D BIM). This entails substantial benefits in terms of team collaboration, lowering of construction costs, reduction of time wasting, variations control, creation of continuous workflows, and overall productivity. Moreover, the live and active BIM interface improves process transparency and understandability, and constitutes an integrated working platform to allow correct materials and accurate components to be produced throughout the project life cycle and eliminate production and environmental waste, reduce energy use, transport emissions, and resource depletion.

Although interest in the alignment of BIM technologies and lean management philosophy is growing, most organizations and companies are still at the beginning of the learning curve. Parallel adoption of both LC and BIM is particularly promising, as it provides better visualization of processes, clear communication and fast information flow, minimization of risks, maintenance and human error and supports informed decision making. LC methods related to waste elimination, value stream establishment, flow encouragement as well as pull production could be used in a complementary way with BIM. However, BIM based LC tools require experienced, trained and engaged stakeholders, integrated and constantly up-to-date interoperable information systems, investment in equipment and technologies, and user-friendly interfaces.

Nonetheless, a deep understanding of all facets of production is necessary to fully achieve the benefits of BIM-LC integration and the link between BIM functionalities and lean construction principles must be taken in small steps. To reach a higher step, the construction industry as a whole should invest in knowledge management through holistic education, training, research and innovation focused on technical and technological skills about greener solutions, LC and BIM.

9.1.4 Construction site digital twin

A promising innovation for CM is constituted by the use of BIM information and image data from the yard to build an actual digital twin model of the construction site, that is, a digital representation of the physical object and all its processes and elements that is updated in real time by feeding on user input, sensors and monitoring devices (see [Section 11.4](#)). Digital twins have seen extensive application in industrial design, manufacturing, maintenance, and operation, where a real-world object is linked to its digital representation that is continuously using data from sensors located on a physical object to establish the representation of the virtual object. This truthful digital representation can be used for visualization, modeling, analysis, simulation, and further planning, triggering the feedback loop of decisions and changes in workflows that influence the control processes of the real object system.

Applied to CM, a digital twin of the building under construction allows access to both as-built and as-designed models, which are constantly synced in real-time enabling project teams to continuously monitor progress as well as make decisions based on forward simulation of different paths of actions.

An accurate digital twin of the ongoing construction yard can be reconstructed by using multimodal sensor data from the site and AI algorithms based on computer vision and deep neural ML. These tools are fed with data coming from the various type of sensors that are increasingly present in the construction site, from standard photo and video cameras to drones, wearable devices, laser scanners (LiDARs), radars, and thermal imaging tools. In particular, daily construction photographs taken by workers' and inspectors' smartphones can have enough resolution and quality to reconstruct the built environment as well as to track personnel, equipment and material over the construction site. Time-lapse cameras, CCTV and webcams, more and more present in modern construction sites, also provide a valuable source for progress tracking and work comparison. Wearable devices such as head- or body-mounted cameras are also gaining traction in jobsites and can provide an exceptional, diffused point of view on ongoing works. Lastly, construction managers can take advantage of drones and robots to carry out automated visual inspections of both interior and exterior spaces, usually combined with data management platforms which can perform surveying, mapping, 3D reconstruction, as well as take volumetric measurements using imaging, thermal and radar sensors (see [Chapter 8](#)).

All these raw image data have to be processed and organized in order to extract the knowledge needed to build, populate, and update the digital twin of the construction site. A high rate of generated data demands an even higher rate of data processing and fully automated pipelines, which are now possible due to the advancements in computing power, graphics processing units (GPUs), extensive datasets, and deep machine learning algorithms also spurred by the

research and development activities focused on self-driving vehicles technology. Images taken from vantage points such as cranes or drones can be simply aligned, corrected and stitched together to obtain valuable photogrammetry data, whereas ground-based images are processed together via structure from motion (SfM) algorithms to produce accurate point clouds to allow 3D reconstruction. AI engines, trained with ML, then analyze images to track location, speed and dynamics of distinct elements and persons on site via object recognition and face recognition algorithms. Finally, LiDAR equipped drones and robots can perform analysis of the construction site by 3D scanning their surrounding environment and keeping track of their position via simultaneous localization and mapping (SLAM), in order to accurately pinpoint objects in a coordinated space.

Once constructed and populated with the required data, the digital twin model can be shared, inspected and manipulated in ways impossible with its real-world counterpart. The as-built state of a building or structure can be compared with the as-planned execution in 4D BIM to identify any deviations and take corresponding corrective actions. This is usually done by reconstructing geometry of a building, mostly as 3D point clouds from LiDAR or 3D photogrammetry, uploading it as IFC files in a BIM cloud environment, then registering it to the model coordinate systems. The IFC file can also be enriched with the event log of the operations carried out in the construction site contextually. The prepared IFC and event log associated with day-to-day operations in the construction phase can be compared to an as-planned model on both the shape and object levels to check works progress and quality. More interestingly, both geometry and event data can be investigated with data mining and ML tools to extract useful insights, assess workers' productivity, discover bottlenecks (Pan and Zhang, 2021a).

The current state of the building can be used for predictive control of operations based on multiple simulations that analyze different paths of actions and estimate their probabilities and cost to identify the most optimal decision for what to do next, as well as preparing what-if scenarios to simulate possible outcomes and prepare accordingly. Changes in the as-built model can be tracked weekly, daily, and even hourly, allowing the earliest detection of any discrepancy to minimize the need for reworks or remedies that would be expensive to apply later on. If needed, it is easy to perform detailed analysis of historical modeling data, which adds an additional layer of information for any further decision-making processes: the course of action that led to the errors can be reconstructed and the future work schedule can be tweaked to prevent repetition.

Moreover, an accurate digital twin enables automatic resource allocation monitoring and waste tracking, allowing for a predictive and lean approach to resource management. It is also possible to know how many times each piece of equipment or machinery has been used, in what part of the construction site, and on what type of work, allowing a more rational management and sooner release of unused tools that may be needed in other sites.

The digital twin is finally complete with presence and whereabouts of workers and personnel, allowing to keep a digital record of presence and position of labor, identified by face recognition algorithms and double-checked with entry and exit registration systems. Workers can be monitored and tracked to ease their rescue in case of accidents, to prevent them from wandering into dangerous areas, and to monitor interpersonal interactions to track possible spread of diseases.

9.1.5 Smart contracts and blockchain

Although most new technologies in the construction industry, as well as advanced processes like BIM, aim to improve profitability of construction projects by increasing their productivity, a still neglected core area which can provide immediate improvement is the automation or reduction of administrative and/or financial processes in construction. The construction sector has in fact several issues regarding its reputation, such as a lack of trust, being unfair to subcontractors, and a slow rate of change in comparison with other industries. Transactions between all actors involved in construction therefore still rely on a network of intermediaries, middlemen and women, and go-betweens whose job is to verify and vouch that the other party is trustworthy by gathering information and developing professional networks (Dakhli, Lafhaj, & Mossman, 2019).

Nonetheless, this industry is filled with legal disputes that result from a wide range of issues such as ambiguity in the terms of the contract, late payments, late or underperforming handover of work, etc. (Shojaei, Flood, Moud, Hatami, & Zhang 2020). One of the suggested major factors of this stalemate has been regulations which have led to companies focusing not on increased productivity, but rather on streamlining compliance and satisfaction of legislation. Although much of this regulation has been to the benefit of worker safety and security, it still diverts time and budget from productivity increases to achieve quicker construction for a lower cost.

Smart contracts are one of the proposed solutions to streamline the current financial/legal environment of the construction industry. The term "smart contract" was coined by Nick Szabo in 1994 and is defined as a computer program

that secures, enforces, and executes the settlement of recorded agreements between people and organizations with an if/then structure which administers the contract clauses (Mohanta, Panda, & Jena, 2018). As such, it is tasked with negotiating and defining these agreements. Once a party executes its tasks, it asks for inspection, and upon verification, a payment is automatically issued. The advantages of such a system are its clarity and enforceability, which may result in smoother contract execution and a significant reduction in disputes. The general objectives of smart contract design are to satisfy common contractual conditionals (such as payment terms, liens, confidentiality, and even enforcement), and minimize the need for intermediaries. Related economic goals include lowering fraud loss, arbitration and enforcement costs, and other transaction costs.

Due to the lack of flexibility in smart contracts, the technology's scalability still poses a significant challenge in their application in construction. Also, because of the numerous uncertainties inherent in construction projects, smart contracts in their current state are not perceived as suitable for complex contracts yet. Furthermore, smart contracts, as proposed today, are of short-term execution and of instantaneous effect, which is at odds with the complex and long running nature of construction projects (Sawhney, Riley, & Irizarry, 2020). Nevertheless, smart contracts for construction purposes have been considered concerning various components including the automation of contract, the execution, programming, payment, and certification. In this picture, BIM, due to its data-intensive nature and the level of details presented in an appropriate model, is considered an excellent way to tie different sections of the construction work to a smart contract. In a BIM process, the model itself can act as the contract between the owner, the General Contractor (GC) and the subcontractors. The physical construction needs to match the contractual BIM model. If it deviates from the model, the contractor may be asked to return and fix it. If, on the other hand, the model has clashes or errors, the contractor could raise a change order. Contractors get paid upon confirmation of completed work, which is usually verified by consultants or the GC by confirming measurements and comparison to the BIM model.

BIM integration is, however, difficult to apply to the payment phase, in which enforcement of trust is still challenging throughout the construction industry due to a perceived lack of reliability and security of the model against its real-world counterpart. Normally, project milestones are negotiated between the GC and the client during bid and construction planning, to determine the points in which further funds are released: along the works progression, the client would receive verifications from consultants checking that the milestone has been achieved, inform finance and issue the payment. More granular milestones are also held by the responsible subcontractors to the GC, with a similar process occurring when they attain these completions. It is apparent that this process of payment management is time-consuming, expensive and requires considerable paperwork. Furthermore, project completion and budget spent can only be deduced from ledgers and payment registrations instead of being tied to the project BIM model.

One way to ensure trust among all parties is by integrating blockchain technology in construction smart contracts based on BIM. Blockchain is a database technology that provides smart and coded schemes to verify and store transactions throughout chains of communications. Blockchain is a distributed ledger technology (DLT), which is a database of transactions which are copied on many nodes of the network and regularly synchronized, keeping the system up to date at all times, instead of being kept on a single server as a centralized ledger or database would. Records in a blockchain are called "blocks," with each block containing a timestamp, transaction data, and a cryptographic hash of the previous block, therefore forming the "chain" so that when changes are made to a block, the whole blockchain is kept in synch and each user's copy of the blockchain is updated in real time (Marr, 2020). The decentralized nature of blockchain also means data can be verified by user consensus, in a peer-to-peer system, rather than being processed and controlled by one central administrator which is inherently vulnerable to errors, attacks, or malicious practices. Involved parties can only access the information stored in blocks and edit parts of the blockchain by possessing the cryptography key needed to alter the file, with each change permanently recorded. A blockchain network is therefore secure as it uses cryptography to store and transfer all the transactions throughout its decentralized network and the data is tamper proof due to the consensus system and chain-like data sequence.

Each block of information is stored in thousands of nodes, essentially making it impossible to change or modify it without alerting the rest of the network, ensuring permanence and immutability of all stored data. These qualities make blockchain an ideal choice to ensure streamlined and productive cooperation via smart contracts among all stakeholders, as it is ultra-secure, decentralized, immutable, transparent, neutral, traceable, and open source.

By using the blockchain infrastructure, the contractual BIM model, the as-built model and the virtual wallets of client, GC and subcontractors can be linked in a trusted, transparent, secure, and automated network in which every change, modification and transaction is shared and kept in a tamper proof record. Whenever a work is performed and updated to the as-built BIM model or to the in-progress digital twin, the blockchain network automatically signals the finished operation, generates the invoice and triggers the money transaction from the client to the GC virtual wallet, or from the GC to the subcontractor or supplier, effectively enforcing the smart contract that was agreed upon by pulling

trusted, transparent data from the DLT. The absolute reliability of data means that it does not need to be checked by intermediaries, effectively removing the bottleneck caused by third party validation from the processes.

A natural extension of blockchain network is upstream the supply chain, so that it can track when a component is produced at the factory, when it is shipped, when it arrives at the construction site and when it is finally installed. Blockchain-based supply chain management in fact can provide greater payment security, ensure product compliance and authenticity, efficient payment handling and reduce the cost of finance, induce trust among suppliers and clients, and provide transparency for auditing purposes as well (Perera, Nanayakkara, Rodrigo, Senaratne, & Weinand, 2020).

To further streamline the CM process, work progress can also be monitored by tracking RFID tags, scanning QR codes or embedding IoT devices in the building components installed, enabling the construction site digital twin to be automatically updated with trusted data via the blockchain, therefore bypassing inspection consultants and accountants. This way, blockchain can be leveraged to create a fully traceable and trusted accountability and audit trail of all that happens during the construction of the building, shared between client, design team, GC, suppliers and consultants, including H&S reports, prescriptions and accidents. Blockchain finds application also during the design phase, being useful for establishing ownership of models and BIM contributions and tracking project progress reliably, benefiting stakeholders by reducing the opportunity for corruption, inefficiencies and contractual disputes (Sawhney et al., 2020). Finally, its reliability and immutability are also exploitable during project close out and handover, as the blockchain provides a building digital twin with a permanent record of every component used in the structure which can be further updated, but not altered in its history, along the building life cycle.

9.2 Drones in construction

Unmanned aerial vehicles (UAVs), also known as drones, have experienced an enormous growth in terms of market and availability of both consumer and professional drones in the last years, and have proven their versatility and utility in several industrial applications, as well as finding exceptional success with hobbyists and the public at large. In the next years, adoption by civil and commercial agents is expected to grow further as UAVs get cheaper and more capable and find their way in even more use cases, with a projected market of US\$21.8 billion and 13.2 million devices by 2027, at a compound annual growth rate (CAGR) of 14.1% during the forecast period of 2020 to 2027. Drivers of the diffusion of this technology include the increasing deployment of UAVs in border patrolling and combating terrorism, and exemptions made by the regulatory authorities around the globe to permit the use of UAVs in several more industries (Unmanned Aerial Vehicle UAV, 2020).

In particular, the construction sector has been an early adopter of drones, in fact construction monitoring is currently the largest use case by shipments worldwide with 210,000 drones in 2020, and more than double expected by 2023, compared to a global shipment of enterprise drones of 526,000 units (itself a 50% increase from 2019). Specifically, drones in construction are taking over tasks such as site surveying and earthworks management, where their benefit are more apparent in terms of cost and time savings: to save costs when surveying sites, the number of global construction employees per drone will decrease from 2400 to 640 between 2018 and 2020 (Gartner Forecasts Global IoT Enterprise Drone Shipments to Grow 50% in 2020). UAVs are set to become a commonplace tool for construction firms, as 27% of companies already use drones, 31% expect to use them by 2022, while 14% think about using drones in the future. As using drones may require additional skills and capacities, large construction companies may be leading in terms of drones adoption rate, in comparison to SMEs. Nonetheless, contractors often prefer to outsource the use of drones to drones suppliers, rather than internalizing the costs (i.e., buying the drones, and the necessary software) (Integrating digital innovations in the construction sector, 2019).

Such high interest in drones is due to their utility in all stages of the project, from the planning phase by providing field information for planners and real estate developers, to its construction and its subsequent operation, by providing measures, photos, assessment, and impact reports (see Table 9.3). UAVs can increase efficiency and productivity in all these stages by surveying the site for progress, verifying contractor's reports, identifying discrepancies, and assisting in confirming compliance with regulations, for example, concerning workers' safety or storage of materials and demolition waste.

More specifically, drones are arguably the most efficient and inexpensive way to map any construction site with exact coordinates and values. Aerial views of a site can be easily captured and converted to 3D models faster and cheaper than other survey techniques, and also with decreases risk for surveyors. This allows to have precise, multi-modal digital representations of the construction site, according to the type of sensors installed on the drone: high resolution cameras, IR sensors for thermal imagery, LiDAR for 3D scanning, and more (see Table 9.4). The added value of drones relies also on their ability to access areas particularly challenging or dangerous for traditional machineries, such

TABLE 9.3 Main uses off drones in building life cycle.

Building life cycle phase	Main uses
Pre-construction	Construction lot survey Topography mapping 3D point clouds from LiDAR and photo reconstruction IR mapping to identify thermal bridges in energy retrofits
Construction	Monitoring construction progress over time with images, videos and 3D models Measuring cut and fill volumes Accurate as-built modeling of the asset Security surveillance Health and safety monitoring on-site Management of traffic on-site Detection of fire hazards and gas leaks Tools and materials delivery Actual construction activities (e.g., painting) Quality control of works
Operation and maintenance	Building documentation for promotional and real estate uses Visual and functional inspection of hard-to-reach places (roofs, facades, bridges) Visual and functional inspection of large infrastructure (powerlines, oil pipelines, dams, and waterways) Detection of faults and malfunctions in systems Detection of fire hazards and gas leaks
Decommission	Accurate 3D modeling of the asset to plan its deconstruction Survey to and materials inventory for reuse/recycling Monitoring of demolition works

TABLE 9.4 Main drones equipment in construction.

Equipment	Main uses
High-res cameras	HD pictures and videos of buildings and infrastructure Georeferenced orthophotos with cm accuracy 3D point clouds from 3D photo reconstruction with cm accuracy
LiDAR scanners	3D point clouds with cm accuracy
IR cameras	Thermography of buildings and terrain Malfunctions, fires and leaks detection Search and rescue operations Vegetation health monitoring
Optical gas imaging (OGI)	Gas leaks detection
Microphones/loudspeakers	Interaction with workers and users

as roofs, scaffolds, bridges, towers, or pylons. Drones can also improve communication and management activities by providing precise real-time data that can be exchanged between different actors, thus reducing the time required for implementing changes and assessing the progresses of the work.

9.2.1 Unmanned aerial vehicles

The term UAV or drone encompasses a class of variously sized aircrafts that may be remotely controlled or can fly autonomously, without the onboard presence of pilots. More correctly, the aircraft itself is just a part of the unmanned aircraft system (UAS), which also includes the other elements required for flight such as ground control stations, data links, and other support equipment (see [Fig. 9.7](#)). Commonly used alternative terms for UAS are unmanned-aircraft vehicle system (UAVS), remotely piloted aerial vehicle (RPAV), or remotely piloted aircraft system (RPAS).



FIGURE 9.7 DJI Phantom 4 RTK Unmanned Aerial System (UAS). *Courtesy of DJI.*



FIGURE 9.8 DJI Mavic2pro consumer Multicopter UAV. *Courtesy of DJI.*

First UAVs were developed for military use, starting from the beginning of 1900 with drone targets for aiming practice, then during the Cold War for military reconnaissance and, in the last years, even for combat. Today, approximately one third of USAF aircrafts are UAVs, and at least 100 countries in the world employ UAVs in their military forces (Horowitz, 2020). As for many other technologies, UAVs development trickled down from military research leading to the diffusion of civil UAVs that today are employed in several commercial applications or for personal recreational use.

The main components of an UAV are the body, which dictates the flight mechanism and can either resemble a scaled-down conventional aircraft or employ proprietary designs, the engine and power supply platform, the on-board flight controller with its dedicated software, as well as sensors and actuators. The operative part of the drone is constituted by its payload, commonly one of more cameras mounted on a controlled gimbal, but may include multispectral or LiDAR sensors, transported goods, power tools, sprinklers, and tanks or even fire extinguishers, according to the mission required and weight allowed (up to 20 kg for industrial UAVs).

Concerning flight mechanism, UAVs can be classified as follows (Alladi, Chamola, Sahu, & Guizani, 2020):

- rotary-wing or multirotor UAVs, which are capable of taking off and landing vertically and can also hover over a particular location, with the drawback of consuming more power since they have to act opposite to the gravitational force and therefore have more limited range and speed (see Fig. 9.8);
- fixed wing UAVs, which travel via gliding in the atmosphere like conventional airplanes and can also carry heavy payloads with greater speed and range compared to other UAV types, but need a runway to take-off and land and are incapable of hovering over a particular area (see Fig. 9.9);
- hybrid fixed/rotary-wing UAVs, which compromise between the above two mechanisms and can switch between the two, for instance, doing a vertical take-off, gliding through their path and then again switching to vertical landing using their rotors.

Among these, multirotor UAVs are the cheapest option available and therefore see wide application in the consumer and commercial sectors, in which they are commonly used for basic purposes such as photography and video surveillance. They include tricopters, quadcopters, hexacopters, or octocopters (Tahir, Böling, Haghbayan, Toivonen, & Plosila, 2019).

Regarding the engine and power supply, a large majority of civil UAVs employ electric motors and lithium-polymer batteries, which are cheaper, quieter, and require less work for flight control, with the downside of lower energy density and therefore lower range, whereas larger scale UAVs for specialty applications may employ conventional gas-powered airplane engines to maximize payload and endurance.



FIGURE 9.9 Delair UX11 fixed wing UAV. *Courtesy of Delair.*



FIGURE 9.10 DJI Glasses VR headset for drone control. *Courtesy of DJI.*

The on-board flight controller gathers remote control instructions and info from equipped sensors to perform the required actions and can be programmed to automate some maneuvers (such as landing assistance, autonomous return to base, wind compensation, or climbing toward better communication spots), up to full autonomous flight.

Concerning on-board flight sensors, they provide the flight controller with information about the aircraft position and movement and are also required for separation assurance and collision avoidance (Fasano, Accardo, Tirri, Moccia, & De Lellis, 2015). The amount and quality of an UAV's sensors suite is indicated by its degrees of freedom (DOF) number: 6 DOF implies 3-axis gyroscopes and accelerometers (a typical inertial measurement unit—IMU), 9 DOF refers to an IMU plus a compass, 10 DOF adds an altimeter and 11 DOF usually adds a GNSS receiver.

Lastly, actuators are used by the flight computer to control speed of the propellers, servomotors of flight appendages, eventual lights or speakers as well as to operate the installed payload.

UAVs employ radio transmitters for remote control and telemetry exchange to and from ground control, which is usually a drone pilot who directly commands or overviews the UAV along its predetermined flight path. When the aircraft is nearby (less than 10 km from operator), video downlink is available to help drone control and immediate feedback on imaging. More advanced control systems include remote networks via satellite link, airborne command, as well as gesture recognition and virtual reality (VR) headsets such as DJI Glasses (see Fig. 9.10), which allow the pilot to control the drone with the outmost precision (Galar, Kumar, & Seneviratne, 2020).

Currently, there are over 100 UAV manufacturers worldwide, including military suppliers. Most military contractors are located in the United States and in Israel, and the civilian drone market is dominated by Chinese companies—DJI manufacturer alone had a 74% market share in 2018.

Established civil uses of UAVs include aerial photography, aerial crop surveys, search and rescue, inspection of power lines and pipelines, wildlife monitoring, emergency delivery of medical supplies, forest fire detection, surveillance, plume tracking, postdisaster investigation, and crowd monitoring. UAVs have demonstrated their utility in the construction industry as well, and in site management in particular, providing important benefits in land surveying, worksite supervision, and inspection of buildings and infrastructure.

9.2.2 Topography surveying

The most widespread, and arguably the most versatile use of an UAV is to equip it with a camera to capture data, either video or high-resolution pictures, from above without the need to resort to manned aircraft or satellite imagery with



FIGURE 9.11 UAV flight plan and control. *Courtesy of Pix4D SA.*

much higher costs (see [Section 6.1.1.2](#)). This makes them an extraordinary tool for performing surveys, a fundamental element of every urban planning and construction activity, that consists in the precise science of determining the positions of points in 2D and 3D space and the distances between them. An accurate survey of the construction site is critical to enable informed decision-making ranging from design choices, construction site planning, design, and upkeep of infrastructure, to delineating cadastral property boundaries. Therefore, drones have already been successfully integrated into surveying workflows to perform land surveys, photogrammetry, 3D mapping, and topographic surveying, as they excel at rapidly acquiring data from vantage points inaccessible to humans. Drones' contribution to surveying is two-fold: on the one hand, when surveying challenging terrain, drones make it no longer necessary for human operators to physically access and measure points in hazardous or difficult-to-reach locations; on the other hand, while traditional surveying methods require meticulous measurement, preparation, and planning, UAVs can capture comparable data in dramatically shorter timeframes.

Drone survey workflow commonly starts from planning the flight path via the UAV own app or specific software that optimizes the waypoints in order to cover the target area with the required image overlaps. The UAVs is then launched and proceeds autonomously to fly along the defined path and acquire the required information, with the capability of manual control override if needed and of automatic pause and resume of operation in case of battery swap or recharging. After the flight, collected data are transferred to a dedicated software to be postprocessed to a usable dataset. Photogrammetry software can take care of both preflight planning and postflight image postprocessing, with most used programs being 3DR Sitescan, Pix4D, DroneDeploy, delair.ai, Bentley ContextCapture, Simactive or Agisoft PhotoScan (see [Fig. 9.11](#)).

Depending on the sensors installed on the drone and the surveying software used to organize collected data, drone surveying can produce the following main deliverables:

- 2D or 3D orthomosaic maps produced by stitching together nadir (straight down) and tilted digital photos captured by the drone's camera;
- 3D models of specific targets in the surveying site;
- high-density point clouds obtained by LiDAR sensors;
- multispectral data beyond the visible light spectrum for various uses, including thermal imaging.

In particular, a 2D orthomosaic is a large, map-quality image with high detail and resolution made by combining many smaller images called orthophotos, which in turn are aerial photos that have been corrected for lens distortion, camera tilt, perspective, and topographic relief to obtain a uniform scale across the image. Resolution of the orthomosaic map depends on flight altitude during the survey: A lower flight altitude will take longer to fly, but it will increase the map resolution. Map resolution is known as ground sample distance (GSD) and is measured in "cm per pixel," or how many cm of ground fit into one pixel of an aerial photo. In order to produce 3D maps, photogrammetry combines images that contain the same point on the ground from multiple vantage points: the conventional parallel flight pattern is doubled to a checkerboard pattern, effectively doubling the flight time but allowing to capture detail in the sides of buildings or ridges with the camera slightly tilted. Overall GSD can be as high as 1 cm horizontal and 2–3 cm elevation (vertical) over hard surfaces.

Accurate 3D models of specific targets or buildings can be generated by combining nadir and tilted images from UAVs with SfM algorithms (Sun and Zhang, 2018). Photogrammetry software such as Agisoft Photoscan, Pix4D and DroneDeploy can also generate a 3D point cloud by extracting pixels from 2D images by triangulation and positioning them within a 3D model, which can be exported to CAD or Rhino3D applications. Empirical trials and observations recommend 1000–1300 photos for a satisfactory 3D reconstruction (Rakha and Gorodetsky, 2018).

LiDAR imaging, which stands for “Light Detection and Ranging,” is based on a sensor that sends out pulses of laser light and measures the exact time it takes for them to return as they bounce from the ground, as well as the intensity of that reflection (see Section 6.1.3.2.). Oscillating mirrors are used to send out laser pulses in many directions to generate a broad sheet of light as the drone moves forward, providing readings of the terrain and of points on the ground with a finer degree of accuracy than image photogrammetry. LiDAR technology has been around for decades, but has only recently become available in a size and power feasible for carrying on drones, albeit larger ones. Working with traced dots instead of whole photos requires a higher precision in order to produce usable data; hence, LiDAR systems must include high-precision satellite positioning antennas and high-accuracy IMUs to determine the orientation of the LiDAR sensor in space, greatly increasing the costs—a complete LiDAR system may cost up to \$150,000, whereas a professional drone and camera setup costs below \$30,000 (Torres, 2021). Weight and power requirements make LiDAR systems compatible mostly with heavy-duty multicopters and fixed wing drones. Compared to image photogrammetry, LiDAR has higher accuracy especially in measuring elevation of both ground and objects (1 cm GSD) and is precise enough to trace small diameter structures such as power lines or metal trusses. LiDAR does not need visible light thus surveys can be conducted throughout the day and even at night. By measuring the intensity of the reflected pulses, LiDAR can also distinguish between soft objects (leaves of trees, grass) and hard objects (walls, roofs, roads, etc.). Differently from image photogrammetry, LiDAR light can also penetrate vegetation and trees canopy and effectively trace the ground below even in denser forests (Wallace, Lucieer, Malenovsky, Turner, & Vopěnka, 2016). Through innovations by leading LiDAR manufacturers like Livox, Riegl, and Velodyne to lower the costs and size of LiDAR models, spurred by their increasing application in the self-driving automotive sector, and system integrators such as GreenValley, YellowScan, or Emesent, more companies are deploying UAV-mounted LiDAR systems as an all-in-one 3D mapping device such as DJI Zenmuse L1 (see Fig. 9.12) and Delair DT26e LiDAR (see Fig. 9.13), which promise reduced cost and weight with survey-level accuracy.

Finally, multispectral imaging allows drones to obtain visual data beyond the normal visible light spectrum, extending to both infrared and ultraviolet wavelengths for specific applications. Several drone cameras, such as DJI’s Zenmuse XT2, Parrot’s ANAFI USA, or Autel’s EVO II Dual, are equipped with high-resolution sensors dedicated to visible light imaging paired with IR sensors, that allow to superimpose thermal data over normal visual information for easier navigation and image reading. A diffused application of drones multispectral imaging is to map normalized difference vegetation index (NDVI), which compares pixel level spectral reflectance to visible red light and near infrared light to evaluate vegetation health for forestry and agriculture monitoring.

The accuracy of the drone survey depends on the quality and quantity of data collected and on the presence of complementary systems, which in turn reflect on time and work needed for flight set-up, image recording and data software postprocessing. For some applications, a relatively lower accuracy, such as that provided by a consumer drone is sufficient. Conversely, when high absolute accuracy is needed, professional UAVs equipped with real-time kinematics (RTK) and postprocessing kinematics (PPK) capabilities are better suited, with most accurate results achieved with the support of Ground Control Points (GCP) (see Table 9.5). RTK processing on a drone records GNSS information and



FIGURE 9.12 DJI Zenmuse L1 LiDAR sensor mounted on a Matrice v300 UAV. *Courtesy of DJI.*



FIGURE 9.13 Delair DT26e UAV with LiDAR payload. *Courtesy of Delair.*

TABLE 9.5 Comparison of land survey techniques.

	Ground measurements alone	Drone without RTK/PPK	Drone with RTK	Drone with RTK and GCPs	Drone with PPK	Drone with PPK and GCPs
Accuracy	High	Low	Medium	High	High	Highest
Speed	Low	High	High	High	High	High
Cost	Highest	Low	Low	Medium	Low	Medium

geotags each image as it is captured during flight, usually recording the GNSS location for the center of the image, while a ground station with a known location acts as a secondary reference position and sends its GNSS data to the drone. The drone's onboard GNSS combines its own observations with this ground data to accurately correct its position in real time. However, an RTK drone must stay always connected to the base station while it is gathering GNSS information, and whenever signal loss occurs, data become unreliable (see [Section 6.1.3.1.](#)). PPK addresses this shortcoming by performing all GNSS data processing after the flight: GPS logs are stored onboard the drone, and calculations postflight via PPK software combine both aircraft data and base station data, matching each picture taken with its accurate position based on its timestamp. Lastly, GCPs are selected points placed in the survey area from which independent, ground-level measurements are made, usually determining their location and elevation using high-precision GNSS devices. These known base points are highlighted using high-contrast markers to be recognized by the postprocessing software in the aerial images taken by the drone. This way, the accuracy of the image rectification process can be determined comparing the corrected points to these GCPs location. If the error is too high, parameters are recomputed for another round in an iterative process that can be repeated until an acceptable margin of error is achieved. For best results, 5–10 GCPs should be spread uniformly on the ground area, 50–100 m apart from each other, across different elevations in case of uneven terrain. GCP assisted drone surveys provide the best accuracy but are more expensive and labor-intensive, as additional work is required to place the markers on site.

Concerning UAV types used in surveying, these include multicopters, fixed wing drones as well as hybrid solutions, each more suited to specific applications.

Multicopters such as DJI Phantom 4 RTK are a preferred choice for entry-level drone surveying because of their lower price tag, high payload, and ease of use (see [Fig. 9.14](#)). Due to their mobility, they are particularly suited to surveying small areas, and they excel at vertical mapping and monitoring small construction sites. Multicopter drones are also usually more compact and easier to transport and handle, and are the only ones that can provide live view to the remote controller for easier navigation in tight spaces. Compared to fixed-wing UAVs, multicopter drones are inherently slower and less efficient, therefore less appropriate for surveying larger-scale projects such as infrastructures or urban districts. In these applications, fixed-wing drones such as Delair UX11 and senseFly's eBee X can be between 5 and 14x faster to map the same area ([DJI Phantom 4 RTK vs. WingtraOne](#)); however, the need for large enough empty spaces for take-off and landing make them less than ideal in dense environments such as cities or forests. Some fixed wing UAVs are launched by catapult (either pneumatic, hydraulic or mechanic) to reduce the need for runway and save battery energy for take-off, and others use parachute for landing ([Aber, Marzloff, Ries, & Aber, 2019](#)). Conversely,



FIGURE 9.14 DJI Phantom IV RTK and remote controller. *Courtesy of DJI.*

hybrid UAVs such as WingtraOne or Aerovironment Quantix allow vertical take-off and landing and gliding flight but are unsuited for stationary flight or slow camera flyovers required for single building 3D modeling.

9.2.3 Worksite supervision and building inspection

9.2.3.1 Drones in construction site supervision

Unmanned aircrafts are employed in a variety of ways both during the actual construction phase and for building maintenance and management: from monitoring the construction site's evolution over time, measuring cut and fill volumes, to performing as-built surveys and generating geo-accurate 3D models, up to close inspections of roofs, facades, infrastructure, and powerlines (see Fig. 9.15).

On-site drone surveys provide high-resolution, geo-accurate snapshots of the construction area, with minimized time and cost compared to conventional visual surveys allowing routine, even daily inspections. The digital outputs provided can be used to assess a site's evolution over time and better manage resources such as vehicles, equipment, and temporary stocks. Digital deliverables include

- color point clouds;
- classified point clouds;
- orthomosaics;
- digital surface models (DSM);
- digital elevation models;
- contour lines;
- facade DSM;
- facade orthomosaics;
- 3D textured meshes;
- digitized vectors;
- index maps;
- thermal maps.

A professional UAV can rapidly collect all the data required to generate a highly accurate 3D building model (including colors, rooftops, external areas, etc.) which can be used to update the construction site's digital twin and compared to the project's BIM model to recognize the current as-built conditions of a project efficiently, to identify disparities between the as-built and as-planned progresses, and to aid in deciding on corrective actions. Aerophotos can be overlaid on design plans on a daily basis to check worksite progress at a glance and minimize the need for reworks (see Fig. 9.16). Real-world scenarios can then be simulated to catch any discrepancies that would be costly if they were not identified until later, such as crane positioning and movement.

Compared to traditional worksite inspections, drone surveys have the added benefit of quick deployment without disruption of ongoing work processes (Freimuth and König, 2018). Additionally, drones equipped with LiDAR can conduct worksite inspection even inside structures under construction, as their sensor doubles as a collision detection tool, to conduct SLAM providing contractors with 3D inspection data while also enabling the drone to operate semi or fully autonomously. UAVs are also particularly suited to document earthmoving works, which are difficult to measure with traditional methods with sufficient accuracy: regular flyovers over the cut and fill worksite produce accurate and



FIGURE 9.15 Drone supervision of UAE Pavilion at EXPO 2020. *Courtesy of Santiago Calatrava llc.*

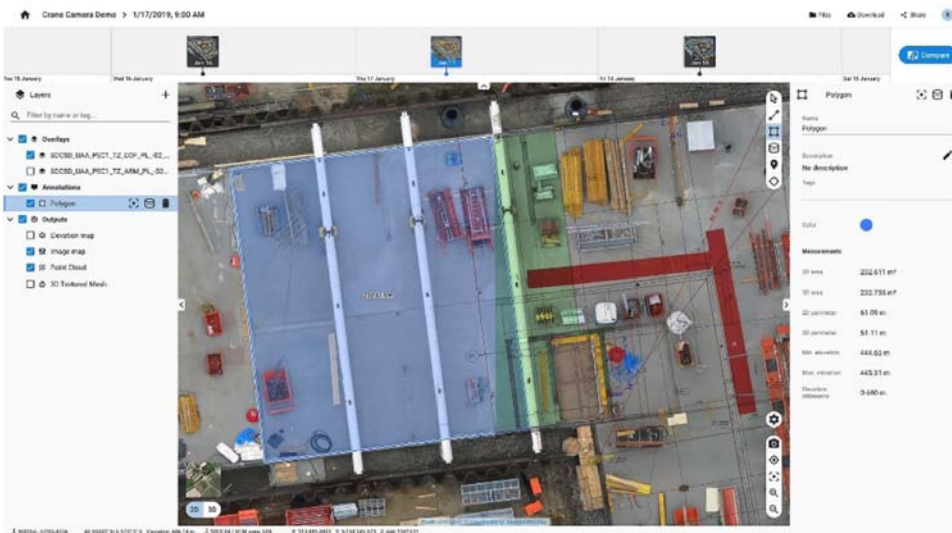


FIGURE 9.16 Measurements and plan overlay on drone footage. *Courtesy of Pix4D SA.*

up-to-date 3D models from which dirt excavated and stored can be easily estimated in order to plan subsequent works, schedule transports and authorize payments.

UAVs can be very helpful to improve health and safety (H&S) monitoring on the construction site, which is one of the most dangerous workplaces all over the industry. For risk assessment and prevention, H&S officers can fly drones over the construction environment collecting real-time information about the location of personnel and tools, hazards materials, moving equipment as well as the blind spots of the construction site in order to prevent unsafe conditions before happening of the accidents and to warn about risk situations in any construction project from site preparation to project completion (Dastgheibifard and Asnafi, 2018).

Images provided by UAVs flyovers can be fed to specific safety monitoring applications such as Smartvid.io which employ AI and photo and video ML to aggregate, organize, and analyze data, automatically detecting objects, materials, and safety hazards. This is compared to historical project data and incident reports to accurately predict safety incidents.

Drones are also effective in managing traffic on site and minimizing transport interference. In a typical construction site, drones H&S monitoring may include the following assessments:

- appropriate waste storage and waste containers protected from rain or covered by canvas;
- protection of construction materials such as steel bars from rain and cover by canvas;
- workers correctly wearing protective equipment (hard-hats, boots, appropriate clothes, and personal fall arrest systems for high elevation services)

- safety platforms not overloaded (dirt, debris, people, equipment, tools), fully floored and installed on the entire perimeter of the building;
- adequate safety systems on scaffolding (safety guardrails, safety nets, life-line, handrails, and toe boards);
- workers on roof or last built floor protected from falling (personal fall arrest systems with safety belt connected at lifeline or guardrails, presence of safety nets);
- isolation and demarcation with warning signs of areas for loading and unloading of materials by crane, winch, or truck;
- access to construction site only allowed to personnel involved in the operations;
- safe traffic routes of equipment, materials, and people inside the jobsite (Santos de Melo, Costa, Álvares, & Irizarry, 2017).

Drones equipped with thermal cameras can also help in early detection of fires, especially in larger construction sites or those with increased fire risks, such as in the oil&gas industry. During the actual firefighting, fire extinguishing drones such as Walkera's Zhun can control fires in hard to reach places where human intervention would be impossible or too risky, and IR imaging can help monitor the health of structural steel elements to evacuate firefighters before collapse (Pecho, Magdolenová, & Bugaj, 2019).

9.2.3.2 Buildings and infrastructure drone inspection

Effective operation, maintenance, and safety of buildings and of infrastructure such as bridges, dams or industrial compounds is based on regular checklist-based inspections which have traditionally been time-consuming, expensive, and often dangerous. UAVs provide a uniquely efficient and safe method of inspecting such sites, producing digital datasets easy to collaborate on and compare over time. In particular, drones are an excellent tool with which to map and inspect difficult-to-monitor linear assets such as roads, pipelines, power lines, rail routes or waterways. Documenting such corridors with a UAV is significantly quicker than via terrestrial surveying methods, at a cost typically much lower than hiring manned aircraft services. In 2016, UAVs were used to thoroughly inspect the Delaware Memorial Bridge in the United States with much less disruption than traditional methods, which would have required lane closures and inspectors climbing over the edge of the bridge with ropes (Sawhney et al., 2020). Other notable cases of inspection by UAV are James J. Hill Stone Arch Bridge in Minneapolis and Blatnik Bridge between Duluth, Minn. and Superior, Wis (Rubenstone, 2021). Notwithstanding limitations to drone usage caused by unfavorable weather, flight control regulations, or space constraints, drone-enabled bridge inspections were shown to produce reports as complete as conventional inspections, or even more detailed (Seo, Duque, & Wacker, 2018). Photogrammetry inspection by UAV allows to get as close as needed to the subject part, for instance to take close up-details of cracks or surface damage or to perform accurate laser scanning of single elements. Detailed 3D models of critical components can be obtained from UAVs equipped with a photogrammetric payload that maneuver around the target object and take images in different positions and orientations to ensure the entire object surface has been observed sufficiently for reconstruction via SfM algorithms or LiDAR sensing. The workflow takes high-resolution drone photographs of the structure to be inspected, and stitches them into a "reality mesh" 3D model comprised of tens or hundreds of millions of polygons, containing far more information than is found in regular 3D model. This mesh can be viewed on a computer or tablet or with AR or VR head mounted displays (HMDs), allowing both zoomed-out tabletop view and 1:1 inspection of the model. Although accuracy is still shy of actual laboratory grade inspection at the millimeter level, mainly due to the influence of image parameters such as environmental light levels, motion blur, and focal blur, these inspections allow to clearly observe performance/damage indicators, and schedule more in-depth investigation when appropriate. For instance, UAV inspection on a wind turbine can allow to detect blade damage such as edge crushing, surface imperfections, or early-stage leading edge erosion in the textured 3D reconstruction profiles (Zhang et al., 2020). Drones equipped with telephoto lens can even read displays or gauges in hard to reach places for instant feedback on plants operation in case remote data is not available. In buildings maintenance, drones can perform regular flyovers of exteriors to assess conformity or elements such as roof, facades or windows, or be rapidly deployed to perform spot inspections on collapsing elements, leaking windows, obstructed inlets or outlets or to check rooftop mounted plants, without requiring any external scaffold of aerial platform or otherwise posing safety problems as with pitched roof structures.

Multispectral cameras enable drones to perform functional inspections in addition to visual ones, in particular by equipping IR-sensitive sensors (see Fig. 9.17). Thermal imaging at the large scale allows to identify quickly any abnormal thermal signature and pinpoint possible failures in power lines and electric equipment, industrial sites, or photovoltaic plants, in situations in which conventional surveying by qualified inspectors would be extremely time-consuming (Kumar, Sudhakar, Samykano, & Jayaseelan, 2018). At the building scale, a flyover by an IR-sensing UAV produces a

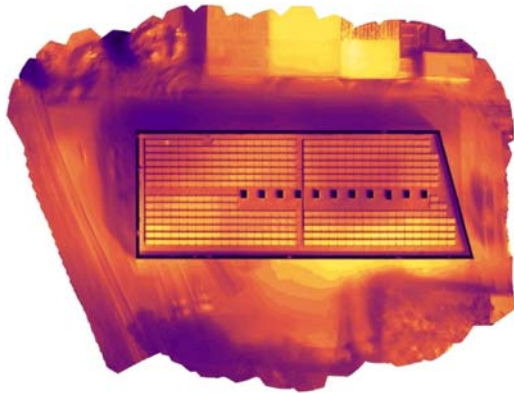


FIGURE 9.17 Building thermography from UAV inspection. *Courtesy of Pix4D SA.*

3D model with textured meshes that indicate point by point temperature and highlight thermal bridges, imperfect insulation, air leakage as well as water infiltration, helping to carry out energy audits of the existing building stock. At the urban scale, conversely, IR imaging allows to keep track of surface temperature of roofs, pavements, roads and green areas, obtaining information on materials' thermal reflectance, thermal inertia (by measuring temperature fluctuations along the day), as well as estimating vegetation health via the NDVI index, providing useful insights to contrast the Urban Heat Island (UHI) effect ([Gaitani, Burud, Thiis, & Santamouris, 2017](#)).

Lastly, optical gas imaging (OGI) cameras are able to identify invisible gas leaks and display them as smoke clouds in the footage, using a special IR filter that lets only a narrow band of mid-wave infrared light to pass through to the sensor, which is absorbed by hydrocarbon gases. Detected substances include methane, sulfur hexafluoride, and other industrial gases which pose poison, corrosion or explosion risks, as well as carbon monoxide and dioxide or R-124 refrigerants. Large-scale gas leaks detection by drones such as Viper Vantage OGI is much more efficient than previous methods of relying on the guess-and-check placement of “gas sniffers” to locate leaks, which need to be placed within inches of the gas to detect it with consequent danger to the inspectors and downtime related to shutting down systems ([Ravikumar, Wang, & Brandt, 2017](#)).

9.3 Wearable devices in construction

The rapid evolution of the Internet of Things (IoT), innovations in sensor technology and progress in short-range communication, such as ultrawideband radio technology and Bluetooth, have enabled the emergence of compact electronic and computing devices that can be embedded on the individuals' body as garments or accessories with the goal to measure users' personal information such as vital signs, location, environments, and movements.

These devices are known as “wearable devices,” “wearable technology,” or “smart wearables” and have found increasing application over the last 5 years across industries such as healthcare, manufacturing, mining, or athletics, allowing individuals to monitor, store, and transfer anywhere and anytime personal information about health status, physical activity, and environment, including body temperature, blood pressure, heart rate, calories intake, calories burned, steps counted, sleep patterns, location, environmental data, etc. According to the International Data Corporation, smart wearables global shipment is expected to total 396.0 million units in 2020 with an increase of 14.5% compared to the 345.9 million units shipped in 2019, with a projected five-year CAGR of 12.4% and a total of 637.1 million units in 2024 ([Worldwide Quarterly Wearable Device Tracker, 2021](#)). According to Gartner, worldwide end-user spending on wearable devices will total US\$52 billion in 2020 with an increase of 27% from 2019 (US\$41 billion).

9.3.1 Uses and benefits

The use of wearable devices can bring significant benefits in the construction sector as well, which has always been characterized by a high rate of accidents and by a workplace—the construction site—where workers are exposed to ever-changing and difficult to foresee risks, because of the continuous evolution of the boundary conditions as the construction proceeds and of the numerous interferences between the different processes.

Climatic conditions and direct exposure to atmospheric agents, presence of dust or chemicals, use of dangerous tools and machinery, moving vehicles, hazardous materials, working at heights, tiring and repetitive operations, long distances, and high levels of environmental noise are just some of the risk factors that characterize the construction site, to which the workers' physical and mental health status, fatigue, level of training and correct use of PPE must be added.

Within the construction site, smart wearables facilitate communication between employees and can allow the acquisition/monitoring in real time of a range of data and information on the worker and on the status of in-progress activities, which can be used to make efficient and proactive decisions to improve the health, safety, and satisfaction/morale of workers, increase the productivity and at the same time reduce expenses for insurance premiums. According to a United States Chamber of Commerce report, it is expected that 23% of contractors will be using construction wearables onsite by 2021, up from just 6% in 2018 ([The Usg Corporation + United States Chamber of Commerce Commercial Construction Index Q42018, 2021](#)).

In particular, wearable devices can monitor physiological data (heart rate, breathing rate, blood pressure, etc.), dangerous movements of the body (body posture, speed, and acceleration), environmental data, worker position, safety distances, and shocks, allowing to know in real time the position, health conditions, exposure to dangerous substances, distances from any danger, occurrence of shocks or falls, or behavior (see [table 9.6](#)). Collected data can trigger real-time alerts for workers such as sounds or vibrations, or can generate requests for help to rescue teams for an emergency response. For instance, wearable RFID detection systems positioned in vests or helmets such as Scan-Link Armor allow passive communication between workers and vehicles operators, alerting both of their respective presence (see [Fig. 9.18](#)). This way, the operator is warned that a person is in the vicinity rather than an ordinary obstacle, ensuring his maximum attention without the risk of false and unnecessary alarms.

Subsequent analysis of data collected through smart wearables allows to identify specific areas of exposure that have the potential to increase injuries, to modify operations before accidents or to positively influence the behavior of people at work, leveraging the emerging technology of Internet of Behavior (IoB). For example, repeated small accidents can reveal ongoing dangers, for example, workers jumping into a pit instead of using the ladder.

By analyzing data on the daily movements of personnel, it is possible to optimize the location of materials and equipment in order to reduce unnecessary travel. At the same time, precise tracking of workers' paths can allow to implement social distancing measures in case of infection risks, e.g., by removing bottlenecks or distributing services more evenly across the worksite.

Furthermore, wearable devices allow automatic counting of the personnel present on site, simplifying the control of timetables and attendance, and can provide additional information about training and certifications of each employee to ensure the correct progress of the various tasks. Lastly, the use of wearables can improve the management of evacuation times in an emergency, by allowing to send targeted communications to the workers involved.

TABLE 9.6 Safety monitoring, metrics and instruments on construction site.

Environmental and personal monitoring	Metrics	Instruments
Physiological monitoring	Heart rate, heart rate variability, respiratory rate, body posture, body speed, body acceleration, body rotation and orientation, angular velocity, blood oxygen, blood pressure, body temperature, user's activity level, calories burn, and walking steps.	Gyroscope, accelerometer, magnetometer, infrared, radar, thermistor, ultrasound, GSR, ECG, EMG, EEG, blood pressure sensor, pulseoximeter
Environmental sensing	Ambient temperature, ambient pressure, humidity, noise level, light intensity, air quality.	Humidity sensor, light sensor, noise sensor, pressure sensor, temperature sensor, smoke sensor, gas sensor
Proximity detection	Object detection, navigation, distance measurement, and proximity detection.	RFID, UWB, infrared, radar, Bluetooth, GNSS
Location tracking	Worker location tracking, materials tracking, and vehicle/equipment location tracking.	RFID, UWB, infrared, radar, Bluetooth, GNSS

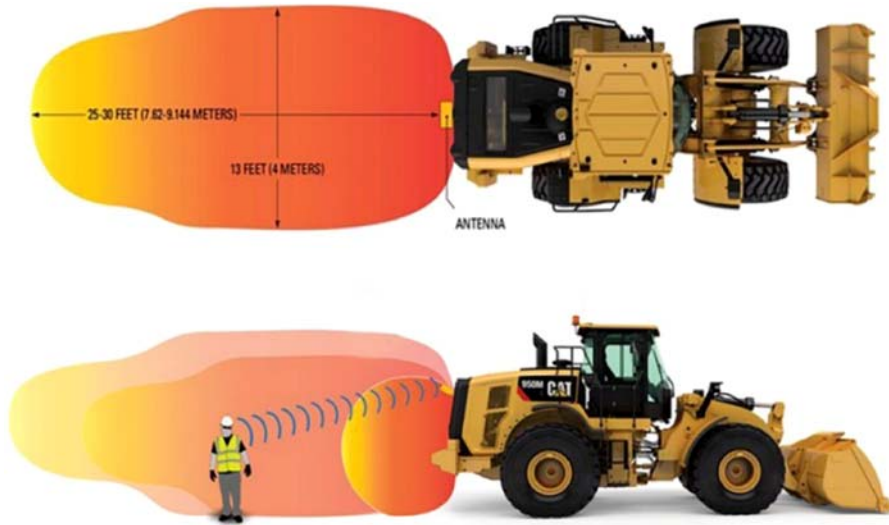


FIGURE 9.18 RFID safety detection system. *Courtesy of Scan-Link.*

9.3.2 Wearable devices on the market

Wearable devices on the market for the construction industry have different specifications in terms of type, size and weight, power source, computation capability, featured sensors' location and mounting, and wireless communication range.

Wearable systems combine different technologies, ranging from radio-frequency identification (RFID), magnetic field detection, radar, ultra-wide band, sonar, Bluetooth, GNSS, laser, video and static cameras, electrocardiogram (ECG/EKG), and electromyographysensors. Sensors like galvanic skin response, accelerometers, gyroscopes, and magnetometers constitute a body sensor network. The data transmission process may use any of the available standard communication protocols including Wi-Fi, Bluetooth, ANT+, and ZigBee. Raw and processed data may also be transmitted through any of the protocols for storage in the cloud for easy accessibility.

Main products available include smart watches, hearables, boots, helmets, glasses, body wear (safety vests, shirts, etc.), wireless adhesive electrodes, armbands, and wristbands (see [Table 9.7](#)).

9.3.2.1 Smart watches

Smart watches are Bluetooth or Wi-Fi capable computing devices that are worn on the wrist with a form factor similar to a conventional watch, or bracelet for more compact products. In addition to telling time, smart watches commonly extend the capabilities of the wearer's smartphone to the watch, allowing the wearer to use the watch's interface to initiate and answer phone calls, read and dictate email and text messages, get a weather report, or interact with a digital assistant. Common features of smart watches, even of consumer ones, are GNSS antennas, sensors to monitor the user's heartbeat and blood oxygen saturation, and dedicated apps capable of gathering and tracking data about the wearer's heart rate or providing walking or driving directions.

Several smartwatches are available on the market, from cheap fitness bands which primary purpose is physical activity tracking, to more premium devices that can function as a small companion computer. Most common devices include Apple Watch, Samsung Galaxy Watch, Fitbit Versa, or Garmin Fenix.

On the construction site, smart watches can find several useful applications. Vital signals such as heart rate and blood oxygen can be continuously monitored to prevent excessive strain, and alerts are issued if atrial fibrillation or respiratory defects are detected. Smartwatches are also able to detect falls from heights and automatically alert emergency services to ensure faster rescue of workers. Lastly, smart watches enable hands-free communication when using tools or equipment.

9.3.2.2 Hearables

A mashup of the terms wearable and headphone, hearables combine major assets of wearable technology with the basic principle of audio-based information services and wireless telecommunication. Hearables are miniaturized, in-ear computers designed primarily for the purposes of mobile communication, real-time information services, activity tracking

TABLE 9.7 Main smart wearables for construction on the market.

Wearable construction typology	Functions
Smart watches	Activity monitoring Fall detection and alert issuing Easier and more safe communication on the job Health monitoring (temperature, heart rate, blood oxygen rates)
Ear-worn/ hearables	Tracking of heart rate, cadence, or proximity detection Hands-free phone calls or voice commands Voice-activated virtual assistants
Boots	Detect pressure from shock and falls Sense location Charge by walking
Helmets	Monitor fatigue, cerebral health stats Prevent microsleeps Detect collisions /proximity detection Location tracking
AR glasses	Detect leading edges Identify hazardous material Display useful information (assembly instructions, tools specifications, safety protocols)
Safety Vest and shirt Sensors	Track core body temperature Detect harmful gases Improve contact tracing Proximity detection
Armbands	Health monitoring (temperature, heart rate, blood oxygen rates)
Wristbands and wearable tags	Location tracking Access control Alerts issuing Proximity monitoring Detect harmful gases Contact tracing
Badges	Access control Proximity detection

and various monitoring applications focusing on the wearer's health conditions and body performance, and are controlled by touch, movement, thought, voice or any combination of the mentioned control mechanisms. They are also known as "smart headphones" or "smart advisors" and are usually integrated with voice driven virtual assistants.

The hardware architecture commonly comprises speakers to convert analog signals to sound, Bluetooth IC chips to communicate with smartphones or PCs, sensors to track heart rate, cadence, or to detect proximity as well as microphones to enable phone calls and voice commands. Differently from vision-based AR tools or wearables with tactile interaction, hearables place the entire interaction unit in-ear and address wearers purely through acoustic signals ensuring a lower grade of overall distraction, with acoustic warning signals also more effective than visual or vibration indicators. Furthermore, in ear monitoring measures biometric data such as temperature, heart rate or oxygen saturation through photoplethysmogram or even electroencephalography with significantly higher reliability and better response times than contact devices placed on wrist or torso.

Applications of hearable devices in construction include hands-free communication between workers and coordinators and easier consulting of generic or specific virtual assistants, as well as accurate health tracking of the workforce throughout the construction site.

9.3.2.3 Smart safety footwear

Safety shoes and boots used in construction are a viable candidate for IoT integration (Janson, Newman, & Dhokia, 2019). United States based SolePower integrates IoT devices in its safety footwear to provide real time location and

health data tracking of the workforce through sensors and transmitters powered by an energy-generating shoe insole. Connected shoes can preemptively identify fatigued employees by the change in their gait along with other parameters, allowing to develop productivity measurements by task as fatigue increases, calibrating the point of diminishing returns. Workers' data can also be used to identify scheduling conflicts, delays, and impacts.

French company Intellinium's smart safety shoes can be used to alert workers of hazardous conditions, and allow the wearer to send for help with the tap of a toe using a derivative of MORSE code via a built-in force sensor membrane. The boot is also equipped with a system of vibration motors, a 90 dB buzzer, and LED lights which allow the wearers to communicate with each other. In case of emergency, workers can acknowledge that they received a message to evacuate by touching a toe to the sensor. The built-in sensors detect falls or shocks and immediately notifies an employee or colleague of a worker's location. Both an internal and an external sensor for acknowledging and sending alerts are present, so if the wearer's leg or foot is injured, their hand is still able to reach down and activate the external sensor. The system integrates smart man-down signaling with integrated doubt removal: once the shoes detect that the worker either has fallen or is still for too long, they vibrate to give the user a way to cancel the alert. If the user does not answer the warning, the alert is automatically sent. These features, sans the force-sensor membrane, are also available on a stand-alone safety pod that can be attached to any shoe or boot.

9.3.2.4 Smart helmets

Helmets are a mandatory safety equipment on any construction site, and therefore a suitable place to integrate connected devices that should be worn by the whole workforce. Hard hats can be embedded with GNSS receivers and sensors to track and monitor employees' conditions, position and actions. In smart hats, bio data-related functions may monitor the wearer's temperature, respiration, perspiration as well as electrical brain activity via EEG, to determine each worker's fatigue level and health status. For instance, SmartCap's Life is a sweatband sensor array that fixes around the inner edge of a helmet, able to monitor brainwave activity to prevent microsleeps before they occur (see Fig. 9.19). Sudden sleep can be particularly dangerous for crane and large equipment operators or truck drivers. The hat may vibrate and/or issue an auditory alert to notify the user about conditions that should be addressed, indicating, for instance, that an employee needs rest. Relevant data may be sent through a wireless local area network to a gateway, from which it can be distributed to managers, archived and aggregated to discern and predict trends and guide future practices.

Similarly, WakeCap is a smart hard-hat monitoring device that can be fixed to any cap replacing its standard ratchet and enables real-time tracking of the wearer as well as proximity of construction workers to each other (see Fig. 9.20). Instead of energy-consuming GNSS antennas, WakeCap employs a purpose site-mesh-network built by placing specific anchors throughout the construction site to enable accurate and consistent tracking even in indoor spaces. Manpower geolocation enables analytics and insights on labor workflows and productivity, by trade, job crew, and site zone. Additionally, proximity tracking is useful to contain infection or contamination hazards on site by enforcing workers distancing and allowing quick and accurate contact tracing in case a worker is infected. In particular, it is possible to trace workers who have come in contact with the infectee, including those who spent an extended amount of time with them increasing their risk, to identify affected subcontractors and tradesmen to plan replacement and anticipate project delays, and to track places visited by the worker for thorough sanitization.

WorkerSense system is similarly centered on hard-hat mounted sensor pods able to capture motion and environmental data, including GNSS, 9-axis motion, temperature, humidity, and light, connected via LTE to a central dashboard to show productivity and environment, health and safety insights on the whole workforce (see Fig. 9.21). The system is integrated by simple, cheap rapid deployment tags that can be placed all over the construction site to provide the sensor pods with environmental context, flagging areas with risk factors, PPE and certification requirements, cost codes,



FIGURE 9.19 SmartCap Life smart band. *Courtesy of SmartCap.*



FIGURE 9.20 WakeCap anchor and hardhat monitoring device. *Courtesy of WakeCap.*



FIGURE 9.21 WorkerSense hardhat sensor and tags. *Courtesy of WorkerSense.*

activity IDs, etc. This way physical areas of the job site can be associated with location, production and H&S data, and workers compliance can be tracked in real time.

9.3.2.5 Smart glasses

Smart glasses are conventional protection goggles integrated with connected functions that include cameras, microphones, speakers, and head-up displays. Pioneered by Google Glass, they are effective miniaturized, lightweight wearable computers optimized for hands-free work. Images and videos are displayed or projected as AR without obstructing the real-world view, either by LCD miniprojectors integrated in the glasses frame or by laminating OLED screens on one or both lenses. Worker's decision-making is improved by the ability to access training videos, images annotated with instructions, or quality assurance checklists. Virtual assistants can be summoned and interrogated in real time by gesture, touch pad, or voice commands. The equipped cameras allow to take pictures and videos and to live-stream clear "point of view" video feed to coworkers and external experts for remote support collaboration and troubleshooting. Smart glasses such as Epson Moverio and Vuzix Blade can also be employed for first person UAV piloting.

9.3.2.6 Wearable badges

In addition to wearable devices integrated in conventional work garments or PPEs, IoT can be easily deployed in the construction site by providing workers with connected badges or clip-on pods which contain all the necessary hardware (sensors, receivers, etc.) and can be kept in pockets or fixed to shirts, vests, or utility belts without the need to buy additional work attire or throw away the device with the accessory it is integrated with (e.g., a safety shoe which is usually replaced on a yearly basis). Most of these devices enable real-time location systems (RTLS) to track workers' movement, activity and conditions to assess productivity, optimize logistics, and improve job safety. Tracking systems, such as Triax Spot-r (see Fig. 9.22) and Redpoint RTLS, are composed by connected tags that can be fixed in specific locations, worn by personnel or placed on equipment and vehicles, and by anchors (receivers) evenly distributed over the worksite to create a self-organizing mesh network. Together, these form a virtual, wireless, geofenced environment and provide location and data services to enable two-way communication with any device on the network.



FIGURE 9.22 Spot-r wearable tag (left) and gateway anchor (right).
Courtesy of Triax Technologies.

Personnel badges or tags commonly feature multifunctional call buttons for sending emergency messages to the server, RGB LEDs to provide status as well as user-alert functionality, on-board buzzers and vibration alerts for safety hazards and incoming messages, as well as 6-axis IMUs for motion sensing and power management, and communicate via LTE, Wi-Fi, Bluetooth Low Energy or Near-Field Communication (NFC-A) protocols. More advanced badges feature electronic paper displays screens to allow the wearer to receive and acknowledge messages and warnings and to display details related to a hazard.

Tracking details are gathered on a central server and are available to project manager via dashboards to show graphical representations and real-time visualization of the worksite, heatmaps and spaghetti diagrams to track paths and visualize activity, roadblocks, interactions, and near-misses, and allow to search and locate individuals or assets, or manage location data, alarms and events. Concerning H&S management, RTLS systems enable real-time worker-generated injury, incident, and hazard alerts, reduce site evacuation times and allow to identify workers in specific areas of interest, no-go zones, and confined spaces, and to manage worker certifications to ensure site safety compliance. Contact tracing is also easily implemented in case of contagion or infection risks on the worksite.

Specific RTLS badges such as Blackline's G7 can integrate swappable gas detectors for real time warning of the presence of hydrogen sulfide (H_2S), explosive gases (LEL), carbon monoxide (CO), oxygen (O_2), Sulfur dioxide (SO_2), hydrogen resistant carbon monoxide (CO-H) as well as ammonia (NH_3). In case of gas detection, the badge sends an alarm to the central safety network that allows to initiate emergency response in seconds, establishing communication with the affected worker and at the same time alerting nearby team members for evacuation or, if breathing apparatus is equipped, for rescue operations.

9.4 Extended reality in construction

Extended reality is finding increasingly interesting and important applications in the construction phase, that can bring important benefits to both the construction process and site management, allowing greater control over the project by all stakeholders involved (Khan, Sepasgozar, Liu, & Yu, 2021).

9.4.1 Virtual reality in construction

In addition to the design phase (see Section 6.3.1.), VR is also finding interesting applications in construction works and site management (Delgado, Oyedele, Demian, & Beach, 2020). In particular, the use of VR on-site can allow to:

- plan and view the site layout to choose machinery and routes (cranes, routes, etc.) (Getuli, Capone, Brutini, & Isaac, 2020);
- experience 4D/5D VDC in VR, for both project managers and for clients;
- monitor the construction site remotely with 360° photos for both project managers and for clients;
- visualize the 3D as-designed or as-built model in an immersive way for information retrieval, even in collaborative environments;
- effectively train workers on procedures, machinery and equipment, improving productivity and safety (Joshi et al., 2021; Li, Yi, Chi, Wang, & Chan, 2018; Shi, Du, Ahn, & Ragan, 2019);
- allow customers to customize and view the property before its final completion or before purchase.

9.4.1.1 Site planning

For the erection of any building, the construction site should be organized in such a way to carry out works in the best conditions of quality, safety, efficiency, and cost-effectiveness.

The design of the construction yard therefore constitutes an indispensable preliminary activity to define the best sequence of the work phases, to select the necessary equipment and machines and their relative positioning, to identify workspaces and storage locations, to establish the viability reserved for vehicles transit, and to prepare scaffolding and temporary works.

In this picture, 3D visualization, and VR in particular, allow to thoroughly analyze the construction site from every angle and to better understand all important spatial relationships and to prevent clashes and interferences (see Fig. 9.23). Within a construction site, in fact, the necessary space is often not available, the ground conditions may not be optimal and the machines may have a limited lifting capacity.

Precisely for supporting the choice of lifting machines and the verification of the load capacities in actual site conditions, Liebherr released “Crane Planner 2.0,” a 3D and VR software tool that combines interactive 3D models with the relevant planning data, based on the load moment limiter of the respective machine. During the planning phase, it enables to survey the whole project, to simulate machines operation, and to directly experience the planned working processes from lifting to setting down the payload, receiving warnings of potential collisions between machine, load or surroundings, or if safety distances are not observed. Parameters such as lifting height or radius, ground pressure, utilization, center of gravity, and erectability are constantly monitored. After planning, the results can be shared via cloud.

Another interesting VR application for site planning is the Scaffold VR Viewer app launched by the UK company Avontus Software along with their Scaffold Designer program. The app allows to navigate in first person the scaffold ensuring that it is designed correctly and allowing to identify potential hazards such as obstructions in order to create a safe work plan, and to familiarize work crews with the project before the build so they can safely hit the ground running. The same company released an AR tool to explore the 3D model in-context directly on site via ground markers.

9.4.1.2 Construction interpretation and visualization

VR visualization is proving to be a useful tool during the construction phase of the work on multiple occasions for various actors involved, improving and speeding up the decision-making process. In particular, the use of VR technology can allow:

- an immersive view of the BIM model under construction and its construction phases (4D BIM simulation) both for better planning of construction site activities and to monitor and show in real time the works progress;
- a faster and deeper understanding of the work, the processes and their correct sequence by the crew, reducing the risks of RFIs or rework;
- the creation of collaborative virtual environments allowing members of the work team to work together remotely;
- the remote monitoring of the building under construction via 360° video and images by combining VR technologies and 3D video cameras.

9.4.1.3 Training

The personnel training using VR tools is having a great diffusion, in particular among large companies, due to the numerous advantages compared to traditional training in terms of speed and level of learning, possibility of planning and compatibility with activities work, fewer travel needs, lower costs, greater safety for both learners and equipment.



FIGURE 9.23 Construction site visualization in VR with Fuzor. Courtesy of Kallos Studios, Inc.

These advantages are particularly evident in the construction sector, where workers need continuous training (including certification of skills), find themselves working in environments and in situations with a high risk for their safety and have to operate equipment even of considerable size.

VR allows the safe simulation of different scenarios, even of extreme danger, in which learners can literally “learn by doing” (even with the support of textual information or audio narrations) without the risk of compromising their life, their health or damage equipment. In this way, learning is faster, deeper, and it is possible to evaluate not only the result and decision-making skills, but also aspects such as the precision of movements and response times, as well as other specific variables, allowing to obtain a bigger picture on the level of training and competence acquired by the learner. Moreover, the possibility of not having to use real equipment even of large dimensions (cranes, etc.), nor of having to actually reproduce danger scenarios, together with the possibility of having training carried out on an individual level without having to change working hours or interrupt company activities (as it happens instead in the case of group courses), allow to considerably reduce the costs of training (Song, Kim, Kim, Ahn, & Kang, 2021).

In addition to training, VR offers construction safety professionals the ability to visually communicate job site hazards to management and design teams throughout the construction cycle. Tablets, mobile phones and wearable visors may provide a clear 3D, 360° view of work environments to members of the project team regardless of their location.

Among the many interesting examples is that of the construction firm Bechtel which partnered with construction safety technology company Human Condition Safety to implement an extensive VR training program for its employees (HCS SafeScan), including the “training on forklifts and scaffolding and on the execution of welds.” With the help of VR, employees were trained in real work scenarios (including working at height), allowing them to perfect their skills in complete safety even on risky situations, such as unloading a crane 20 stories in the air on a foggy morning, without sending them into the field first. Training sets were further optimized using data collected from ongoing programs combined with geographic information, safety histories, regulatory requirements, and real-world safety programs and practices, obtaining a predictive engine that pinpoints which elements might combine to create the riskiest circumstances on a job, and sends alerts to avoid injuries.

Several contractors, including Conewago Enterprises, have been routinely using construction machinery simulators (mobile or tower cranes, backhoe loaders, excavators and wheel dumpers), such as CMLabs Vortex, for training their staff.

Likewise, construction machinery and equipment vendors provide VR training programs for their products. For example, the Dutch company Riwal, specialized in platforms and telehandlers rental, introduced VR simulators as an effective training method to increase onsite safety and efficiency. Each device comes equipped with a working basket for operators to stand in, virtual reality goggles and a control panel with joysticks and switches that mimic those on real machines. The simulators are designed to increase safety and efficiency by providing additional training for machine operators on different machine models and in a variety of high-risk scenarios tailored to the construction industry.

American training and certification company CertifyMe.net, specialized in forklifts, has introduced a VR program to practice in a risk-free environment as well. The tool eliminates any kind of injury or damage to equipment, allowing a trial-and-error approach without any kind of risk.

Lincoln Electric Company, specialized in welding equipment, has created its own VR training system called VRTEX 360. The system supports all position welding from flat, horizontal, vertical to overhead, immersing the learner in a realistic environment, including sounds, allowing them to train safely without using welding consumables, wire, or producing wastes.

Finally, VR training may prove invaluable for workers abroad or in rural areas, by providing the opportunity to train local crews without having to separate them from their families for extended periods for training programs.

9.4.1.4 *Communication and real estate*

With the advancement of VR technology, construction companies and real estate professionals have started to use VR to show their assets to promote sales.

Potential buyers have the opportunity to explore their future property in an immersive way and possibly choose the interior finishes by testing different alternative solutions.

Examples include Japanese firm Freedom Architects which annually builds around 400 custom designed homes providing their potential clients with a virtual tour of the property, or Woodhouse Workspace company which uses VR to show potential layouts of buildings, offices and different ways of using the building space. With VR, real estate companies have the possibility to show houses and apartments to all their customers without the need to personally visit each property, greatly expanding their territorial presence.

9.4.2 Augmented reality in construction

AR is the application of XR technology in real-world scenarios and has found considerable utilization in construction activities, allowing workers to superimpose data to the real-world view while on site by using wearable HMD or a camera-equipped mobile device (Behzadan, Dong, & Kamat, 2015; Kwiatek, Sharif, Li, Haas, & Walbridge, 2019). With the ability to provide real-time information, AR is being used within the industry to increase efficiency, improve safety, streamline collaboration, manage costs, and overall boost project confidence. AR merges physical and digital into one environment by projecting 3D images on a person's physical surroundings with a mobile device or HMD. Using GNSS positioning and cameras, the AR unit is able to present real-time data geospatially, updating, and displaying the necessary information as the user moves throughout space. Data such as schedules, operational details, and structural plans are easily accessible, supporting informed decision making on-site.

For instance, a project manager could hold a tablet up inside a home while standing in front of a window and take the client through several proposed window designs superimposing them on their actual position. AR technology also makes it possible to generate 3D models on top of a 2D plan, allowing for more accurate architectural visualization on-site. AR tools such as Trimble's SiteVision (see Fig. 9.24) and GAMMA AR can display the view ahead on a mobile device and superimpose 3D models with cm accuracy to preview buildings, infrastructures and utilities on-site. AR glasses also allow the wearer to teleconference with remote colleagues while in the field, offering workers offsite an effective view on the ground rather than relying on traditional communication methods.

Concerning CM, most BIM-based platforms and mobile field applications already enable users to plan, update, and manage construction works, as well as manage documents, visualize 3D models of a project and monitor construction project's status (see Section 9.1.2). In addition, some of those, such as Dalux TwinBIM and Autodesk BIM 360 Docs, allow AR fruition and interaction with 3D models and documents on site to assist inspection and report issues, enabling users to access to the latest project information through a 3D model and put it into a real perspective using AR. However, these are still limited in their ability to manage construction processes according to lean management practices. A more accomplished integration of AR into lean CM, in addition with 3D visualization and navigation, shall provide users with context-aware information on current progress, current performance with respect to the expected one, percent of completion reason for not completion, delay indicators, extra efforts, quality checks, construction errors as well as extra cost expected (Ratajczak, Riedl, & Matt, 2019).

AR finds application in progress tracking as well: Several solutions in the market use smartphone and tablet AR features to identify where they are in the floorplan and automatically take pictures at every capture point. Doing so ensures that team members always capture at the exact same location over time, thus improving progress capture efficiency and accuracy.

Overall, applications of AR in construction include the following main use cases (Röltgen and Dumitrescu, 2020; Song, Koeck, & Luo, 2021):

- assembly/disassembly support, by retrieving and displaying relevant digital work instructions, documentation protocols and animated procedures. In contrast to static paper-based instructions, AR provides information in a context-sensitive and intuitively understandable manner, thus enabling efficiency advantages and more flexible employee deployment;
- data visualization, by displaying data in a spatial context, including, for example, the visualization of real-time data from sensors, process parameters or aggregated performance;



FIGURE 9.24 Trimble SiteVision AR system. Courtesy of Trimble.

- remote collaboration and assistance, allowing to audio-visually connect people in real time, making expert knowledge available across different locations and organizations. By using mobile devices or smart glasses, the field of view of the person seeking help is streamed to coworkers and experts, allowing them to gain insights into the local conditions and provide verbal and visual instructions;
- quality control, enabling comparisons between the as built configuration and the design model by positioning the virtual information in the correct location, and allowing inspection-relevant features and deviations to be highlighted directly on the single component;
- construction process planning, by visualizing and virtually testing different process sequences, including crane trajectories or machine movements in a spatial context, or evaluating manual process sequences such as assembly/disassembly sequences;
- 3D modeling, by creating and modifying virtual geometries, and relating them to objects and environments of the real world. This enables an immediate contextualization of the virtual models at actual scale in the operational environment and the evaluation of critical aspects at an early stage, such as space requirements, potential collisions with adjacent objects and the accessibility to connections;
- safety on the worksite, by using AR glasses or mobile devices to scan tags or labels placed in specific areas or objects. These labels can then bring up text or 3D models to communicate specific safety or hazard information.

9.4.3 Mixed reality in construction

Mixed reality (MR) extends AR technology by allowing a more direct interaction between real and virtual elements, allowing the user to manipulate virtual elements as they would in the real world with the 3D digital content responding and reacting accordingly (Marr, 2020). MR goggles such as Microsoft Hololens or Magic Leap are advanced head mounted wearable devices that are able to scan and capture the surroundings and overlay them with interactive virtual data by integrating gyroscopes, accelerometers, Wi-Fi antennas, digital compasses, GNSS, conventional and depth sensing cameras (Sawhney et al., 2020). This sensor array reads a room in real time, understanding corners, edges and surfaces, and enables full interaction with the surroundings: digital content is rendered in the physical world at the appropriate distance based on the viewer's position and where they are looking. This way MR devices can give workers hands-free access to building plans, generate structural models from surrounding site scans, make distance measurements independently, and allow technicians and designers to make modifications while on-site. Hololens sets are more popular in the construction industry as they are already certified as basic protection goggles and are available integrated into hard-hats such as Trimble XR10 (see Fig. 9.25).

In construction planning, MR can be used to improve information retrieval from BIM models and thus reduce time and errors in related tasks. Using MR glasses, project team members can walk the construction site and digitally “tag” issues they encounter, such as cracks or misplaced elements. Each tag is attached to a 3D model of the space and is complete with embedded links to RFIs, drawing details, additional images, or preset tags, allowing workers to use the same glasses later to locate, diagnose, track, and ultimately resolve issues.

Moreover, MR can be used to measure a space's physical properties, including its height, width and depth. Construction companies can incorporate this data into as-built models, allowing them to generate even more accurate structures and have a more comprehensive view of how the project comes along. When wearing an MR unit, workers will be able to tap to automatically make measurements of the built components and compare them against the

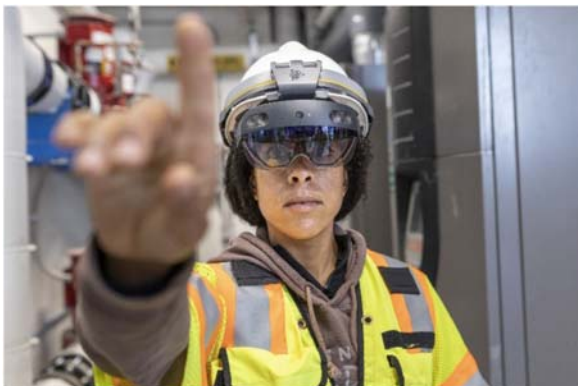


FIGURE 9.25 Trimble XR10 with Microsoft Hololens 2 MR device. *Courtesy of Trimble.*

measurements specified in the building models. This allows workers to find any inconsistencies in the structures and quickly adjust them to prevent higher costs and delays down the line (see Fig. 9.26).

One major innovation in MR is the ability for users to make changes intuitively to building models directly on site. As interoperability between different MR systems and BIM systems is completed, it becomes possible to automatically update BIM models and construction schedules (Delgado et al., 2020). Workers can easily display interior and exterior views of a structure and make any modifications to the virtual plans while keeping one view intact, for instance, removing and relocating walls or components or modifying the layout on their MR-enabled headset or mobile. This allows experts to troubleshoot any errors in a virtual view before applying changes to the physical structure. Since these digital data are continuously updated, it removes the guesswork from any projects change while improving the workflow and preventing any wasted materials.

By far, the most promising feature of MR is the ability to combine all digital data and documentation with one's physical view: information including the locations of pipes, walls, outlets, switches, and ventilation can be accessed directly on the site in layers that can be easily switched on and off. Having precisely positioned MEP overlays superimposed to the actual construction sites can guide subsequent works with great precision: For instance, contractors have been using robotic total stations and Hololens to visualize the planned underground piping grid and mark required excavations layout accordingly directly on-site, thus minimizing redundancy and unnecessary earth movements. The MR device can also overlay information about the working task at hand, by highlighting tools and components necessary or superimposing visual guidelines for brickworks or electrical installations (Fazel, 2018), up to entire step-by-step assembly instructions (see Fig. 9.27).

In particular, MR models have been observed to be easier to comprehend compared to conventional paper documents, allowing for faster assembly, and reduced number of mistakes made during construction. Furthermore, MR assisted construction showed that participants with no previous assembly experience achieved the best times using MR, and they were also faster than the most experienced participants who used traditional paper plans



FIGURE 9.26 MR overlay and interaction with BIM model with Microsoft Hololens 2 and Trimble XR10. *Courtesy of Trimble.*



FIGURE 9.27 MR overlay of brickwork guidelines with Hololens. *Credit: G. Janh, Fologram.*

(Chalhoub and Ayer, 2018), confirming the potential of MR to address the current lack of experienced or skilled labor in the construction industry.

BIM information retrieval also allows field workers to effectively monitor a project against its building plan and ensure its successful completion. MR can allow users to virtually see the building's progress against its schedule, providing an additional level of project management (see Fig. 9.28). Progress monitoring interface can provide color-coded overlays to easily identify sections of the construction site that are ahead, or behind schedule (Golparvar-Fard, Peña-Mora, & Savarese, 2009).

MR wearable devices can also enable a collaborative workspace between different professionals: as more complex construction projects require a great deal of collaboration between multiple teams, including designers, managers, carpenters, electricians, plumbers, welders, etc., a successful collaboration is needed at all times even if all the workers involved in a project are not always present on the job site. Instead of waiting for all the parties to assemble and review blueprints and make any changes, MR allows users to take notes and share video views of any suspected errors or design issues and send the information to remote teams in real time. On-site and remote team members are able to consult with each other and work with the information needed, greatly lowering the time and costs needed to make a decision among teams. This possibility of foregoing on-site group meeting can be particularly appealing whenever social distancing is desirable due to health concerns.

MR devices applications in H&S concern their ability to improve identification of field safety risks, improve risk recognition, and enhance real-time communication between the construction manager and workers, as well as supporting safety training and education. Communication of safety information with MR can be improved by video-feed sharing between the MR device on site and a tablet/PC off-site, allowing bidirectional communication between workers and safety coordinators concerning potential hazards, violations and suggestions on the worksite, and annotations and verbalized comments that can be tagged and georeferenced on both their actual digital and real position (Dai, Olorunfemi, Peng, Cao, & Luo, 2021). As MR glasses like HoloLens continuously build and maintain the 3D map of the environment, it is also possible to provide premises orientation and navigation on a construction facility or site with superimposed arrows, markers, and informational panels that precisely align with halls, doorways, and equipment.

Although only large construction firms have put MR to scaled use so far, it will become more accessible in the coming years as the technology comes down in costs. Many consultants and vendors are offering the technology on a per-project basis and with free trials, allowing construction managers to experiment with the new technology and apply it to their business. Despite its potential, however, this technology is still seeking momentum for widespread use. Comfort and safety are major concerns for a user wearing HMDs for long working hours. The equipment is often susceptible to

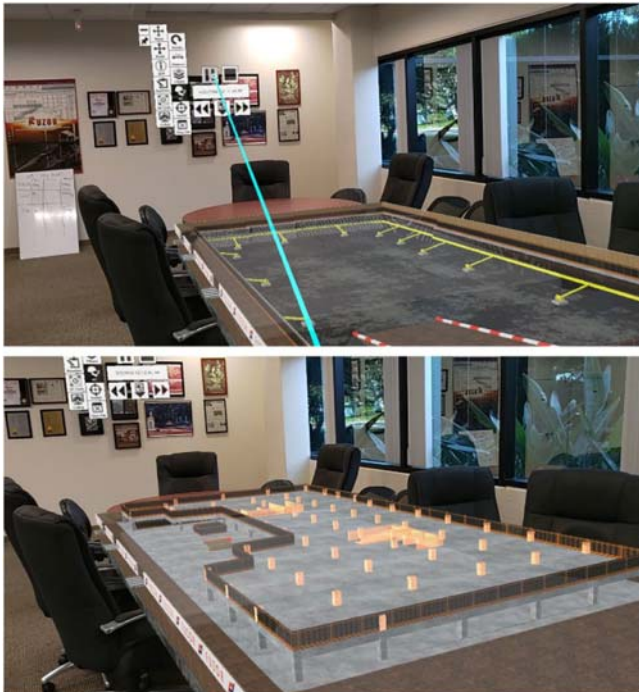


FIGURE 9.28 Integration of Fuzor VDC with Microsoft HoloLens. Courtesy of Kallos Studios, Inc.

adverse weather conditions and function best with a solid internet connection and static environment, all factors often incompatible with construction sites. Furthermore, as a novel application MR has a learning curve that may deter companies in the construction sector, more adverse to digitization, from investing in the technology.

9.5 Connected construction sites

All activities in the construction site generate daily a large amount of data and information relating to employees, machines, processes, materials, and environmental risks which, if properly collected, organized and analyzed, have the potential to provide a valuable support to management activities with the objective of improving productivity, safety, and compliance with times and costs.

Gathering these data, extremely difficult and burdensome if carried out with traditional manual methods, is now possible thanks to the integration of the IoT technology within the construction site, that is, “an infrastructure of interconnected objects, people, systems and information resources together with intelligent services to allow them to handle information of the physical and the virtual world and react” (ISO/IEC 20924, 2021).

With the development of IoT technology, more and more construction sites, especially larger and more complex ones, are characterized by the network connection of construction machines, equipment, materials, structures, and employees, able to monitor in a continuous and integrated way productivity and reliability of both personnel and resources (connected construction sites).

The application of sensors and wireless communication technologies to objects, machines, or people allows to generate real-time information on their position or physical state which can be collected for monitoring, control, statistical analysis, and decision support, creating an actual intelligent space. Relevant information can be displayed on mobile devices (see Fig. 9.29) or in web dashboards showing real-time data, trends and alert also over multiple construction sites (see Fig. 9.30).

Information sharing can also take place directly machine-to-machine, allowing devices to communicate and interact even without human intervention (e.g., by automatically programming the repair or maintenance of an equipment based on its state of use or its performance). Thanks to the development of edge computing, now smart devices are also able to process collected data directly without having to send them to the cloud for their analysis, with numerous advantages in cybersecurity against attacks and data theft, in reducing network load, in avoiding possible delays in case of immediate need to activate alarms, as well as in the overall dependability and quality of service of the system (Kochovski and Stankovski, 2018).

Construction specific IoT devices include connected time-clocks such as SmartBarrel, which enable employers to monitor workers, activities, schedules, and payrolls in real time among different construction sites, or connected hard-hats such as WakeCap which allow continuous tracking of manpower between production zones, support areas, and rest facilities to get insights on workflows and productivity.

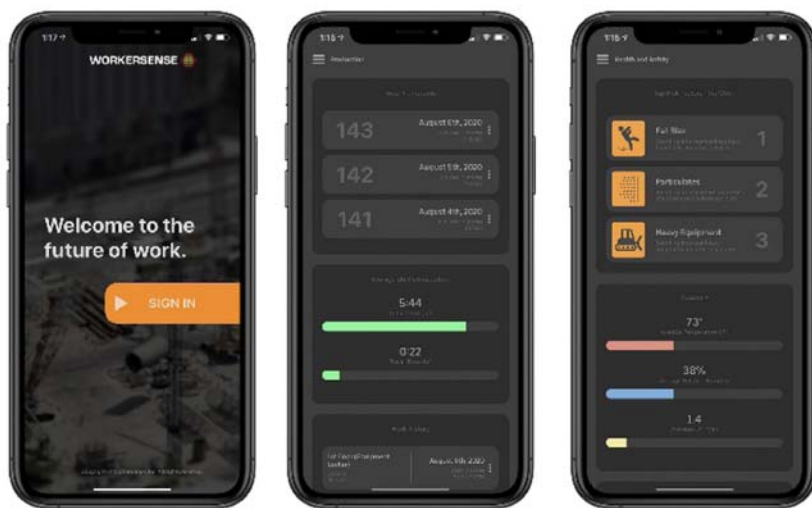


FIGURE 9.29 Construction site monitoring app. Courtesy of Workersense.



FIGURE 9.30 Construction site web dashboard. *Courtesy of Worksense.*

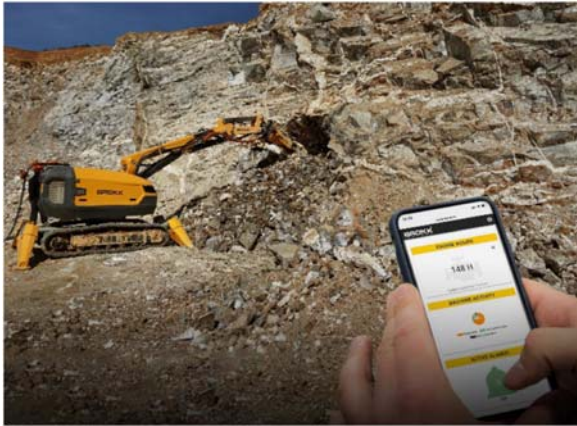


FIGURE 9.31 Brokk Connect app for remote fleet management. *Courtesy of Brokk.*

Solutions for site management such as Trimble CrewSight deploy RFID tags to workers and equipment, allowing to enforce access rules to the jobsite, reduce equipment theft, receive alerts if unauthorized access occurs, capture attendance and track workers' hours. Safety features include the possibility to send targeted mass communications and document workers' emergency contact information.

IoT devices distributed in the construction site can be used to monitor risk factors such as fires, smog, vibrations and high noise. In an emergency, safety devices can be activated alerting site workers to evacuate immediately. Furthermore, IoT technology can be incorporated into wearable personal devices such as helmets, jackets, or other objects, to identify and locate the worker and to determine their action and vital state. In materials management, IoT technology allows to quickly collect information on the state of consumption and stock, to automatically calculate supplies, to send notifications for purchase and to control the material delivery schedule. In addition, sensors can monitor the location and operating conditions of equipment and vehicles, monitor abnormal situations, and issue alerts for timely repair or maintenance in advance. For instance, systems such as Brokk Connect allow to access information on their demolition robot fleet that include tool time and operating hours, locations, current status and service notifications (see Fig. 9.31).

IoT can be useful for improving management of construction and demolition waste as well. Wireless sensor networks can be deployed to monitor on-site waste storage, determining how waste loads vary across the year and preventing waste pileups. Waste collection routes can be optimized to reduce recycling and disposal costs. Real-time waste management data can be used for reporting and improvement practices, as well as for the development of automated waste recycling protocols.

Statistical analysis based on all this information can allow to optimize workflows, reduce setbacks, detect deviations and anomalies, or identify potential risks. Predictive analytics engines can help prevent equipment and vehicle failures, thus reducing downtime, fuel costs, and maintenance expenses.

For instance, United States-based Uptake provides a unified scalable platform able to seamlessly ingest disparate, real-time and historical data from single or multiple construction sites to generate valuable insights via data analysis and workflow integration with ML algorithms, with particular focus on fleet management and deployment. Achievable benefits include prevention of unscheduled downtime, extension of the lifespan of machinery, and improvement of equipment dispatching and planning.

Particularly interesting is also the possibility of connecting the information provided by IoT devices to the BIM model of the building under construction, so that spatial relationships and current states can be viewed simultaneously in real time. Through the integration of BIM and IoT, it is possible to have a virtual replica of construction projects in which the IoT provides the dynamic information of people, structures, resources, and building status and the BIM model provides the structure for IoT information that can be systematically integrated and spatially demonstrated, achieving a complete digital twin of the construction site.

A key step for IoT in construction is to integrate the several point solutions now available into a “planned IoT ecosystem,” that is, an integrated layer of hardware, software, connectivity, and information flows linked to key decision making activities. This layer can be much wider than the construction industry itself and may include all other sectors that play some kind of role in a continually adapting built environment (Woodhead, Stephenson, & Morrey, 2018).

Main IoT communication technologies include RFID, NFC and WSN (Wireless Sensor network).

RFID technology enables automatic identification and storage of information relating to objects or people (automatic identifying and data capture, AIDC) by specific electronic labels, called tags (or transponders, or electronic and proximity keys), able to store data and to respond to remote interrogations by fixed or portable readers (also called interrogators). Through radio frequency, the reader is able to communicate and update the information contained in the tags it is querying. The RFID reading distance ranges from 10 cm to 10 meters as the output power and radio frequency increase (120–150 kHz—low frequency, 13.56 MHz—high frequency, 860–960 MHz and 2.45 GHz—ultra-high frequency). RFID technology is evolving rapidly, with equipment costs decreasing (scanners, receivers, and tags) and new applications emerging. Tags under development will include information on specifications, dates, defects, original equipment suppliers and manufacturers, maintenance records, operating parameters and other data to monitor for instance vehicle inspection, track tool usage and train workers on construction sites.

NFC is another very short range wireless communication technology, through which mobile devices can interact with each other over a distance of few centimeters only. All types of data can be transferred between two NFC-enabled devices in seconds by bringing them close to each other. This technology is also based on RFID, as it uses variations in the magnetic field to communicate data between devices. NFC operates over a frequency band of 13.56 MHz, which is the same as high frequency RFID. There are two modes of operation: active and passive. In the active mode, both the devices generate magnetic fields, while in the passive mode, only one device generates the field and the other uses load modulation to transfer the data. The passive mode is useful in battery powered devices to optimize energy use. One benefit of the requirement of close proximity between devices is that it is useful for secure transactions such as payments. Finally, NFC can be used for two-way communication unlike RFID. Almost all smartphones in the market today are NFC enabled.

A WSN system, on the other hand, typically comprises wireless functional sensor devices that can intelligently collect and communicate environmental information and even judge and act. The general application wireless network specification includes Wi-Fi (100 m range), Bluetooth (10 m), and ZigBee (50 m), as well as long range optimized networks such as LoRaWAN (+10 km).

Finally, IoT networks can take advantage of blockchain technology to create a verifiable, secure, and permanent method of recording data. Several blockchain providers, such as France based Kalima Systems, have developed embedded solutions for IoT devices in industrial applications in which trust and security are paramount, such as in construction sites. Blockchain allows in fact to hold the data produced by IoT in a transparent, secure and convenient environment, integrated with BIM as the baseline tool to digitize the construction project data (Hunhevicz and Hall, 2020).

9.6 Artificial intelligence in construction

The application of AI tools in CM can bring numerous advantages in construction site planning, activity scheduling, workforce and subcontractors management, fleet management, material procurement, safety, and security management,

in terms of optimization of both resources and time, of identification of current or potential issues and their characterization based on priority, of prevention of workplace accidents, and of identification of solutions and strategies to be implemented in management (Hong, Wang, Luo, & Zhang, 2020; Pan and Zhang, 2021b; Yan, Yang, Peng, & Ren, 2020).

In general, AI and ML may be used either for data analytics to derive knowledge from past experiences, for predictive modeling to apply the knowledge to predict new instances, or for decision making (McKinsey Global Institute, 2016).

Depending on the type of output desired, tasks performed through ML are generally divided into three main categories: classification, regression, and clustering (Gambella, Ghaddar, & Naoum-Sawaya, 2021). The choice of which learning method to employ depends on the nature of the problem and on the type and quantity of data available.

In classification problems, the objective is to find a solution that allows to predict to which category a new observation belongs among a finite set of known categories (classes), to assign it a label accordingly. Instances with a known category (labeled data) are used as a training set input. Classification can assign a single label or multiple labels to observations (multiclass classification). An example of classification problem is object recognition, in which the AI is tasked to determine what category of objects the item it is presented with belongs to, as well as character recognition or email classification problems (Soofi and Awan, 2017).

Regression problems can also provide prediction, but with different tasks respect to classification, as the model produces a numerical value instead of a label. Predicting real estate prices or power usage in an electrical grid are some examples of problems requiring the AI to predict numerical values.

Clustering, in turn, aims to group observations into homogeneous clusters according to their similarities, or lack thereof. Data instances are clustered by maximizing intraclass similarity and minimizing the similarity between different classes. Contrary to classification, the set of clusters are not known a priori but are driven by the training data. The goal is to assign autonomous labels according to the features of objects that may emerge as patterns. Clustering applications include anomaly detection, whereby algorithms can identify unusual data points in data sets—a capability particularly useful to identify faulty products, human errors or fraudulent activity; as well as association mining, where algorithms find associations among data points, a capability that retailers, for example, can use to identify what products are often bought together.

Construction managers have been finding value with AI and cognitive technologies to help automate many of the mundane but essential tasks to running their operations. They are finding AI helpful with scheduling-related tasks in order to prevent delays, conflicts, and other issues, both on the staff level and on the project and materials side.

In particular, large-scale, multiyear projects require the coordination of many complicated tasks and moving parts such as designs and blueprints, permits, and unexpected delays and changes that quickly get out of control for humans to manage without the assistance of technology. ML excels at finding patterns and outliers in these data.

In fact, a typical construction project can have thousands of open issues, hundreds of RFIs, and numerous change orders that are open on any given day. Trained with ML, AI acts like an actual smart assistant, helping managers to identify the most critical risk factors from a construction safety and quality perspective, automatically classifying them into actionable categories and alerting about the top critical things that need the quickest response.

Using pattern recognition and historical data, along with connections to scheduling systems and other associated information, AI has proven to help better manage schedules. Using ML, AI tools are able to spot and catch potential issues faster than humans. When it comes to scheduling, the use of AI can help to prevent costly delays on sites or amongst suppliers, vendors, and others involved in the process. Data from weather and traffic cameras can help determining optimal timing for construction phases. Lastly, construction AI assistants can perform a lot of duties on their initiative as well, for instance monitoring available materials and sending notifications in the case of depleting resources.

AI in construction can be exploited essentially either by using the AI services and tools provided by specific platforms (AI as-a-service), or using AI enabled software available on the market (software as-a-service).

9.6.1 Artificial intelligence as-a-service

Today, several software vendors provide access to AI as-a-service platforms (AIaaS) allowing professionals and companies to take advantage of AI for various business purposes. Well-known types of AIaaS include (1) cognitive computing APIs; (2) AI apps and agents; (3) ML frameworks; (4) fully managed ML services. Popular AI cloud offerings include the following: Amazon AI, Azure AI, Google AI, and IBM Watson.

In particular, AIaaS platforms such as Azure AI provide several options for APIs (see Table 9.8) that include cognitive services to make smarter decisions faster, to extract meaning from unstructured text, to integrate speech processing

TABLE 9.8 Azure AI cognitive services ([Azure Cognitive Services](#)).

AI objectives	AI services
Make smarter decisions faster	• Identify potential problems early on. • Monitor metrics and diagnose issues. • Create rich, personalized experiences for every user.
Extract meaning from unstructured text	• Help readers of all abilities comprehend text using audio and visual cues. • Build natural language understanding into apps, bots, and IoT devices. • Create a conversational question and answer layer over your data. • Detect sentiment, key phrases, and named entities. • Detect and translate more than 60 supported languages.
Integrate speech processing into apps and services	• Transcribe audible speech into readable, searchable text. • Convert text to lifelike speech for more natural interfaces. • Integrate real-time speech translation into your apps. • Identify and verify the people speaking based on audio
Identify and analyze content within images and videos	• Analyze content in images and video. • Customize image recognition to fit business needs. • Detect and identify people and emotions in images. • Extract text, key-value pairs, and tables from documents. • Analyze the visual and audio channels of a video, and index its content.

into apps and services, to identify and analyze content within images, videos, and text or to extract key phrases and other insights within all stored documents, images, and media (knowledge mining).

For instance, Azure's Computer Vision features built-in categories to search for features including faces, colors, and other content, and enables personalized models using the Custom Vision API. Applications allow to analyze video in real time and label content with object and concept classes, to extract text, generate image descriptions, and understand people's movement in physical spaces. Extracted features could include the number or quantity of objects in the construction site or whether a wall is fully erected or still in progress. (see [Fig. 9.32](#)).

The Anomaly Detector API, in turn, can add the capability to monitor operating data of construction vehicles and recognize anomalous trends that could lead to malfunctioning, so that problems can be quickly identified and solved before they generate downtime. This is accomplished by ingesting time series data of all types and selecting the best-fitting detection model.

Natural language processing (NLP) APIs allow instead to search unstructured text to identify key phrases and entities such as people, places, and organizations to understand common topics, trends and intentions. It can be used to classify construction terminology using domain-specific, pretrained models ([Suna et al., 2020](#)) (see [Fig. 9.33](#)).

AI and algorithms-based approaches can automate and streamline most workflows in CM; however, a user interface that adapts to the specific environment of construction works is key to ensure all players can exploit their full potential. Digitization of building documents and operations produces in fact large amounts of data which still need to be processed and aptly interrogated to provide meaningful knowledge, an ability that is usually delegated to IT technicians and consultants but can be automated and made available to all stakeholders for easy, quick, and hassle-free use via chatbot and voice interface technologies.

A chatbot is a software designed to automate regular Q&A queries and menial tasks a human would typically do, such as checking/adding an activity to the schedule calendar or asking the weather forecast, by having moderately complex conversations with users and following informal instructions provided by text or voice instead of task-specific commands. Thanks to advances in NLP as well as natural language generation (NLG), widely used virtual assistants such as Google Assistant, Apple Siri, Amazon Alexa, or Microsoft Cortana can already identify valuable information from everyday speech and determine the intent, the task or action requested, and the entities, parameters and keywords needed to complete the task, up to the communication of results to the user.

With a chatbot or voice interface, a simple textual or spoken request effectively replaces the entire process of opening different software tools, checking data, finding results, crossing them, and finally obtaining the answer of the action requested. Benefits are twofold: on the one hand, much time is saved by delegating these repetitive operations to the more robust AI engines, on the other hand, the simplest user interface, that is, common language, can be used by



FEATURE NAME:	VALUE
Objects	[{ "rectangle": { "x": 316, "y": 441, "w": 179, "h": 497 }, "object": "person", "confidence": 0.85 }]
Tags	[{ "name": "sky", "confidence": 0.9978939 }, { "name": "outdoor", "confidence": 0.9914944 }, { "name": "person", "confidence": 0.921316862 }, { "name": "clothing", "confidence": 0.896938562 }, { "name": "demolition", "confidence": 0.884053946 }, { "name": "man", "confidence": 0.826420367 }, { "name": "footwear", "confidence": 0.7437974 }, { "name": "crane", "confidence": 0.6842411 }, { "name": "building", "confidence": 0.6002346 }, { "name": "construction", "confidence": 0.529902637 }]
Description	{ "tags": ["outdoor", "man", "person", "woman", "snow", "orange", "people", "walking", "construction", "holding", "standing", "group",

FIGURE 9.32 Computer vision image processing in construction site. Image by the author.

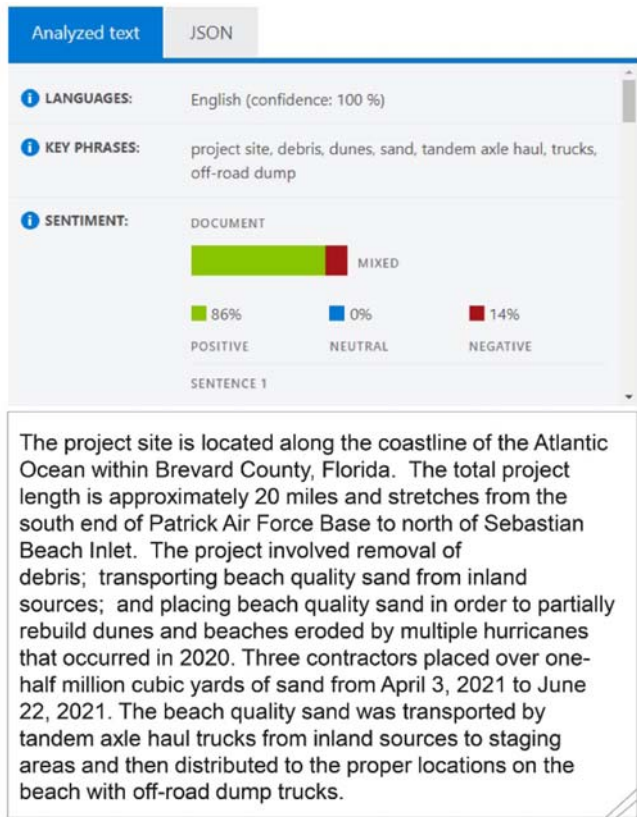


FIGURE 9.33 Data extraction from unstructured text with NLP. Image by the author.

anybody without any training or computer proficiency. These advantages are increased for voice interfaces, which can be activated hands-free by simply talking into a smart-speaker, wearable microphone, or headset. Possible uses in the construction site are several with great potential in increasing job productivity. Given the susceptibility of construction sites to noise, however, voice interfaces must be able to distinguish humans' voice from noise generated by construction equipment.

Leveraging the vast information pools available today in the digitized construction sites, voice commanded AI can quickly search through extensive data sets, do impromptu analyses and extract the knowledge or make decisions that would take human beings much more time. Activities that can be performed are numerous and can assist both works management and actual operations. For instance, a voice-assisted CM system would collect and process the required information through conversations with subcontractors, and automatically generate and share a daily report for general contractors (Cho and Lee, 2019). When asked by project managers about a persisting issue, a chatbot or voice-assistant can generate ad-hoc reports by browsing the databases and finding relevant data and repetitive patterns, and even provide tentative solutions based on its machine-training on similar recorded events. With the increasing integration of IoT in power tools, machines and equipment, and tapping in site surveillance data, chatbots are able to access any information on machinery (position, usage, battery level, suitability of the job at hand) and provide instantaneous feedback to the operator, including suggestions on what action to take. Tasks and whereabouts of any worker can be retrieved, and actions requested accordingly to ensure the best team productivity. Voice recognition techniques can be used for tasks such as recording and updating site material logs, as well as tracking and documenting project progress (Akinosho et al., 2020). Site workers should be able to summon the AI assistant to query and search real time information in project databases and BIM model just by using few words, such as by asking how to install a specific component or which materials in stock meet a design specification.

Finally, AIaaS platforms also provide ML framework tools that developers can use to build their own ML models. The company's own data or datasets provided directly by the platform can be used to train, distribute, automate, manage, and track the models themselves. Services such as Microsoft Azure Machine Learning offer environments for the development of any type of machine learning, from classic methods to deep learning (DL), with or without supervision, and able to interact with the most popular open-source DL and reinforcement learning (RL) tools, such as PyTorch, TensorFlow, scikit-learn, and Ray RLLib.

9.6.1.1 Machine learning

Traditionally, ML approaches are divided into three main categories, according to the nature of signals or feedbacks available to the learning system (Djenouri, Laidi, Djenouri, & Balasingham, 2018):

- *Supervised learning*, where the algorithm is presented by a “teacher” with example inputs and their desired outputs, with the objective to generate a general rule that maps inputs to outputs;
- *Unsupervised learning*, where unlabeled examples are given to the algorithm, leaving it on its own to find structure in its input. Unsupervised learning can be a goal in itself (discovering hidden patterns in data) or a means toward an end (feature learning);
- *Reinforcement learning*, where the algorithm interacts with a dynamic environment in which it must perform a certain goal. As it navigates its problem space by trial and error, it is provided feedback that is analogous to rewards, which it tries to maximize.

Regardless of the category of ML envisaged, the general framework comprises four main steps: data collection, data preprocessing, learning, and interpretation.

Data collection consists in harvesting information from different sources, including environmental sources such as sensors, archive sources such as events log databases, or other data sources. All data collected from heterogeneous sources must be stored in a single database.

Data preprocessing prepares raw data stored in the previous step before its use in ML techniques. Data is first enriched by adding statistical information, and cleaned of unnecessary noise, then is normalized according to the features desired for learning. The learning step is where input data are fed to the ML algorithm to generate functions and models. Lastly the learning from the previous step shall be interpreted depending upon the application used.

In supervised learning techniques, an algorithm uses training data and feedback from the programmers to learn the relationship of given inputs to a given output. In this technique, the ML algorithm is specifically told what relationship to look for, and the model is trained until it can detect with sufficient accuracy the underlying patterns and

relationships. Therefore, supervised learning requires to collect quality training datasets and label the inputs and outputs as pairs (x, y) , with the goal to generate a function $(F: x \rightarrow y)$ that accurately mimics the patterns between x and y . Once trained, this function would process inputs and deduce, or predict, the corresponding output even for unknown data. Supervised learning is good for classification and regression problems, such as determining what category a news article belongs to or predicting the volume of sales for a given future date.

In unsupervised learning techniques, on the other hand, the objective is to make sense of the data in itself., and there are no external measurements or guidelines to aim the learning process. The algorithm has to comprehend and sort the unlabeled data by detecting the patterns or similarities within them, instead of relating it to some external measurement. Unsupervised learning is commonly used when one does not know how to classify the data a priori and expects the algorithm to find patterns and classify the data itself. Unsupervised learning is popular in applications of clustering (the act of uncovering groups within data) and association (the act of predicting rules that describe the data).

Semi-supervised learning method combines aspects of both supervised and unsupervised learning techniques, and accepts data that are only partially labeled, making it appropriate whenever supervised learning would be optimal but there is a lack of quality training data. Semisupervised learning first determines the correlations between the data points, like unsupervised learning, then uses the labeled data to mark those data points. Finally, the entire model is trained based on the newly applied labels. Semisupervised learning has proven to yield accurate results from data sets with at least 25% labeled data. A suitable application for semisupervised learning is facial recognition, in which the vast number of images of different people is first clustered by similarity and then classified according to a labeled picture.

Finally, RL represents yet another category of ML, which is based on learning by trial and-error. RL is directly inspired by the human learning process, which interacts with unknown environments by exploring the effect of its actions and whether they are positive or negative according to rewards or punishments received. In RL, the algorithm takes an action on the environment, then receives a reward or a punishment if the action brings the machine a step closer or further to maximizing the total rewards available. The algorithm optimizes for the best series of actions by correcting itself over time according to the effect of its actions and the perceived rewards. There are no encoded data that directly pair the input to the output; rather, given the inputs, there is an estimation of how good or bad the output is. The general goal of the developed model is to learn patterns within a dataset that maximize the chances of acquiring a desired output or reward.

9.6.1.2 Deep learning

Today, DL constitutes the dominant approach in ML research and development and has been producing highly accurate results in several advanced applications such as computer vision, machine vision, speech interpretation, pattern recognition, natural language processing, audio recognition, machine translation, material inspection programs, and others. Compared to traditional ML techniques, DL can process a wider range of data resources, requires less data preprocessing and can often produce more accurate results, with reductions in error rate of 41% in image classification, 27% in facial recognition, and 25% in voice recognition problems (Chui, Kamalnath, & McCarthy, 2018). Conversely, DL typically requires a larger amount of data to do so.

DL is commonly based on extended artificial neural networks (ANN), which are inspired by how biological brains operate and consist in several interconnected layers of software-based calculators known as neurons (Afram, Janabi-Sharifi, Fung, & Raahemifar, 2017). An ANN can ingest vast amounts of input data and process them through subsequent layers to learn increasingly complex features and representations of data. The network learns how correct its outputs are and self-adjusts its structure accordingly, then uses what it has learned to make determinations about new data inputs. ANN and DL are explained with additional detail in Section 10.4.3.2. Deep learning algorithms include convolutional neural networks, recurrent neural networks, long short-term memory networks, generative adversarial networks, and deep belief networks. Although the idea of AI based on the observations on biological neural nets has been around since the 1980s, their computational complexity limited their diffusion by late 90 s, and it was not until 2012 that DL got real traction with the success in AI challenges such as the ImageNet where it outperformed all other ML models in computer vision tasks (Akinosho et al., 2020). DL development and applications have boomed since, spurred by the wider availability of much cheaper computing powers such as imaging GPUs, particularly suited for DL calculations, and its invention has contributed to a majority of the recent success of AI on several fronts, including natural language understanding.

The layered structure of deep neural networks enables in fact much smarter results when dealing with problems that require subsequent layers of abstraction, such as computer vision or language recognition. In case of face recognition,

for instance, the only data available are pixel colors; thus the problem is split between the first layers that process the image to extract data on lower-level features such as colors, contrast, edges, lines, then shapes, and subsequent layers that try to categorize this processed information to decide what the subject is (Taskirana, Kahramana, & Erdemb, 2020). This process also allows transfer learning, that is, the reuse of parts of a trained neural network to solve similar kind of problems without retraining the whole system, which may consist in hundreds of layers and thousands of neurons, with substantial benefits in terms of speeding up the training process and reducing the amount of training data required, therefore extending the possibility of employing accurate DL models over more candidates (Wei, Kusiak, Li, Tang, & Zeng, 2015).

Potential and available applications of DL-driven AI in construction are several, and take advantage of its abilities of computer vision, pattern recognition, as well as speech recognition (Yan et al., 2020).

Computer vision, in particular, can take advantage of the widespread adoption of image acquisition equipment in the construction site (fixed cameras, UAVs, LiDAR sensors, workers' body cameras, and smartphones) to convert captured image data into actual information useful for interfacing with other CM tools (Ekanayake, Wong, Fini, Peter, & Smith, 2021).

DL models have been used to improve site safety and health monitoring, for instance by detecting unsafe actions and behaviors from the site's video feed (see Fig. 9.34) (Ding, Fang, Luo, & Love, 2018), or tracking tiredness or fatigue of workers to ensure productivity and wellbeing (Akinosho et al., 2020). Object recognition can also find application in computer vision programs used in site navigation by autonomous vehicles and robots, improving their accuracy and allowing to track construction progress as well (e.g., by recognizing when certain building elements have been put in place). Image data can be also leveraged to automate structural monitoring and inspection activities, detecting and assessing defects, damages, and changes from referenced images such as concrete cracks, steel corrosion without resorting to laborious, error-prone, and often dangerous human inspection (Spencer, Hoskere, & Narazaki, 2019). Computer vision techniques can be applied to recognize the class of construction and demolition wastes (CDW), incorporating additional features extracted from the spectral analysis to enhance classification accuracy, such as the infrared radiation spectrum, which have discriminatory power to classify the chosen materials and facilitate a safer CDW recycling work environment and a higher quality in recycling (Hong et al., 2020).

Concerning project management, DL excellence in pattern recognition, along with regression and classification abilities, can be employed to perform advanced analytics on the progress of the project and of all subcontractors, tracking milestones and tasks against Gantt charts and activities schedule to identify and prioritize the main risks in terms of time, safety, quality, and cost issues, highlighting probable problem occurrences.

DL can find application in project accounting and cash flow prediction as well, in which AI tools can be trained with time-dependent real-world data, including some level of uncertainty and disturbance, in order to accurately forecast cash flows over the entire project delivery period based on the effects of determining factors/levers like sales, labor costs, material costs, subcontractors, margin, retention, and risks on the overall outcome of the project. An accurate forecast helps identifying potential issues and bottlenecks since the tender phase, enabling the identification of likely problems on time as well as the simulation of alternative what-if scenarios. In addition to cash flow, DL can also be applied to construction cost prediction, which is usually marred by nonestimated uncertainties such as duration, labor and equipment, seasonal changes as well as changes in economic variables and indexes (e.g., liquidity, wholesale price index, building services index) which together end up reducing the estimation accuracy. These additional factors can in turn be reconstructed via DL methods applied on a large enough project training dataset: for instance, by extracting relevant features from data via unsupervised DL then applying regression methods to perform more accurate cost predictions (Rafiei and Adeli, 2018).

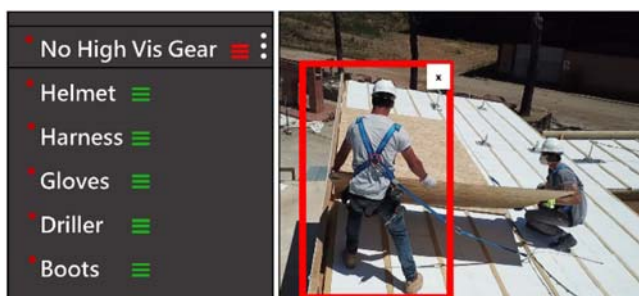


FIGURE 9.34 Use of object recognition to detect PPE compliance. Image by the author.

9.6.2 Artificial intelligence-enabled software-as-a-service

SaaS programs empowered by AI can offer unique features unavailable with traditional SaaS, such as transcribing and operating on new forms of data previously unidentifiable to computers (computer vision, NLP and NLG) or operating on a system or task that is too complex to handle without AI (pattern recognition, predictive analysis, process optimization).

For instance, Pye's SmartPlans leverages AI to manage core construction documents, including spec books and submittals. This AI-based application scans the spec books, then applies NLP and ML to put all of its elements into categories, enabling the automatic creation of request forms and other documents that need to be shared with stakeholders. By reading through unstructured drawings and documents, contract compliance items can be extracted ensuring no requirements are left behind.

Construction simulation platforms such as ALICE Technologies employ AI tools to support construction teams with the ability to explore alternative construction plans in real time and answer "what-if" scenarios on the fly, allowing the optimization of key project resources (e.g., labor, equipment, materials, etc.) to minimize risk, cost, and duration. This is achieved by first capturing the set of constraints that govern each project, then digitizing building methods, construction costs and production rates, allowing to capitalize on best practices and share them across projects. The software can be used to explore optimal sequencing scenarios for the whole construction process or for single complex bottlenecks. BIM-based generative simulations also allow to define strategies for faster completion times with optimized materials and workforce.

PAVE is another AI-based tool for construction monitoring, issue, and task management, that claims a 7% reduction in overall construction costs by automating construction documentation, task, and issue management using AI and Big Data analytics. In a first step, customers use PAVE app to access a digital construction plan or BIM model, locate defects on there, describe them using voice to text and images, and send them directly to subcontractors. As soon as PAVE gathered and analyzed a sufficient amount of data, it is able to automate the process: users would just take a picture of an issue and PAVE will automatically add all contextual information and address it, for example, by sending defect notifications automatically to subcontractors. The collected historic data from all construction execution projects using PAVE further allow to identify potential liability issues and legal claims in advance to inform and warn users (predictive analytics). Next to that, PAVE detailed database and ML algorithms allow to provide users with remaining time and cost predictions during a project, subcontractor ratings, and much more. To protect and secure crucial information as accurately as possible (unalterable information), PAVE is currently experimenting with different blockchain technologies such as Ethereum.

Construction companies are also starting to use AI and machine learning to better plan for distribution of labor and machinery across jobs. An AI constantly evaluating work progress and location of workers and equipment enables project managers to know instantly which job sites have enough workers and equipment to complete the project on schedule, and which might be falling behind where additional labor could be deployed.

Many construction sites are also using AI to run through what-if scenarios and contingency planning. The same pattern detection software that works well with scheduling can be deployed to look for common trends in the project. The AI is able to extrapolate from there what might happen if a permit is delayed or an incident happens and run through multiple scenarios very quickly. This forecasting exercise can help ensure plans are in place to deal with unexpected situations.

Increasingly, modern machines and equipment are adding various sensors to help with the overall function and operation. These sensors can monitor a variety of different conditions relevant to construction activities such as temperature, engine condition, and aspects of application of materials. When combined with AI tools, these data can be analyzed in real time to predict with a high degree of certainty problems, delays, or malfunctions that might occur.

For instance, predictive software can analyze a company's purchase history on project supplies and compare it against the actual amount that was used, and generate more accurate orders for future projects, preventing expensive surpluses.

By combining IoT with predictive analytics software, construction managers can establish more efficient supply chain processes and save money in the process. In logistics, managers have begun equipping units with web-connected ID tags. This makes it possible for a system to quickly count, track, and map the number and location of each individual unit at any moment in time. With access to accurate inventory numbers, project managers can provide their predictive analytics software with more accurate inventory data, resulting in better estimates on future projects.

A particularly interesting application of AI in construction is for image recognition and computer vision. The increasing integration of sensors and imaging devices in the construction site, that include CCTV surveillance cameras,

drones, wearable devices, and even smartphones, produces every day a wealth of data—roughly 50GB/week from an average sized project ([Enterprise Photo & Video Management](#)), constitutes in fact an untapped resource, commonly difficult to exploit to support site management.

Through AI is possible to quickly and automatically inspect and categorize these visual data for observation, monitoring, and prediction.

Computer vision, also referred to as machine vision, allows software to “see” and interpret the world around them—with facial recognition (which uses computer vision to identify people) being a prime example ([Pan and Zhang, 2021b](#)). The data being analyzed are in the form of photos or videos and can also include images from thermal and infrared cameras and other visual sources. AI powered by DL and ANN employs pattern recognition to distinguish the content of an image, after learning from a specific data set of other relevant images. Computer vision progressed from 50% accuracy to 99% in less than a decade, making modern software more accurate than humans at quickly reacting to visual data.

In particular, computer vision can be used in the construction site for the following main applications:

- safety monitoring and enforcement by recognizing how PPEs and other protection equipment are used and signal eventual unsafe or risky workers behavior;
- productivity monitoring by identifying activities, estimating their progress, and assessing performance of worker teams compared to schedule;
- logistic monitoring by identifying the position of vehicles and tools and tracking quantity of materials and wastes stored on the building site;
- workforce monitoring by detecting the number of people, the distance between individuals, and counting waiting, dwelling and working times;
- security oversight by monitoring unauthorized access to the construction site.

As an example, Doxel company offers AI-powered software that uses images provided by robots and UAVs to measure currently installed quantities and production speed and compare them with expected planning and design parameters. Construction errors can also be detected by comparing the construction site’s daily scans with design templates.

Regarding H&S, AI can contribute substantially to the reduction of the number of accidents. Several safety management platforms such as Easyflow CV and Smartvid.io can aggregate all sources of photo and video content into one system, which is fed to AI engines to sort and organize data using face and object recognition algorithms, allowing project teams to search on the imagery content (e.g., steel, trucks, ladders, rebar) in addition to more conventional metadata (date, project name, creator, etc.).

This way, AI technology can be used to identify and analyze security risks, and send notifications when PPEs are not used correctly on site. It can also be used to identify who is violating safety standards and tag them and/or their supervisors to address the problem or to anticipate possible dangerous situations. Safety Managers can add comments and markups, share with the project team or trades to drive behaviors, or use photos in safety trainings and jobsite orientations.

For instance, Easyflow CV software developed by Agmis can determine if workers are wearing personal protective equipment (PPE compliance) and identify certain worker actions. The software recognizes helmets, safety goggles, high visibility vests, protective boots, harnesses, and other safety equipment. If the software detects a PPE misuse, it can alert the site security officer in real time. Infringements are filed in a database with the corresponding video footage. Computer vision can also identify the duration of manual work cycles. For example, when building a scaffold, the software can determine the start of construction for a particular section and when builders move on to the next.

Construction-trained AI can be also instructed by ML on a multitude of previous projects and accident reports and can operate like a virtual H&S manager to automatically detect safety hazards and create dashboards and safety risk assessment reports to enable cross-project benchmarking for leading risk KPIs, such as PPE compliance, workers at height, ladders by type, slip trip, fall hazards, etc. Furthermore, predictive analytics can be carried out by collecting signals of risk from project image data, gathering information on safety culture and employee interactions, collecting indicators of risk for past safety incidents, and provide context by using data already collected in company systems.

For instance, Smartvid.io released its AI engine, nicknamed “Vinnie Predictive Analytics” that can predict accidents by automatically analyzing photos coming from CM systems like Procore and Autodesk BIM 360, plus site camera data from OxBlue cameras. The Smartvid.io predictive model was instructed through a partnership with the contractor Suffolk which contributed massive amounts of data concerning ten years of activity, including photos, PPE compliance reports and other observation-based analyses. Vinnie’s observation-based AI looked at every picture and automatically

identified safety risks like workers missing PPE (e.g., hard hats, high vis gear, etc.). Also considered was project information like the project type, weather, phase, and more. Lastly, Smartvid.io evaluated every single safety incident by project and date for the same 10 year period. This set of information gave Vinnie enough information to build an effective predictive model.

AI-enabled surveillance systems can finally help watch over the construction site for an additional level of security to prevent theft of materials and machinery at the site. Construction sites are using AI to automatically monitor security footage to spot any suspicious activity. These software perform traditional analytics such as alerting for movement as well as watching for specific actions or images that come into frame. The AI can monitor equipment, tools, and supplies and send out alerts if anyone attempts to steal something from the site.

9.7 Conclusions and future trends

To boost productivity, reduce project delays and cost overruns, enhance safety and quality, and manage the ever-growing complexity of building activities, contractors need to deploy more advanced and effective tools and methods for managing the construction site. Increased digitalization and the development and deployment of digital technologies and processes are driving a substantial evolution of established approaches to task scheduling, procurement and inventory, quality control, and safety.

In fact, new cloud-based CM programs allow to automate traditionally manual tasks, including monitoring progress stages, creating a centralized communication and collaboration space for the members of the team, planning resources, keeping track of client requests, etc. Integrated with the BIM model of the project, they allow virtual inspection, design review, quantity take off, planning and management of the sequence of processes and times of execution (4D), as well as construction costs and proceeds (5D).

During the construction phase, LiDAR scans and 3D reconstruction, performed by drones or autonomous robots, can be used to compare the as built geometry with the as-designed model to assess progress and identify any deviation, or with the final outcome, to verify that the construction is compliant with the initial plan. Drones and inspection robots increase efficiency and productivity in all these stages by surveying the site for progress, verifying contractor's reports, and assisting in confirming compliance with regulations, in the case, for example, of the storage of materials or waste or of safety violations on the worksite. The improved mobility of UAVs also provides easy and secure access to areas particularly challenging or hazardous.

Construction sites, especially larger and more complex ones, can deploy IoT devices pervasively to connect construction machines, equipment, materials, structures, and employees: this creates a continuous data flow which allows to monitor productivity and reliability of both personnel and resources (connected construction sites). Real-time information is generated on the position or physical state of any entity (power tools, waste/materials inventories, wearable devices) and can be collected for monitoring, control, statistical analysis, and decision support, including material requirements, preventive maintenance, usage data, workers' location and vital state, potential clashes, and interferences. Collected data can be fed to the digital twin of the construction site and to advanced analytics to gather insights to optimize site operations, for example, benchmarking fuel spending and energy usage, optimizing equipment utilization, locating storage areas and workstations to reduce nonproductive movements.

With the increase in available data, future trends in construction site management concern the integration of AI and ML in CM software to perform data analytics to derive knowledge from past experiences, for predictive modeling to apply the knowledge to predict new instances, or for AI-supported decision making. AI allows the optimization of both resources and time, the real-time identification of current or potential issues and their characterization based on priority, the prevention of workplace accidents, and the identification of solutions and strategies to be implemented in management. The insights gained from on-site data through the adoption of advanced analytics can help to improve efficiency, timelines, and risk management, saving time and money. Field-sensor data, construction-progress data, and workforce and vehicle movements can be fed to statistical and AI analysis to detect anomalies and identify potential risks. Moreover, ML driven computer vision allows recognition and categorization of visual data from cameras and drones, enabling automated inspection and prediction of productivity, logistic, and safety issues.

Finally, blockchain allows to address the various issues that conventionally emerge in CM pertaining contract enforcing, payments issues, quality control and, more generally, diffused distrust between clients, professionals, and contractors. In fact, the absolute transparency and trustworthiness of blockchain-certified data allows to implement so-called smart-contracts able to automatically match works' supervision, deliveries and payments, as well as ensure data delivery that is 100% reliable during delicate phases such as design delivery or project handover.

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Part IV

Smart building operation and management

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Building automation systems

10.1 System architecture, components, and services

In addition to the geometry, envelope and equipment, the final key element for reaching an energy efficient, comfortable and green building lies in how all its technological features are managed and operated over its lifetime. In fact, it is apparent that a good energy and environmental design, by itself, cannot guarantee appropriate performance levels during the whole life cycle without proper commissioning and technical management (Aste, Manfren, & Marenzi, 2017). Therefore the integration of Building Automation Systems (BAS), tasked with reducing energy consumption and facilitating building operation, monitoring and maintenance while improving occupants' satisfaction, has become an essential feature in industrial infrastructures such as factories, in enterprise buildings and malls, and in the last years even in the domestic domain, as part of the common strive to make buildings greener and smarter (Domingues, Carreira, Vieira, & Kastner, 2016). Smart buildings, in particular, are heavily based on real-time dynamic control over the different building activities, implemented by assimilating the main building systems on a common network and functionality to provide improved operational effectiveness, security, and safety (Younus, ul Islam, Ali, Khan, & Khan, 2019).

BAS, also called Building Automation and Control System (BACS), Building Management System (BMS), or Home Management System in residential applications, aims at monitoring, integrating, and automating the operation of most, if not all building services, including electric power, heating, ventilation and air conditioning (HVAC), lighting, active envelope components, access control, safety and security systems, transportation, and more, while allowing different degrees of interaction with the occupants. As long as any of these tasks is carried out in a technologically enabled and connected environment, it can be integrated into the BAS, which operates by first collecting and analyzing data, then by providing insights or taking necessary action by means of underlying control networks. A BAS is inherently scalable, that is, can control from just one device up to several thousand according to the application.

BAS have indeed been identified by several studies as a missing link for the successful implementation of zero-energy buildings and the deployment of an effective smart grid. Increased digitalization of building operation, including smart thermostats and smart lighting, could cut total energy use in residential and commercial buildings between 2017 and 2040 by as much as 10%, with cumulative energy savings of 65 PWh—equal to the total final energy consumed in non-OECD countries in 2015. Moreover, these benefits would be realized at a limited energy cost, as active controls are projected to consume only 275 TWh in 2040; far less than the 4650 TWh they could potentially save that same year (IEA, 2017). In addition, the optimized operation of systems connected to the BAS reduces wear and tear of machines and appliances, leading to longer operating lives and fewer maintenance interventions. The global BAS market is expected to reach US\$8.4 billion by the year 2027, trailing a CAGR of 12.4% over 2020–27 period (Research and Markets, 2020a). This fits into the forecasts of the overall smart building market size growing between 7.3% and 11.6% annually to overall market revenues of between US\$65.2 billion and US\$82.7 billion in 2025 (Research and Markets, 2020b), more of US\$25 billion of which added by increased connectivity, Big Data, machine learning (ML), and mobile applications (McKinsey, 2018). Research on BAS started in the early 1980s, when the raising development of information and communication technologies and a growing awareness on sustainability supported the industry shift to provide a more comfortable living environment for the occupants while consuming less energy. Early research focused on the automated operation of buildings, ignoring most interactions with occupants, but today the aspects related to users' satisfaction, involvement, productivity, morale, and well-being have achieved the same importance as energy conservation (Mofidi & Akbari, 2020).

Fundamental concepts of BAS are prescribed by the EN 15232 and ISO 16484 standards, which characterize the scope of functionality expected and their effects on typical buildings types and profiles. In particular, EN 15232 provides a structured listing of the control automation and BAS functions, the method for defining the minimum

specifications applicable to buildings of varying complexity with regard to automation control and BAS functions, as well as the way to estimate energy-saving factors within a building's energy evaluation. Four ranks of BAS energy performance are specified, namely, class D (nonenergy efficient), C (reference standard), B (advanced BAS), up to A (high energy performance). For reference, class B has become mandatory in the EU for both nonresidential new constructions and deep renovations; however, a large majority of technological systems in existing buildings still persist in class D. Energy savings achievable by installing an A-class BAS in place of a D-class system, according to EN 15232, are reported in [Table 10.1](#). A BAS consists of both hardware and software components. Hardware includes meters and sensors for data collection, computers, and cloud services for data analysis and visualization, as well as controllers and actuators to carry out the intended actions. BAS software programs instead serve as the interface between measurements taken and the building controllers. The building controller in turn applies the desired control strategies and can be a human operator or, more often, an optimization algorithm. Controller logics can take advantage of artificial intelligence (AI) and ML to be able to learn users' needs and behavior, to anticipate solutions or provide use recommendations.

Main BAS suppliers today in the market include Optergy, Computrols, ABB, Honeywell, Bosch Building Technologies, Omron, Priva, Schneider Electric, Nortek, Tridium, Johnson Controls, Siemens Desigo, General Electric, Energis, Wattics and Reliable Controls, with some systems more leaning toward HVAC and energy management and other more focused on security and access control. Although hardware has traditionally served as the primary revenue driver for BAS providers, in the connected era much of the intellectual property, feature set, and differentiation lies in the software and digital services portions of the infrastructure, which has led to new monetization approaches to service provision:

- Conventional product-based, in which hardware and software components are either sold individually, or, in the case of existing infrastructure players, provided at low or no charge in order to generate pull-through for the base infrastructure hardware. Customers incur greater up-front cost, although this can typically be capitalized;
- Subscription-oriented, in which hardware is sold as a product, while software and services are provided through a subscription-based platform, including background analytics, cloud hosting, and user interfaces as well as updates and support;
- Connectivity-as-a-service, in which end-to-end solutions are licensed through a subscription model that includes all hardware, software, and services for connectivity-enabled use cases. Sensors and controls are provided, maintained, and upgraded as part of the subscription and unlocked upon a subscription to each use case.

Among these business models, both subscription-oriented and connectivity-as-a-service approaches are beginning to take hold, outpacing a product-based approach in early adoption ([McKinsey, 2018](#)).

Most BAS enable user interaction via web-based dashboards, with more advanced ones also allowing a more natural-human interface based on gesture recognition, vocal commands, and chatbot conversation. Common functions of BAS include providing insight, enabling smart controls, metering, utilities billing, after-hours billing, automated

TABLE 10.1 Theoretical savings achieved by installing an A-class BAS in place of a D-level system (UNI EN 15232: 2012).

Building type	Thermal energy savings (%)		Electrical energy savings (%)
	Heating	Cooling	
Residential	26	—	15
Office	51	64	21
Conference halls	75	52	16
Schools	33	—	20
Hospitals	34	—	9
Hotel	48	57	16
Restaurants	43	57	12
Retail	71	65	16

reporting, live dashboards, and foyer displays. Overall, BAS allows for easy management of a building with minimal staffing, more so if enabled with remote access via the internet.

However, the production of large amount of data pertaining both the building systems and their occupants, as well as the digitization of sensitive building services such as fire detection, security alarms, or escalators/elevators, create new concerns about both privacy and cybersecurity issues.

Concerning privacy, challenges stem from the proliferation of sensors, data, and personalization at the heart of many connected-building use cases. For instance, for personalized temperature, lighting, or wayfinding services, user identity and location must be identified and transmitted across the network, likely out of the building's bounds toward cloud-based storage or services. Therefore infrastructure players need to be highly transparent with building occupants about what data are collected and how it will be used. Furthermore, increasingly stringent regulations on privacy, in particular, the EU General Data Protection Regulation 2016/679 on data protection, require occupants to be provided the choice to easily opt out of the collection of personally identifiable information if they so choose. To prevent too many users from opting out, thus decreasing the efficiency of the services that feed on their data, BAS needs to visibly link data collection with its associated use-case benefits directly to the end-users. This association, along with transparent data aggregation and anonymization whenever possible, should mitigate adoption headwind due to privacy concerns.

In addition to these privacy issues, the increasing digitalization creates significant risks, as the increased exposure to cyberattacks and incidents potentially jeopardizes the security of the building and the safety of its occupants, as well as the privacy of consumer data. New risks related to data theft, fraud and system hacking become increasingly severe in more connected BAS scenarios, in which malignant cyberattacks may target access control and CCTV security systems, electricity supply, internal and external communication, HVAC or, worse, fire detection and suppression systems. Therefore ensuring cybersecurity in BAS applications is a key issue to foster trust in digital technologies and prevent their exploitation as a means of compromising the cybersecurity of energy networks and sensitive buildings and infrastructure (e.g., large energy or industrial facilities, military or law enforcement installations, government buildings, etc.).

By definition, cybersecurity entails the preservation of confidentiality, integrity, and availability of all information in the cyberspace, intended as the complex environment resulting from the interaction of people, software, and services on the Internet or local networks. The relevant standard is ISO/IEC 27032—Information technology—Security techniques—Guidelines for cybersecurity. Today, several regulatory cybersecurity actions have been initiated at both national and international levels, including both guidelines and certification frameworks to provide comprehensive set of rules, technical requirements, standards, and procedures. In the EU, the current legislative framework refers to European Union Agency for Network and Information Security through the “EU Cybersecurity Agency” and the “Cybersecurity Act” on ICT cybersecurity certification, which provide the establishment of an EU cybersecurity certification framework to ensure the trustworthiness of connected devices in diverse sectors such as telecom, energy and transport networks, and new consumer devices, such as connected cars and smart buildings (Verbeke, Aerts, Reynders, Ma, & Waide, 2020).

Worldwide, advanced BAS applications grow by the day and are today an essential feature of high-end developments and retrofits for tertiary, residential, or industrial uses. A remarkable example of benefits achievable by BAS integration is Dubai Silicon Oasis technology park, a multifunctional district which was successfully brought under a single management system in 2020. This system connects almost 60,000 points of control from 40 buildings and plants including the District HQ, six office towers, a shopping center, the operations and facilities center, light industrial units, two residential complexes, a mosque, the Dubai Digital Park smart district, as well as multiple reverse osmosis systems, and several dewatering and storm water plants. Data are aggregated centrally and analyzed with AI algorithms designed to recognize patterns and react accordingly, enabling predictive scheduling and maintenance (see Section 11.2). Claimed benefits of the new system included energy saving totaling 36% per year, the reduction of the number of operators required to manage the 40 buildings from 110 to 5, and the ability to monitor electricity usage in real-time across all facilities from a single centralized control room.

BAS can employ AI and ML algorithms to greatly optimize the building management using weather forecasts, occupancy, usage, energy prices, and patterns identified in consumer behavior. Relevant examples include Google's DeepMind AI, which reduced the energy used for cooling in one of Google's data centers by 40% in 2016 (a 15% overall reduction in power usage) using only historical data collected from sensors within the data center (e.g., temperatures, power, pump speeds, set points) to improve data center energy efficiency. This AI system predicts the future temperature and pressure of the data center over the next hour and directly controls data center cooling, while remaining under the expert supervision of center operators (Gamble & Gao, 2018).

Most advanced BAS manage the connection of all building's systems in a centralized center of control, fully exploiting the synergy potential that comes from their integration. An example is the Edge office building in Amsterdam, fitted with 28,000 sensors which track movement, lighting levels, humidity, and temperature. Real-time data are used not only to respond and use building resources more efficiently, adjusting heating, air conditioning, and lighting to the effective needs, but also to change the way users work and interact with the building. A smartphone app helps users to find parking spaces, to share desks (there are about 1000 for 2500 staff), to reach other colleagues, as well as to adjust temperature and lighting levels around them. The app checks their schedules for the day and directs them to a sitting or standing desk, work booth, or meeting room. For smarter cleaning, activity is tracked by sensors built into light panels, so at the end of the day, people, and robots responsible for cleaning can focus on the areas that have been used most heavily that day. All HVAC systems, lighting, lifts, serving machines, towel dispensers, and robot security guards can be monitored and controlled centrally, and continuously generated data on how the building and its employees interact that are tracked by central dashboards.

In Microsoft HQ in Frasers Tower in Singapore, Bentley Systems and Schneider Electric implemented sensors and telemetry to create a fully connected workplace. A mix of 179 Bluetooth beacons in meeting rooms and 900 sensors for lighting, air quality, and temperature generates nearly 2100 data points that are stored and analyzed in the Microsoft Azure platform to optimize various aspects of the spaces, making them more comfortable for employees while reducing energy consumption and costs.

10.2 BAS topology

The architecture of a BAS can be organized into three levels (see Fig. 10.1): the field level, in which the interaction with field devices (sensors, actuators) happens; the automation level, in which measurements are processed, control procedures are executed and alarms are activated; and finally the management level, in which all the information from the entire system is collected, aggregated and represented in a unified way to the operator or optimization agent, and activities like system data forwarding, trending, logging, and archival take place (Domingues et al., 2016; Lilis, Conus, Asadi, & Kayal, 2017). The field level, in particular, concerns the relations with the occupied environment, either through data collection from sensors or by performing the required action with field actuators.

10.2.1 Controllers, sensors, and actuators

Sensors, and actuators are the devices interconnected by the communication network explained above and tasked with the actual interaction with the physical reality (field level), and therefore represent an essential component of any BAS. In particular, sensors are devices that convert a specific quality of the environment (temperature, humidity, number of occupants, etc.) into a measurable electric signal, whereas actuators react to these signals by closing or opening circuits or varying the intensity of determined electric loads, performing predetermined actions (e.g., operating window blinds, motorized valves, door locks). Both actuators and sensors are attached to I/O ports of hardware modules called

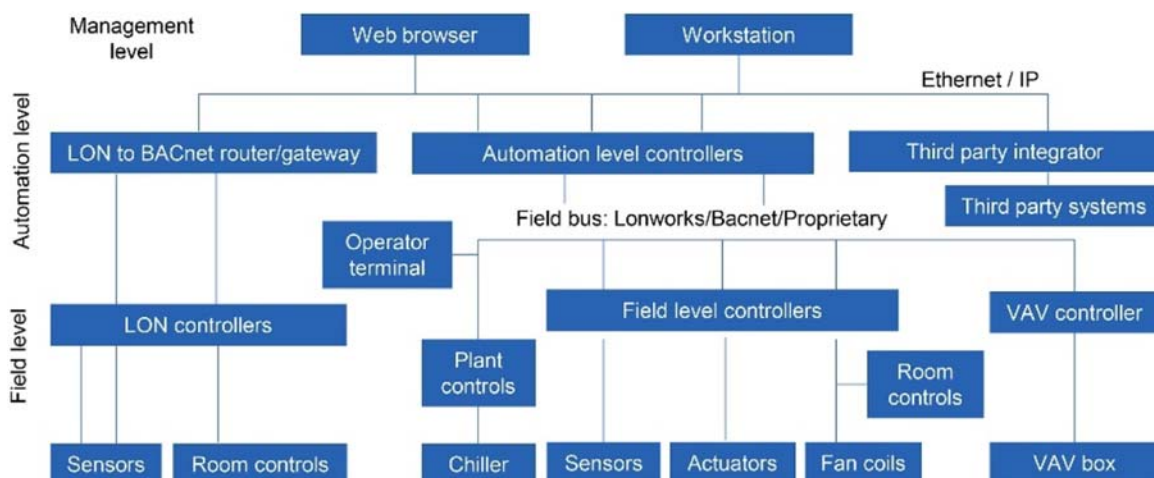


FIGURE 10.1 Typical system components-networks.

controllers, which in turn convert output commands from the BAS to electric signals and, conversely, create readings from sensors' inputs (automation level).

Sensors measure physical quantities, convert them to a digital or analog signal and communicate measurement and status information to the control and monitoring modules of the BAS. The rapid development in the last years of micro-mechanics, microelectronics, integrated optics, and other related technologies has facilitated the development of different types of sensors seamlessly integrated into daily objects and building infrastructure or worn by the users, referred to as Internet of Things (IoT), which allow to collect contextual information about daily living activities more efficiently and faster, with lower energy consumption and less processing resources (Qolomany et al., 2019). Main BAS sensors are reported in Table 10.2.

Specifically, occupants' comfort and well-being are mainly monitored with the following sensing applications:

- indoor environmental quality (IEQ) sensing, which requires ambient thermometers, humidity sensors, air velocity sensors;
- indoor air quality (IAQ) sensors, which include CO₂ sensors, VOC detectors, particulate matter (PM) sensors, and gas detectors (E-noses);
- illuminance metering, which is carried out with photometers, pupilometers, or photoresistor sensors;
- occupancy detection, which can be done through image-based sensors (IR and visible light cameras), motion sensors (ultrasonic ranging, passive IR sensors, photosensors, heartbeat detectors), radio-based sensors (wearable tags with RFID, Bluetooth, or Wi-Fi transmitters, mobile phones), or threshold/mechanical sensors (doors and windows contacts, badge readers, piezoelectric mats, IR beams, chair sensors) (Dong, Prakash, & Feng, 2019).

In particular, in the last decade, BAS have been benefiting remarkably from the advancements in computer vision technologies, that allow to analyze images and video footage like a human operator would, to extract information and activate actions in response to the detected content. This effectively integrates CCTVs and IR surveillance camera into the building smart sensor network. Through computer vision it is now possible to:

- determine a person's identity, age, gender, or emotional state from face analysis (face recognition);
- identify the number of occupants;
- measure distances between individuals or objects;
- distinguish the actions performed by the supervised subjects;
- discern gestures;
- identify dangerous situations;
- mark objects;
- recognize clothing and accessories;
- evaluate the state of equipment for repairing and predictive maintenance.

Within the building, this information can be used unobtrusively to authenticate people for access, count people for crowd control, start customized scenarios (HVAC, lighting, music, etc.) according to the recognized identity, send

TABLE 10.2 BAS subsystems and sensors.

Subsystem	Sensors
HVAC	Temperature, relative humidity, air pressure, particle counters, air flow patterns, CO ₂ concentration, dew-point sensors
Energy	Energy meters, consumption indicators, power sensors
Environment phenomena	Luminescence (light level), wind speed and direction, rainfall, irradiation
Safety	Gas, fire, smoke, heat detectors
Security	Occupancy sensors, motion detectors, volumetric sensors, doors status, biometric sensors, surveillance cameras, wearable tags
Water management	Pressure sensors, flowmeters, leak detection, water tank level, flooding sensors
Miscellaneous	Vibration, noise sensors

notifications, activate alarms or warnings, etc., making computer vision techniques particularly suitable also as smart human interface.

Conversely, the great progress in the field of applied nanotechnology, in particular in nanostructured materials, has advanced the capability and lowered the price of gas sensing and IAQ monitoring devices. Nanomaterials of 0D, 1D, 2D, and 3D types, characterized by large surface-to-volume ratio, excellent semiconducting properties, and high surface sensitivity, have been applied to the production of photonic, electronic, and chemical-sensing devices which can be utilized for a wide range of IAQ detection applications (Van Tran, Park, & Lee, 2020).

Actuators, on the other hand, link the control signal coming from management to the controlled device, translating the signal from sensors into an action of the device. Depending on how advanced the BAS is, actuators are used in different ways. In basic applications, they have to manage sensors input themselves and directly actuate the predetermined control function. In more evolved systems, the supervisory control layer first acquires data from sensors, then controls actuators; therefore they do not act in a direct way.

The interaction between sensors and actuators is orchestrated by the controllers, which usually consist of application-specific hardware with embedded software that dictate their operational logic. Depending on its sophistication, the controller can run more than one control program simultaneously, read and write I/O ports or communicate with other controllers over the fieldbus network, and the complexity of the control logic may range from simple binary conditions developed using ladder logic or function blocks, to mathematical expressions or more sophisticated algorithms. According to their control functions, controllers are categorized as programmable logic controllers or direct digital controllers (DDC): the former execute simpler and more rigid functions that require little or no configuration, the latter are more flexible and typically implement functions that require extensive configuration such as time scheduling or complex scenario management. Finally, control functions can also be implemented in nonembedded software running in the BAS server (management level), where the control logic can make use of aggregated data from different fieldbus segments. The advantage of a software solution is that it may undertake more complex decisions or explore additional information gathered from the system (Domingues et al., 2016). When DDCs are networked together, they share information through the data bus with each other and with the central control system using proprietary or, more commonly, open protocol languages. These communication protocols are described in Section 10.2.3.

10.2.2 Communication infrastructure and protocols

In any BAS, thousands of information flow continuously between the three different levels (vertical communication) and between devices within the same level (horizontal communication).

Horizontal communication between devices at the field level is carried out by the fieldbus, a digital data bus with an improved communication quality in comparison with previous analog communication buses. Devices connected to a fieldbus network are expected to have some computational power, thanks to on-board microprocessors, and may even replace several analog devices simultaneously, further contributing to decreasing installation costs (Domingues et al., 2016). The fieldbus allows to gather on a single line of communication all information relating to the operation, status, and alarms of all the devices that make up the system, with the possibility of creating all the operating logics.

Vertical communication between levels takes place, instead, via a common, IP-based backbone referred to as control network, which in turn is a digital connection that allows to link groups of nodes (computers) between each other.

10.2.2.1 Communication infrastructure

The communications between BAS devices, and with cloud services or gateways involve different networking technologies that can be wired (USB, Ethernet, optic fiber, etc.) or wireless (Wi-Fi, Bluetooth, Zigbee, cellular technology, etc.). Fieldbus communication to sensors and actuators is usually demanded to cabled connections, with the traditional 4–20 mA twisted pair standard conventionally employed for industrial automation having been replaced over time by fieldbus-specific systems based on Ethernet or CAN BUS standard. These allow much more flexibility in organizing field devices as a single cable can carry the signal of dozens or more devices, instead of having a single pair per each instrument gathered in cumbersome multipair cables. Similarly, control network in modern BAS is usually based on the UTP LAN infrastructure of the building already used for ICT applications.

As an alternative, powerline communication (PLC) instead employs the building electrical network, using the available electrical outlets to transmit data and control signals to devices, appliances and services that are already connected to the building's power supply. Information transmission and exchange is ensured by first coupling data onto the power line with a transmitter via brief radio frequency burst, then decoupling information on the receiver end with a modem.

PLC was originally used to secure the electric power supply system in case of failures or breakdowns through the direct exchange of information between the distribution center and the power plant. Advantages of PLC include its inherent robustness and low cost, as no dedicated wiring is required. However, cheapest PLC devices only enable one-way communication (i.e., they can only receive commands but do not acknowledge their status to the rest of the network), in addition to inferior bandwidth and worse noise interference compared to separated physical networks.

BAS networks, and fieldbus communication in particular, are heavily based on industrial automation practices, which typically impose severe requirements in terms of real-time communication, reliability, and dependability. Therefore wireless fieldbus networks have seen limited development so far because industrial plants represent a hostile environment due to the presence of different noise sources which can easily interfere with the wireless information signals and creates erroneous interruptions on the data transmitted (Kim & Tran-Dang, 2019). On the other hand, wireless BAS connections have seen increased interest as building services and management systems have become increasingly complex, with labor related to wiring activities becoming a primary factor in overall system costs. Wireless communication is also essential for the increasing integration of IoT devices in BAS. Traditional wireless solutions such as Wi-Fi and Bluetooth can be prone to frequency disturbances and clashes with other devices and are therefore more suited to domestic applications for home automation. For full-sized BAS, specific wireless systems, such as ZigBee, have been developed, which forego the traditional point-to-point or point-to-multipoint approaches and implement a mesh network offering the potential of more resilient, easily expandable and flexible solutions. Most mesh networks use end nodes, which are the primary sensing devices, to relay their signals through one or more router nodes (which may also act as sensors). Each router then forwards the signal to a gateway device. All mesh devices relay signals for each other, so if a given sensor fails or is out of range of the gateway, other members of the network can carry that data (self-healing mesh network).

Wireless BAS are particularly suited for retrofit projects, in which wiring may be challenging, or for spaces which may often be reconfigured, such as offices, where moving partitions or cubicles would not require wire rerouting.

Maximum flexibility is achieved by employing battery-powered wireless sensors and devices, which have the advantage of quick, plug-and-play installation at any location regardless of powerlines and make upgrading systems and introducing new technologies much simpler. However, regular maintenance such as battery changes need to be factored into the time/cost equation.

A recent alternative for wireless communication based on radio frequency (RF) signals, such as Wi-Fi, Bluetooth or mesh networks, is constituted by Li-Fi, a data transfer system that uses light as a medium to transmit digital information. Li-Fi operation is based on the high frequency modulation of light emitted by LED lamps, which is switched on and off repeatedly to transmit the equivalent digital sequence of 1s and 0s binary numbers toward a light sensitive receiver. Uplink communication is instead usually carried out by IR pulses. Light bulbs flickering occurs at more than 1 MHz, hence is invisible to the human eye which can only sense flickering below 150 Hz. Li-Fi is a form of visible light communication (VLC), which in turn belongs to the optical wireless communication category along with more conventional light-based transmission such as IR communication. The term was first introduced by Harald Haas during a 2011 TEDGlobal talk (Haas, 2011), and today several companies are entering the market with Li-Fi solutions, such as Trulifi (Signify), Zero1, Oledcomm, and Haas' own pureLiFi. Li-Fi potential advantages over conventional wireless RF methods include low cost, no interference with other transmission, high speed of information transfer, and data security.

Li-Fi is considered a low-cost solution because it can largely leverage the existing lighting ecosystem of any building: it is sufficient to install Li-Fi enabled luminaries or integrate existing LED lamps with a driver which is tasked with encoding the bits data stream in the light by changing the flickering rate of the LED. However, Li-Fi luminaries themselves have to be connected via cable or Wi-Fi to relay data.

Concerning interference, Li-Fi depends on visible light between 400 THz (780 nm) and 800 THz (375 nm) (Benson Mansingh, Nithya, & Krithika, 2016), whereas radio-based wireless methods operate on a limited frequency band (between 2.4 and 5 GHz for Wi-Fi) with much lower capacity, leading to signal overcrowding of the same wavelengths and therefore interference with other devices. Li-Fi effectively eliminates any overlap with conventional RF networks and allows its application even in electromagnetic sensitive areas where interferences with other equipment are not allowed, such as hospitals, military installations, power plants, industrial facilities, up to aircraft cabins.

Data transfer rate of Li-Fi is theoretically very high (> 1 Gbps), with effective bandwidth of commercial solutions up to 250 Mbps. This speed is comparable to last generation Wi-Fi protocols (IEEE 802.11ax, known as "Wi-Fi 6"), but with a more reliable and stable infrastructure that is able to handle numerous devices without degrading its performance. This is mainly due to the light spectrum being more than 1000 times larger than radio wave spectrum used in RF connections.

Finally, Li-Fi is considered an inherently secure form of data transmission, as light waves are physically constrained into the indoor environment by opaque walls and are therefore impossible to hack into from outside the room. This on

the other hand limits Li-Fi range relative to Wi-Fi (around 8 m in barrier-free areas compared to 25 m), although more luminaries can be installed to expand reach. Li-Fi bulbs have to be kept on to transmit data, but can be dimmed to the point that they are not visible to humans and yet still functional. Direct line of sight is not necessary for Li-Fi to transmit a signal, as light reflected off the walls is still sufficient to achieve 70 Mbits/s (Kalidhas, Ninan, Mathew Chacko, Saseendran, & Chandran, 2016).

In view of these characteristics, Li-Fi has great potential as a communication infrastructure for BAS applications. The growing adoption of wireless field devices, also spurred by the diffusion of consumer-grade IoT products, is already taxing the existing wireless and mobile network, and shifting BAS communication to the light spectrum frees capacity for other uses by the occupants. Li-Fi security characteristics are also perfectly suited for building automation, in which interferences and malicious intrusions may hinder the building's operation and the safety of its occupants, in particular by disrupting subsystems such as lighting, fire safety, access control, or building security (Ismail, Ahmad, & Arshad, 2020). Finally, VLC technologies such as Li-Fi are already used as a mean for indoor navigation, with each luminaire sending its own unique identifier to a user's smartphone, allowing the system to accurately pinpoint their location in the building and provide step-by-step guidance.

10.2.2.2 Communication protocols

Simply connecting BAS devices in a network is not sufficient to allow information flows: in fact, a set of rules must be defined for specifying the ways in which these nodes can exchange data (communication protocol). Interoperability between subsystems and equipment of different nature and by different manufacturers has traditionally been suboptimal, since every vendor on the market employed proprietary communication protocols requiring extensive work for their integration, normally by developing specific hardware (gateway) or software (driver) solutions. As the market progressed, fewer, standardized communication protocols emerged, greatly simplifying system integration, reducing the numbers of communication wires between the different nodes of the system, and therefore reducing costs. Standard communication protocols are also a guarantee for the investment of the end customer, who is no longer bound to a single manufacturer, but can use systems of different manufacturers without having to modify or replace the installed devices.

Currently, there are several communication protocols on the market, each with its own technical specifications (i.e., transfer speed, maximum cable length, supported transmission media, number of connectable peripherals, wired or wireless communication, etc.). In the field of BAS systems, most widespread and internationally regulated standard protocols are KNX, Lonworks, and BACnet, with Modbus, ZigBee, and EnOcean protocols also widely employed. Wi-fi and Bluetooth wireless communication is mostly employed by IoT sensors and devices, whereas short-range protocols such as near-field communication (NFC) and radio-frequency identification (RFID) see little application in BAS.

KNX

KNX communication protocol is designed to be used in electrical installations, in order to manage the different functions of a building—lighting, solar shading, HVAC, security systems, energy management, remote control, accounting—within a single system ensuring the reduction in wiring and complexity. KNX comes from the merge of the three standards European Installation Bus (EIB), Batibus and European Home System (EHS). In the field level, the standard defines the physical layer based on either twisted pairs, PLC, RF, or Ethernet. In the automation level, the KNX supports various modes for their compatible devices, permitting both autonomous device functionality and customized programming interfaces. KNX is widely used in Germany and parts of Europe and is approved throughout the world as an international standard for “Home and Building control” by the following bodies:

- International Standard ISO/IEC 14543–3 (since November 2006);
- European standard CENELEC EN50090 and CEN EN 13321–1;
- Chinese standard GB/Z 20965;
- American standard ANSI/ASHRAE 135.

LonWorks

LonWorks standard is designed so that it can be used in the centralized automation of both large buildings and small and decentralized automatic controls. LonWorks is widely used in BAS, particularly at a European level. Although most installations on the market favor the use of LonWorks for the field level, its application can also be extended to the automation level given its characteristics and functional profiles. This bus system is standardized according to

ANSI/CEA-709.1-B and ISO/IEC DIS14908, and consists in the LonTalk communication protocol, in a dedicated system-of-a-chip (neuron chip) and in the network management utilities and infrastructure. The standard does not require a single particular network topology or physical layer, and instead enables direct communication between devices using repeaters, bridges, routers, and gateways, instead of transporting the data through a master. The neuron chip, essential for interfacing the field devices and for communicating on the LonWorks network, contains the entire LonTalk protocol stack as well as the required firmware and the operating system on a multi-CPU and shared memory setup.

BACnet

BACnet standard was created by ASHRAE (American Society of Heating, Refrigeration and Air-Conditioning Engineers) precisely for use in building automation and is also recognized as ANSI/ASHRAE standard 135/2008 and ISO 16484–5. BACnet is widely used in BAS applications around the world, particularly in North America where it was initially developed. BACnet employs an object-oriented programming approach to standardize the representation of data and processes within the building, exposing standard services for accessing data and for acting on building infrastructure. However, it does not define the internal data structures, control logic, and configuration vectors of each field device, which are left open to the discretion of the manufacturer. Furthermore, to ensure highest interoperability between different vendors and types of field devices, BACnet does not standardize the data link and physical layers of communication between the field devices, which are only interfaced by the BACnet's network layer (Lilis et al., 2017). Given its characteristics, this communication standard offers the maximum of its potential in medium/large size, multi-site, and highly integrated systems.

Modbus

Modbus is one of the most widespread standard protocols in the field of automation. Although dated, it still has a strong diffusion as a result of the extensive availability on the market of field devices that use it. The transmission technique penalizes it in terms of performance compared to the other standards described, but its simplicity, the size of the installed base, and the wide offer make it an option that is still widely used at the field level, especially in electrical systems for acquisition of measurements from multimeters or network analyzers. Many HVAC equipment manufacturers such as refrigeration/boiler units still support this standard protocol.

ZigBee

ZigBee is a wireless technology based on the IEEE 802.15.4 standard. It was developed as an alternative to the already existing wireless standards, such as Bluetooth and Wi-Fi. Unlike these, however, ZigBee is used in embedded applications, in which a low communication speed is sufficient but at the same time a low power consumption is required. Advantages of ZigBee include low costs of devices and their installation, suitability for installations on existing buildings, low consumption, possibility of creating reliable and easily extendable communication networks up to 65,000 nodes, as well as good interoperability between devices by various suppliers on the market. The worldwide approved ISM radio bands for Zigbee are 2.4 GHz, while other frequencies are also available to use in different countries. Transmission distances range from 10 to 100 m, depending on power output and environmental characteristics. Sub-GHz channels transmission ranges up to 1 km.

EnOcean

EnOcean radio protocol is a passive wireless communication technology optimized for transmitting information with minimum energy consumption and maximum reliability, and for allowing to design and use battery-free devices. As with ZigBee, this technology offers numerous advantages in terms of application, including flexibility and ease of installation, compatibility with existing buildings, wide range of interoperable products by different manufacturers, low environmental impact, zero consumption, and lower maintenance costs as devices do not need any energy source.

Bluetooth low energy

Bluetooth is a wireless communication protocol, widely used by IoT wearables and devices for short-range communications. In particular, the bluetooth low-energy (BLE) standard was designed for the needs of low consumption of battery-powered IoT devices. Compared to standard Bluetooth and Wi-fi, BLE has a relatively shorter range and transfers only smaller portions of data at a time, with no data streaming support. BLE is not compatible with standard Bluetooth. There

are two types of devices in BLE: a master device, which acts as a central control, and various slaves to which it connects. To save energy, slaves are by default in sleep mode and wake up periodically to receive packets from the master, whereas in classic Bluetooth the connection is on all the time even if no data transfer is going on. BLE supports 40 channels with 2 MHz channel bandwidth (double of classic Bluetooth) and 1 million symbols/s data rate, and supports star network topology with unlimited number of nodes (Al-Sarawi, Anbar, Alieyan, & Alzubaidi, 2017).

Wi-Fi

Wi-Fi is a communication technology that uses radio waves for local area networking among devices based on the IEEE 802.11 Standards, using the 2.4 GHz UHF and 5.8 GHz SHF ISM radio bands. This technology is widely used in consumer electronics such as personal computers, phones and tablets. Crucially, Wi-Fi supports IP connectivity, and enables any device within the range of wireless modem to attempt to access the network. However, this is also a shortcoming due to security issues, as it is comparatively vulnerable to attack in contrast to wired cable connection (Jia, Komeily, Wang, & Srinivasan, 2019). Most suitable for BAS application, in particular for integration of IoT devices, is the recently developed “Wi-Fi HaLow,” based on the IEEE 802.11ah standard, which consumes lower power than a traditional Wi-Fi device and also has a nearly twice range. IEEE 802.11ah operates in the subgigahertz band (900 MHz) and is also designed to support large star shaped networks, where a lot of stations are connected to a single access point.

Long-range wireless communication

For wireless long-range communication (Wide area network, WAN), most common technologies include low-power wide-area network (LPWAN) and cellular technologies. LPWAN was created specifically for IoT devices to allow long-range wireless communications between objects at a low bit rate on low power consumption by sending data periodically in small portions. LPWAN data rate ranges from 0.3 to 50 kbit/s per channel. The operating range of LPWAN technology varies from a few kilometers in urban areas to over 10 km in rural settings, and its simplified and light-weight protocols reduce complexity and costs and allow battery life in the dozens of years. Notable LPWAN techniques include LoRa modulation and the associated LoRaWAN protocol.

Cellular networks in turn offer reliable data transfer and nearly global coverage, at the cost of higher energy consumption compared to LPWAN. These are most indicate for freely installed IoT devices in both indoor and outdoor spaces. There are two cellular standards developed specifically for IoT things. LTE-M (Long-Term Evolution for Machines) enables devices to communicate directly with the cloud and exchange high volumes of data. NB-IoT or Narrowband IoT uses low-frequency channels to send small data packages. The already widespread Long-Term Evolution (LTE) was developed for high-speed wireless communication based on GSM/EDGE and Universal Mobile Telecommunications System/High-Speed Downlink Packet Access (UMTS/HSdPA) network technologies and is in service in the industry for mobile phones communication, due to its capability of providing multicasting and broadcasting service. The wider adoption of 5G cellular network all around the world promises even better bitrates and lower latency, competitive with WAN technologies such as Wi-Fi.

However, none of the aforementioned BAS specifications and protocols provides singularly all the functionality prescribed by ISO 16484–3 and EN 15232, although BACnet is the one closer to full coverage (Domingues et al., 2016). Consequently, more than one technology is commonly required to get all the desired functionality in more complex infrastructures, requiring the integration of distinct technologies mainly through the deployment of gateway-based solutions that translate messages from one protocol to another (e.g., Intesis MPAS), or of multiprotocol devices (e.g., Ilevia Eve X1, compatible with KNX, Modbus, Z-Wave, and EnOcean standards). Nevertheless, such gateways come at extra cost, consume power to function, and can be a source of system failure. As introduced above, coupling of former separated and heterogeneous technical systems is a prerequisite for an effective deployment of BAS at all scales. Building services will be invoked from systems of third parties, therefore latency, bandwidth, and other properties have to be taken into account as well, making building infrastructure, such as broadband connectivity, another aspect to condition interoperability.

Specifically, ISO/IEC 2382–01 defines interoperability as the capability to communicate, execute programs, or transfer data among various functional units in a manner that requires the user to have little or no knowledge of the unique characteristics of those units. Concerning BAS, interoperability can be applied to a multitude of topics and applications:

- technical interoperability is usually associated with hardware/software components, systems and platforms that enable machine-to-machine communication to take place, and is often centered on communication protocols and the infrastructure needed for those protocols to operate;

- syntactical interoperability is usually associated with data formats;
- semantic interoperability is usually associated with the meaning of content and concerns the human rather than machine interpretation of the content.

To address the issue of the multiple overlapping and competing standards within BAS, industry consortiums and international bodies have promoted the development of unified ontologies. One of those is SAREF (Smart Appliance Reference), a common ontology for the BAS domain developed by the European Commission/DG CONNECT. SAREF is conceived as a shared model of consensus that facilitates the matching of existing semantic assets in the BAS domain, reducing the effort of translating from one asset to another and enabling semantic interoperability between appliances and systems from different manufacturers. SAREF focuses on an application-independent “horizontal” service platform with architecture capable of supporting a very wide range of services including smart metering, smart grids, eHealth, city automation (smart cities), consumer applications, car automation, and smart appliances. Other initiatives include Smart Premises Interoperable Neutral-message Exchange, IEC TS 62950 ED1, ZigBee DOTDOT, the IoT schema.org initiative and the IoTivity and oneIoTa Data Model Tool by the Open Connectivity Foundation (Verbeke et al., 2020).

10.2.3 Internet of Things for smart buildings

The IoT can be defined as the suite of technologies and software crafted to equip all objects with identifying, sensing, networking, and processing capabilities, so that these objects could exchange and share information with each other over the Internet to allow instant data retrieval, analysis and, ideally, inform “smart” actions. The “thing” in IoT can be ultimately any object that has an Internet Protocol (IP) address and sends data over the internet about its state, position and its immediate environment or other attributes (Woodhead, Stephenson, & Morrey, 2018). Battery-powered IoT sensors and devices can be integrated in everyday or even wearable objects, turning them into valuable sources of information to track environmental, energy or personal features. This wireless sensor network (WSN) of small devices can enable the BAS to autonomously sense, communicate, analyze, and act or react to people or other machines in a nonintrusive manner, at an unprecedented granular level, for a fraction of the cost of a traditional system. This way, IoT devices can effectively complement the functionality of the BAS infrastructure and greatly expand its scope, particularly in applications centered on occupants’ behavior and interaction such as smart homes or commercial real estate. It is considered a key element for the control and the surveillance of smart buildings (Plageras, Psannis, Stergiou, Wang, & Gupta, 2018). IoT integration in building sector is already underway, with sensor deployment in the sector likely to grow at a CAGR of 78.8% between 2015 and 2020 to nearly 1.3 billion devices (Kejriwal & Mahajan, 2016). In particular, BAS will see the highest growth in IoT and connected device adoption in 2020 (Goasduff, 2019).

IoT allows to impart everyday objects (home appliances, doors, windows, lights, smoke detectors, etc.) with edge computing capabilities and bringing them online, where they can be used to track occupants’ and visitors’ movement and activity, to monitor IEQ parameters or to inform the BAS on real-time status, consumption, and health condition of anything they are integrated with. Achievable benefits are multifold, from cost and energy savings to improved wellness and productivity, to smarter safety and security management up to insight on users’ and consumers’ behavior.

For instance, in the retail sector the clients’ cellphones may act as an IoT beacon, providing localization of the consumer and enabling services such as parking assignment, indoor navigation, and targeted marketing. Behavioral data then feed the client historical profile to extract insight, together with aggregated data from thousands of other users, to inform future decision making.

In residential multifamily tenements, IoT enabled appliances and electrical sockets provide owners and tenants with real-time tracking and trends about their consumption, remote control, and setting of home systems, as well as anomaly detection to help early or even predictive address of failures. BAS can use extracted data from IoT thermostats and IP camera to learn users’ habits and preferences and allow customized experiences and scenarios.

In office environments, IoT connected devices scattered around the premises or integrated in wearables or personal badges allow to track staff members’ location and movements and detect occupancy of desks, rooms, or amenities; these data can be crossed with environmental sensing to optimize HVAC and lighting operation and can be analyzed to boost the productivity of workers by better designing tasks and breaks to facilitate collaboration and even socializing between employees.

10.2.3.1 Internet of Things architecture

IoT systems architecture is heavily based on the net for information sharing, as each of these devices is commonly associated with its own IP address. Specifically, IoT architecture can be articulated in three layers—the perception layer,

the network layer, and the application layer (see [Table 10.3](#))—although four, five, or six level architectures have also been proposed ([Goyal, Sahoo, & Sharma, 2021](#)).

The perception layer, also called the device or the physical layer, is that integrated into the IoT devices, which contains the sensor nodes and is responsible for sensing and data collection. Common technologies of perception layer include ambient sensors (e.g., temperature, humidity, CO₂), IP cameras, passive infrared, RFID tags, and smart meters. Within the perception layer, devices may access the internet directly, using TCP or UDP/IP stack, or via gateways, hardware, or software modules performing translation between different protocols as well as encryption and decryption of IoT data.

The network layer, also referred to as the transportation layer, is responsible for connecting to other smart things, network devices, and servers and is the convergence of various devices (e.g., gateway) and communication infrastructure ([Sethi & Sarangi, 2017](#)). Moreover, this layer takes care of functions such as computing and data management processes. The network layer commonly relies on wireless technologies such as W-Fi, Bluetooth and BLE, Zigbee, cellular LTE, although wired connection (USB, ethernet, optical fibers) is required by some IoT devices. A variety of existing protocols are used to carry out data transportation, mainly relying on HTTP and Message Queue Telemetry Transport (MQTT). HTTP/HTTPS is the basis of the client-server model used for the web. In case of IoT devices, the safest way to implement it is to include only the client with no server. This allows greater security as the IoT device can initiate connections to a web server, but cannot receive connection requests. However, HTTP protocol is considered excessively heavy for the IoT context, as it uses many network resources and is difficult to compress.

MQTT is instead a communication protocol specifically developed for connecting remote embedded sensors and middleware over limited bandwidth networks. MQTT is based on a publish/subscribe message transport, constituted by broker and client devices: the cloud-based broker is tasked with distributing messages to the subscribed clients, according to the message content. This approach allows to allocate much of the system complexity on the broker side, enabling a much simpler and lighter implementation on the client, that is, by edge computing on the IoT device itself. MQTT is intended for large networks of small devices that need to be monitored or controlled by a back-end server on the internet; therefore it was not designed for the transfer between devices, nor for multicast data to many receivers, and requires IP protocol to communicate at the higher level. For IoT applications, best suited IP is 6LoWPAN, which combines LoWPAN and IPv6. It is one of the infrastructure layer protocols that provides header compression for transmission overhead reduction. The advantages include high connectivity and compatibility with low-energy consumption.

Finally, the application layer receives the data transmitted and presents them to users or programs for further services. This layer serves as the front-end interface to integrate IoT technology with specific intelligent application solutions of information processing and analysis. These may include the BAS or smart home environment as well as AI powered services such as predictive analysis, learning of users' preferences, machine vision, natural language processing (NLP), possibly carried out through cloud computing services ([Jia et al., 2019](#)). This way, IoT-powered system is able to communicate and integrate with existing wired BAS infrastructure bypassing expensive, obtrusive modifications, while adding a new data layer for more efficient building management.

TABLE 10.3 IoT architecture.

IoT layer	Location	Components	Functions
Perception	- IoT device (common) - Gateways	- Environmental sensors - Power/water meters - Cameras	Collection of data from the physical world via sensors
Network	- IoT Gateway (common) - IoT devices	- Wi-Fi - Bluetooth and BLE - Zigbee - LTE and 5G - Wired data connections	- Gathering of data from connected IoT devices - Data transfer to the application layer
Application	- Remote or local server - Cloud server	- Data storage and processing - Web interfaces and dashboards - AI and ML algorithms (computer vision, vocal commands)	- Analysis of data to extract information - Presentation of results to users - Storage of historical data - Feedback inputs to the IoT devices - Connection to other services via APIs

10.2.3.2 IoT and BAS applications

To achieve the maximum benefits allowed by IoT systems, these shall be integrated organically with the BAS and its functions. Interoperability of IoT WSN and BAS architecture is eased by specific systems called application enablement platforms (AEP). The AEP can be defined as an industry-agnostic, extensible middleware core that can connect a wide variety of IoT devices to provide a heterogeneous wealth of data and allow for direct integration with industry-standard BAS communication protocols, such as BACnet. By providing a single destination for both IoT and BAS data, AEPs can solve a major gap with legacy systems, which is the lack of common analytics and delivering data to allow industrial enterprises to implement predictive maintenance, ML, asset logistics, surveillance, and many other applications. AEPs also provide data aggregation and visualization tools to allow for all types of data to be easily displayed contextually, for instance displaying BAS data such as HVAC status directly alongside IoT data like granular room occupancy, providing a more holistic view of the facility's operation. Broader insights into disparate building aspects can be unified in this single platform to enable streamlined and integrated management activities. Besides significant economic advantages, the use of IoT wireless connectivity infuses great flexibility to the network architecture. One can easily relocate existing sensors or install additional devices along the line as new business requirements and renovation needs arise. Crucially, AEPs allow seamless integration of IoT systems into legacy BAS systems already in operation without requiring expensive upgrades, thus greatly expanding their range of adoption in retrofit interventions.

Leading vendors of AEP platform capabilities include tech giants Microsoft Azure IoT, IBM Maximo, AWS IoT, Oracle IoT Intelligent Applications, SAP IoT as well as Losant, Altair Smartworks, Clearblade, Ericsson IoT Accelerator, Fujitsu Intelliedge, PTC ThingWorx, Siemens Simatic IoT, and Software AG Cumulocity IoT, and offer a blend of generic (cross-vertical), end-user and application focused, and horizontal technology focused propositions.

Successfully integrated with the BAS, data from IoT devices can conveniently expand its operative and analytical capabilities, as well as improving the buildings efficiency, monitoring and productivity.

Concerning energy efficiency, IoT WSN provides real-time, granular sensor inputs that enable on-demand, micro-zoned equipment control to reduce wasteful occurrences such as overheating or underheating across the property. For instance, IoT-based thermostat and light control units are used to save energy in the built environment, which uses occupant information and resets the temperature and luminaire intensity based on human feedback (Dong et al., 2019). Leveraging occupancy and behavior data from IoT cameras, motion detectors or CO₂ sensors can also unveil important trends in HVAC and lighting needs to optimize equipment on/off schedules. Real-time data from an IoT weather stations can predict with AI temperature/humidity and precipitation changes and anticipate the building's reaction.

Regarding building monitoring, wireless IoT utility submeters on cabinets, switches, or electrical plugs help deliver consumption data at discrete building areas or even on individual building equipment—especially energy-intensive ones, whereas a conventional BAS commonly provides only data on major operational units. Power or water usage trends can be identified to drive corrective measures, and abnormal values can trigger proactive verification. For example, IoT water leak and flood detectors help notify early-stage pipe failures and enable immediate valve shut down to prevent severe water damage. Likewise, temperature and vibration metrics of critical assets (e.g., chillers, elevators) can reveal impending or ongoing issues for timely inspection and repair. In older buildings, sensor inputs on inclination, vibration, crack formation and humidity exposure, coupled with advanced analytics algorithms, help examine and monitor its structural integrity.

Concerning building productivity, IoT devices can monitor occupants' activities, waste management, fire safety as well as real-time location of both people and equipment. Leveraging motion data from environmental and wearable IoT sensors, traffic and usage of different building areas can be assessed to accordingly prioritize maintenance and cleaning activities and to inform space layout and amenities managing in offices and commercial buildings. Similarly, a smart parking system can reduce lost productivity in blindly finding a parking lot, and indoor navigation enhances the experience of both visitors and clients. IoT IAQ sensors can allow accurate monitoring of indoor pollutants in real-time, with E-noses equipped with multisensor arrays, and digital pattern recognition algorithms powered by IA able to recognize and measure different air pollutants (i.e., VOC, CO₂, CO, PM10, and NO₂) and gases to prevent users' discomfort and sick building syndrome (Van Tran et al., 2020).

IoT can also allow distributed monitoring and feedback on the building's status by connecting to each occupant. Platforms such as CrowdComfort empower every building user to report comfort or maintenance issues with their smartphone, producing geo-located reports. Such real-time crowd-sourced user feedback allows facilities and property management teams to improve energy efficiency, prevent failures and maintenance, and increase safety and comfort in the building, with no hardware sensors and little training, and can also be integrated into the building's existing management systems (PEEB, 2019).

10.3 Connected services

Basically, all individual building components with an electric connection can become part of a single centralized BAS. The functionality of these individual pieces of equipment is linked via BAS subsystems, so that they operate as one complete integrated system. Examples of BAS subsystems include video management systems, access control systems, fire alarms and suppression systems, HVAC systems, power/lighting and elevator systems (Froufe et al., 2020). Together, all these subsystems constitute the BAS. Main BAS subsystems and building components therein connected are reported in Table 10.4.

Advanced BASs are most commonly implemented in large projects with extensive mechanical, HVAC, and electrical systems. Systems linked to a BAS, mainly HVAC and energy management, typically amount to 50% of a building's energy usage (Shi, Yu, & Yao, 2017), approaching 70%, if lighting is included.

Some of these components already require a degree of interconnection at the subsystem level to properly operate. A typical example is HVAC systems, which are commonly composed by a heat pump, an AHU and, for air-water systems, a number of fan coil units: such configuration needs at least thermostat controllers and temperature and humidity sensors to correctly manage hot and cold fluid production and distribution as well as fans speed. However, only the integration of components from different subsystems into a single BAS allows to unlock the full potential for substantial energy savings and improved comfort and productivity for occupants, with the added benefit of the reduction of control centers and command points which allow full facility management even with a reduced, even remote workforce. Nonetheless, the integration of several subsystems of different nature into a single BAS is rarely straightforward, as technology standards primarily emerged from different manufacturers and are often in disagreement not only on communication protocols, but even with regards to concepts and terminology (Domingues et al., 2016). Historically, in fact, subsystems management applications have been mostly sold as self-contained packages where the user relies on one vendor for the entire system including the hardware, the communications protocol, the central hub, and the user interface, although in recent years some dominant standards and open-source alternatives have emerged.

10.3.1 Energy management system

As previously stated, the main objective of BAS systems should be to optimize building services to allow a reduction in building's energy consumption and operational costs while maintaining or even improving the levels of comfort for occupants. Therefore it is apparent that the monitoring and control of the main electrical loads concurrent in the buildings and of available electrical energy supply play a pivotal role in BAS operation and should be implemented for all components and subsystems connected via electrical and data (either wired or wireless) connection. In particular, the BAS subsystem tasked with these activities is commonly indicated as Building Energy Management System (BEMS), Home Energy Management System (HEMS), or just EMS (see Section 12.3). According to its degree of evolution, the EMS can perform some or all of the following functions:

- monitoring of electrical loads and energy consumption;
- monitoring of energy generated on-site by combined heat and power (CHP) plants or building-integrated renewable energy sources;
- monitoring of energy taken from and given to the electrical grid;
- management of energy storage systems such as batteries or connected electrical vehicles (EV);
- scheduling of electrical appliances and services;
- optimization of building energy services and grid exchange.

A basic component of any EMS is the array of power sensors and meters dislocated in the building's energy cabinets, conduits, and even in single power outlets, in order to collect continuous data on electrical loads linked to any of the buildings services and gather them in a centralized energy consumption monitoring platform. This allows to display energy expenditure values such as consumption, costs, and other input on any PC or smartphone app, helping customers identify the most effective and efficient actions for correct energy optimization. Compared to scarce cumulated data available from monthly energy bills, the continuous monitoring of electrical loads enables to leverage field data to perform complete analytics, obtaining useful insights which include comparison with performance indicators, identification of energy performance trends, generation of automatic reports, notification of abnormal events, up to the identification of recommended actions to implement to optimize energy and costs. These monitoring-focused EMS have gained important traction in the last years both for business applications geared toward tenants and facility managers, and for

TABLE 10.4 BAS subsystems and connected components.

BAS subsystem	Connected components
HVAC	Chillers and boilers Air handling units (AHU) Duct dampers Fans Radiators Thermostats
Access Control System	Turnstiles Door locks Badge readers Biometric scanners
Energy management	Power outlets Building-integrated renewable energy sources Energy grid Energy storage EV charging stations
Lighting	Lighting appliances Lighting switches Smart windows Sun shading systems
Transportation system	Elevators Escalators Shuttles
Safety systems	Smoke sensors Gas leaks sensors Flood sensors Fire alarms Fire suppression Fire doors
Security systems	Surveillance cameras Motion detectors Alarms
Plumbing	Domestic hot water Leakage detection Water recovery Water reuse
Vegetation	Irrigation systems Lighting Weather stations
Home appliances	Refrigerator Dishwasher Clothes washer Clothes dryer
Media and entertainment system	Audio systems TV/monitor Media facades Water features
Indoor navigation	Bluetooth low-energy beacons Li-Fi Wi-Fi

domestic DIY installations, thanks to the wider availability of IoT wall plugs, luminaries, and switches that enable seamless tracking of home energy expenditures.

As building energy systems grow in features and complexity, the need for advanced EMS becomes central, in particular as on-site energy generation via building-integrated renewable energy sources (PV panels, wind turbines, mini-hydro—see [Section 12.3.1](#)) and battery energy storage have become an essential element for both new constructions and renovations. On-site energy generation systems must in fact interface with the building's EMS to keep track of energy production and, most usefully, to coordinate it with the buildings energy loads to manage whether energy is best consumed on-site, sold to the grid or stored in the building's batteries. Methods for balancing energy production and consumption can range from basic, scheduled energy rerouting to more evolved algorithms that take into account additional factors such as climate parameters, weather forecast as well as current and predicted building loads.

In this picture, the external utility grids and suppliers become primary agents with which the EMS can interface to allow further cost reduction via the optimization of building's energy production and consumption within demand-response programs (see [Section 12.3.4](#)). Key to this interaction is the diffusion of smart meters, which enable bidirectional communication between the energy supplier and the user: this way, the EMS can take into account and react dynamically to energy market factors such as energy availability and price, on-peak and off-peak demand charges, incentives, or scheduled grid disruption ([Groumpos, 2018](#)).

EMS can interface with the other BAS subsystems at varying levels of integration, according to the building's use (commercial, office, industrial, or residential) and complexity. At a basic level, EMS can be tasked with monitoring service-related loads and energy exchanged with the grid, leaving the optimization of energy cost and consumption to the users based on the results of analytics provided. More evolved EMS, in turn, coordinate with the central BAS to proactively control (on/off or modulation) specific services such as HVAC or lighting: this can be implemented by integrating the BAS overall control strategies with information and logics pertaining energy cost and data exchanged with the energy suppliers. Overall EMS control functionalities at increasing levels of sophistication are reported in [Table 10.5](#).

10.3.2 HVAC and DHW automation

HVAC systems were the first building subsystem to be integrated with advanced controls and monitoring, and today constitute the main application of more advanced BAS. Indeed, HVAC plants account for a majority of a building energy expenses and are responsible for several environmental parameters that directly influence comfort and well-being of occupants. Basic control of any HVAC system is commonly thermostat based and allows for simple instructions such as temperature set points and daily scheduling. The most common physical devices controlled in HVAC systems are valves and dampers (respectively to control water or airflows), pumps and fans (to control pressure of water or air), and employed actuators normally switch on/off the equipment, according to a simple programmed logic. Such operation, however, offers little freedom in managing “flexible” building loads, that is, loads that can be temporarily curtailed with little impact on the occupants and the services levels, that alone allow up to 20% reduction of building's electricity consumption ([Fernandez et al., 2017](#)). More advanced control functionalities rely on real-time data concerning room sensors, renewable energy availability, and external information from the grid to modulate HVAC and domestic hot water (DHW) operation to reduce energy waste and improve system efficiency as well as indoor comfort (see [Tables 10.6 and 10.7](#)). Moreover, the HVAC subsystem has potential for advanced integration with the following building components:

- fire systems, in order to automatically close duct dampers to prevent smoke diffusion in case of fire;
- automated windows, to allow mixed-mode ventilation by automatically balancing windows opening and closing and HVAC operation according to indoor and outdoor climate parameters and air quality (carbon dioxide, pollutants, VOCs) ([Daaboul, Ghali, & Ghaddar, 2018](#));
- security cameras and occupancy sensors, to regulate itself according to the number of occupants, their performed activity or the preferences of the user, who can be identified via facial recognition;
- EMS, to balance operation according to external factors such as on-site production from renewable energy sources, charge of the building's energy storage or cost of energy withdrawal from the grid;
- access control and indoor transportation systems, to detect workers numbers and direct them to specific rooms via escalators and elevators allowing to switch off air conditioning in underutilized spaces;
- weather stations and weather forecast, to adapt preemptively to varying climate conditions;
- the BAS scheduling system, to precisely set operations at the day and hour level and to program specific functions such as protracted leave periods.

TABLE 10.5 EMS electricity control functionality.

Control function	Level 1	Level 2	Level 3	Level 4
Optimizing self-consumption of locally generated electricity	Schedule of plug loads and appliances	Automated management of local loads based on current RES availability	Level 2 + predicted energy needs and RES availability	
Control of CHP plant	CHP control based on RES availability; overproduction fed into the grid	Dynamic charging and run-time CHP control to optimize RES self-consumption		
Support of grid operation modes	Automated management of electricity consumption based on grid signals	Automated management of electricity consumption and electricity supply to the grid		
Reports on electricity consumption	Real-time electricity consumption on building level	Real-time feedback or benchmarking at the building level	Real-time feedback or benchmarking at the appliance level	Real-time feedback or benchmarking at the appliance level with personalized recommendations
Reports on local electricity generation	Real-time generation data available	Level 1 + historical data	Level 2 + forecasting and/or benchmarking	Level 3 + predictive management and fault detection
Electricity storage	Electricity storage present	Control based on grid signals	Optimization of the use of locally generated electricity	Optimization of using and selling locally generated electricity
Reports on energy storage	Current state of charge (SOC) data available	Level 1 + historical data	Level 2 + forecasting and/or benchmarking	Level 3 + predictive management and fault detection
EV charging grid balancing	1-way controlled charging (e.g., including desired departure time and grid signals for optimization)	Level 1 + Vehicle to Building (V2B) operation		

10.3.3 Smart lighting

Indoor and outdoor lighting is another building subsystem which integration with the BAS has great potential in improving visual comfort of occupants and at the same time achieve remarkable energy savings. In particular, lighting automation, also called smart lighting, has been the subject of notable development in the last years, spurred by the availability on the market of increasingly high-tech LED devices already embedded with chips or controls and the relatively low cost and ease to retrofit. Benefits of smart lighting systems are manifold, the most immediate being increased energy savings, but also including improved light quality, circadian rhythm regulation, increased productivity, accelerated plant growth, and the possibility to implement human-centric lighting (Chew, Karunatilaka, Tan, & Kalavally, 2017).

The main components of a smart lighting system include dimmable RGB LEDs, photodetectors, occupancy sensors, and controller units, which in turn can be integrated with the BAS to allow greater interaction potential. Typically, a smart lighting system is centered on the controller unit that adjusts the luminaires dimming level according to the

TABLE 10.6 BAS heating/cooling and DHW control functionality.

Control function	Level 1	Level 2	Level 3	Level 4
Heating and cooling emission	Central automatic control	Individual room control	Individual room control with communication between controllers and BAS	Individual room control with communication and occupancy detection
Distribution fluid temperature	Outside temperature compensated control	Demand-based control		
Distribution network pumps	On/off control	Multistage control	Variable speed pump control based on internal estimations	Variable speed pump control based on external demand signal
Avoidance of simultaneous heating and cooling in the same room (interlock)	Partial interlock by sliding set points	Total interlock via control system		
Thermal energy storage (TES) operation	Time-scheduled storage operation	Load prediction-based storage operation	Heat/cold storage capable of flexible control through grid signals	
DHW storage (with integrated electric heating or hot water generation)	Automatic on/off control and scheduled charging	Level 1 + multisensor storage management	Automatic charging based on local availability of renewables and information from grid (electricity, district heating)	
Solar collector and supplementary heat generation	Automatic control of solar storage charge and supplementary storage charge	Level 1 + and demand-oriented supply or multisensor storage management	Level 2 + supply and return temperature control	
Generator control for heating/cooling	Multistage control depending on the load or demand	Variable control depending on the load or demand	Variable control depending on the load and external signals from grid	
Report information on system performance	Central or remote reporting of current KPIs	Level 1 + historical data	Level 2 + forecasting and/or benchmarking	Level 3 + predictive management and fault detection
Flexibility and grid interaction	Scheduled operation of cooling system	Self-learning optimal control of cooling system	Flexible control through grid signals	Optimized control based on local predictions and grid signals

photodetectors' output, occupancy condition, and type of visual tasks running or programmed in each zone (see Table 10.8). However, the design of lighting control algorithms that are at the same time energy efficient and able to maximize visual comfort of occupants is a challenging task, which complexity stems from the fact that lighting systems are by nature nonlinear and time-variant, and that ambient light may come from uncontrollable sources that are hard to model (Seyedolhosseini, Masoumi, Modarressi, & Karimian, 2020). Nonetheless, recent advancements in sensing technologies can provide feedback information previously unavailable, including accurate occupancy information about users' location and activity, light spectral data from microspectrometers, and richer light information such as chromaticity and illuminance distribution.

Smart lighting is mainly employed in the residential and office sectors, in which people tend to spend lengthy periods of time performing light sensitive activities such as working, reading, writing, etc., and has seen interesting applications in healthcare facilities.

TABLE 10.7 BAS ventilation control functionality.

Control function	Level 1	Level 2	Level 3	Level 4
Supply air flow	Time schedule	Occupancy detection control	Centralized control based on air quality sensors (CO ₂ , VOC, humidity)	Local control based on air quality sensors
AHU air flow and pressure	On/off time control of fixed air flow	Multistage control	Automated load dependent air flow without pressure reset.	Automated load dependent air flow with pressure reset.
AHU supply air temperature	Fixed setpoint	Variable set point with outdoor temperature compensation	Variable set point dependent on the loads in the room	
Free cooling	Night cooling	Free cooling available at all times	Modulation of outside and recirculated air based on temperatures and humidity (enthalpy).	
IAQ Reporting	IAQ sensors and real-time monitoring	Real-time monitoring and historical information of IAQ available to occupants	Level 2 + warning on maintenance needs or occupant actions (e.g., window opening)	

TABLE 10.8 BAS artificial lighting control functionality.

Control function	Level 1	Level 2	Level 3	Level 4
Occupancy control for indoor lighting	Scheduled daily switch off (e.g., at night)	Automatic detection (auto on/dimmed or auto off)	Automatic detection (manual on/dimmed or auto off)	Occupancy control for indoor lighting
Control artificial lighting power based on daylight levels	Manual (per room/zone)	Automatic switching	Automatic dimming	Automatic dimming including scene-based light control

Smart lighting systems can be broadly divided into two categories:

- commercial, off-the-shelf systems, which include consumer-grade smart lighting systems that can be purchased in stores today and are generally focused on system esthetics, mobile control, and the integration of user input, preferences, and data in an easy to set-up package suitable for DIY installation;
- advanced smart lighting control systems, which are implemented, often as part of a broader BAS, to maximize energy saving and optimize specific lighting metrics.

In the last years, commercial smart lighting systems have been introduced by several major lighting companies such as Philips Hue, General Electric Link, WiZ, or Osram Smart + , with early iterations allowing user control via smartphone of brightness, correlated color temperature (CCT) and RGB color of selected lamps. In particular, Philips Hue system was one of the first to enter the market and is today implemented in several luminaries and LED bulbs which can be controlled wirelessly via ZigBee through a Hue Bridge controller. Feature wise, it allows users to create scripts to change the light state, enabling novel applications such as programming the lights to flash when the smartphone receives an email, turning lights on when the owner reaches home via geofencing, making the lights vary in CCT throughout the day based on one's schedule, or controlling the RGB channel intensities individually. Philips Hue bulbs also allow bridge-less control via Bluetooth, however, with more limited functions, and feature external accessories such as motion and daylight sensors to enable some automation. Other commercial products allow similar functionalities; however, all those are more focused on the novelty factor and esthetics/accent lighting aspect of smart lighting, rather than towards a robust, multisystem integration with BAS.

On the other hand, more advanced lighting automation systems are primarily focused on energy saving and exercising a deeper control on more specific light metrics such as spectral power distribution (SPD), CCT, color coordinates, color rendering index (CRI), and gamut area index.

Concerning energy saving, a primary strategy already promoted in North American and European building codes is linking lights on/off control to occupancy sensors that detect presence or motion in the area of interest, instead of user operated switches. Occupancy sensing alone can achieve an energy reduction up to 86% in spaces with irregular usage such as storage rooms, but is less performing in regularly used environments (Chew et al., 2017). More advanced control systems integrate daylight sensing to either switch light on and off (open loop control) or to modulate illuminance according to detected daylight to achieve a target illumination level (closed loop control). An additional lighting control strategy is the programming of lights activities according to a predefined scheduling, which may range from basic scripts such as outdoor lights switched on at sunset to more advanced functions like self-switch on after a prolonged absence following learned patterns to simulate human presence for security reasons. Time-scheduled systems are, however, best suited to applications in which light can be synced to a fixed, predictable timetable, which include classrooms, offices, or auditoriums, and must include manual override switches to allow operation on request.

In addition, finer control of light dimming and of nonvisual effects such as SPD and CCT allows the manipulation of photobiology in living beings, which effect on human comfort, well-being and productivity has been subject of extended studies in the last decade. Humans have in fact evolved and adapted to natural daylight, which is inherently a variable light source to which our circadian system is tuned. Whenever interior daylight availability is inadequate (for example in deep plan workspaces), it is necessary to introduce some time-variability in the artificially lit environment. This can be achieved, for instance, by dimming lighting to change the intensity of illumination in the central and perimeter zones of deep plan areas, or by adjusting the balance of lighting layers within the field of view acting on wall lighting and ceiling uplighting. Another strategy consists in adjusting the color and intensity of illumination of CCT tunable light sources, replicating the variation of natural light in harmony with humans' internal clock to create a healthier environment and prevent misalignments that may lead to insomnia and decreased productivity (circadian lighting). In particular, “cooler” (rich in blue wavelengths) light promotes wakefulness and activity and is best used in workspaces such as offices, warehouses, and classrooms and in the central hours of the day, whereas “warmer” low-intensity light fosters rest and recovery and is preferred in spaces such as hotel rooms, bedrooms, and living rooms (see Fig. 10.2). This circadian approach to lighting is particularly suited for spaces in which the occupant is separated from the outside routine, such as hospital rooms or offices for shift-workers, to prevent disruption in their sleep-wake cycles (Chew et al., 2017).

10.3.4 Adaptive facades

Among all building components, the building envelope plays a strategic role in the energy and environmental performance of the building, significantly affecting the levels of indoor comfort. It consists in a complex system of environmental barriers and filters, able to regulate the flows of heat, solar radiation, air and steam, and also to convert solar, wind and mechanical energy into heat and electricity to meet different demands of the building. By integrating operable

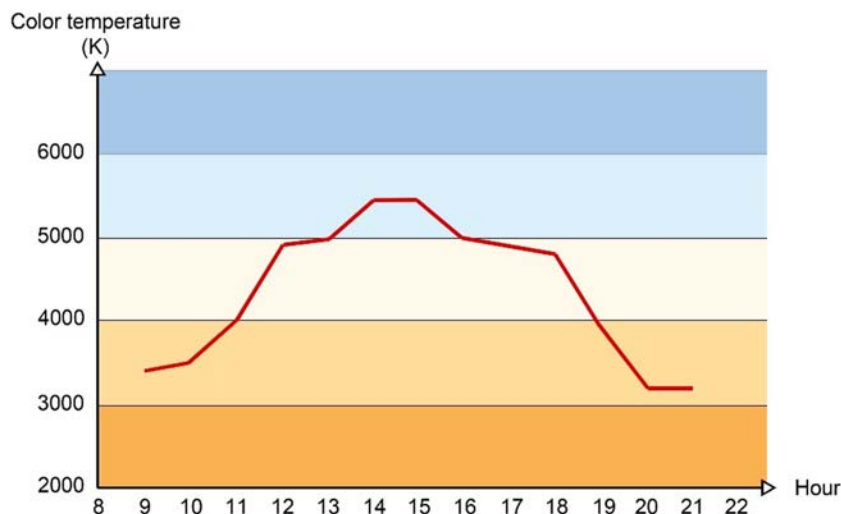


FIGURE 10.2 Color temperature shift according to human circadian cycle.

envelope elements with the BAS, it is possible to obtain an intelligent, adaptive building envelope which is able to cope with the environmental conditions in a dynamic way, ensuring, in full synergy with the systems and equipment, an efficient continuous and automatic management of all matter and energy flows in accordance to climate, user behavior, and market conditions of energy (Casini, 2016).

To enable an adaptive façade system to satisfy users' comfort and minimize energy consumption, the BAS intervenes in managing the flows of energy between the building, its occupants and the external environment, according to variations in external climate and in occupants' behavior (presence of people, users' activity, interaction with HVAC and lighting, etc.) (Alkhatib, Lemarchand, Norton, & O'Sullivan, 2021).

This operation is mainly carried out at the façade level and is enabled by the addition of motorized actuators for sun screening (dynamic shading systems) and window opening, as well as the integration of active dynamic smart windows, which together allow the manipulation of ventilative and solar heated airflows and the direct control of daylight luminance and solar heat gain.

Dynamic shading systems allow to overcome the limitations traditionally associated with fixed or manually operated sun screening methods, such as external brise soleil and awnings or internal shutters, blinds, or curtains. Manually movable shading systems are in fact mostly internal and work primarily by reflecting and diffusing the radiation outward, often absorbing a significant share resulting in the release of heat inside the indoor environment. These elements have anyway good efficacy in preventing glare. External elements are much more effective in heat gain control as they block the solar radiation before it reaches the building skin and penetrates the windows; however, they must be carefully designed to provide a differentiated behavior over the year, typically to exclude solar radiation in the summer while allowing it in during winter. Even if accurately dimensioned using shading masks, they are inherently compromised in blocking the sun path only in the hours or seasons in which solar radiation is not desired. Furthermore, the presence of a fixed screen may interfere with the visual enjoyment, natural lighting, natural ventilation, and the possibility of leaning out or passage offered by the window.

On the contrary, dynamic shading systems are able to change their geometric shape and optimize the amount of incoming solar radiation according to the climatic conditions, keeping the possibility of users' override (kinetic facades). Dynamic shading systems have seen larger and larger application in the last 20 years, from automated window blinds to complex façade elements especially in education and office facilities where, in addition to the energy and comfort gains, their architectural value can strongly characterize the external image of a building. Deployment of dynamic shading systems have followed closely the development of building automation and the availability of a wider range of motorized actuators, sensors, and controllers, which today allow precise operation and the effective integration with several building services.

Renowned examples of the integration of dynamic shading systems in building include the Al Bahar Towers in Abu Dhabi, where a special software allows the flower-like screening elements to open and close depending on the angle and power of solar rays (see Fig. 10.3), or the Museu do Amanhã in Rio de Janeiro, which envelope, composed by movable components integrated with photovoltaic modules, is able to expand and capture energy in all directions, optimizing sunshine conditions over the course of the day.



FIGURE 10.3 Adaptive façade of Al Bahar Towers, Abu Dhabi. *Courtesy of Arup.*

Motorized actuation can also be installed on windows and doors themselves, not only for basic operation such as direct control over difficult to reach panels, but more so to allow automated functions such as opening in case of detection of indoor pollutants (smoke, CO₂, VOC), or self-closing in case of rain, up to their deeper integration as in hybrid HVAC/ventilation systems in which they contribute with natural ventilation according to logics driven by climate parameters (temperature, humidity, wind direction, etc.) (Daaboul et al., 2018). Off-the-shelf actuators are widely available and can easily be integrated in inward and outward opening windows, skylights, sliding, and jalousie windows.

An effective strategy for making the building envelope adaptive is the integration of dynamic glazing, that is, window panels that allow selective and dynamic control of thermal energy and incident light with the ability to change their optical properties in response to a light, electrical, thermal, or chemical stimulus, thanks to the inclusion of so-called smart materials (see Section 7.4.4). In particular, dynamic glazing can be categorized as passive and active: the first include photochromic and thermochromic windows, which operate autonomously according to incoming heat or light and cannot be controlled directly, and the second includes electrochromic glass (EC), suspended particle devices, and liquid crystal devices (LC/PDLC), which instead operate according to an external electric stimulus and can therefore be controlled by the occupants or, more interestingly, be integrated into the BAS.

Active dynamic windows, EC glazing in particular, have proven effective in both allowing energy saving and improving visual comfort of buildings and are considered a suitable solution in the cases where more adaptive building skin capacities are required, such as areas with different needs for winter and summer seasons and on the East and West facades, especially in hot dry climates (Casini, 2018).

Operation of all elements of the adaptive façade subsystem (dynamic shading systems, automated windows and active dynamic glazing) can be controlled independently but reaches its maximum efficiency when concerted with other building services, namely, lighting and HVAC, in order to exploit at best natural lighting and ventilation when possible and modulate artificial light and air conditioning accordingly to reach the programmed threshold for interiors comfort (see Table 10.9).

10.3.5 Water management

Water management has become a relevant aspect of buildings' operation, stemming from an increased awareness of water scarcity and water saving, even in developed countries, and the quick economic and population growth of developing countries in which water supply and quality is still an issue. Besides the general concerns of freshwater scarcity for human consumption, there are rising concerns for scarcity of water for agricultural purpose, further driving the need for an effective water management system to tackle this challenge (Singh & Ahmed, 2021).

In fact, some sort of water management system is required in most strategies to reduce water consumption, which involve:

- the use of appliances with high water use efficiency, of smart taps that self-adapt to the users' activities, of heat recovery systems from discharged water, of leakage control systems with alert and flow stop, and of consumption measurement and display systems to encourage users' good practice;

TABLE 10.9 BAS adaptive façade control functionality.

Control function	Level 1	Level 2	Level 3	Level 4
Window solar shading control	Motorized operation with manual control	Motorized operation with automated control based on sensor data	Combined light blind and HVAC control	Predictive blind control
Window open/closed control	Open/closed detection to shut down HVAC	Level 1 + automated window opening based on room sensor data	Level 2 + centralized coordination of windows (e.g., for natural night cooling)	
Reporting information on system performance	Position of each product and fault detection	Level 1 + predictive maintenance	Level 2 + real-time sensor data	Level 2 + real-time and historical sensor data (wind, lux, temperature...)

- the use of native vegetation with low water demand and of automated watering systems based on soil conditions and weather forecasts;
- the recovery, treatment, and reuse of rainwater, graywater, or condensation from air-conditioning systems.

Water management systems are mainly concerned with monitoring the water level of building reservoirs and the quality of water supply, and with operating valves and faucets in the water distribution grid according to predetermined logics geared toward water saving and water use optimization. In the last years, water management systems have gained attention following the wider availability of smart water sensors able to integrate in BAS and home automation systems, as well as the diffusion of rainwater harvesting and graywater recovery and reuse systems which have become mandatory in several building codes (Lee & Jepson, 2020).

Complexity of building water management systems ranges from simple, IoT-based home solutions to complex systems able to manage multiple water sources, tanks, and terminals in larger facilities.

A comprehensive water management system is composed by an array of sensors and actuators and controllers, linked by a wired or wireless network, which may interface with the rest of the BAS or with a dedicated application, normally web-based. Sensors include water level, flood, flow, and pressure detectors as well as water quality sensors that measure temperature, pH, turbidity, salinity, total dissolved solids, and dissolved oxygen.

Actuators in turn mainly consist in motorized valves able to shut, modulate, and divert water flows but also include smart sockets for controlling service appliances such as clothes washers or dishwashers.

Concerning its operation, the water management system can perform the following functions:

- remote operation of water supply, water connected appliances, and irrigation systems;
- continuous monitoring of flow and pressure through pipes and their rate of change, allowing to collect and store data, learn user's behavior and detect abnormal values that may signal potential leaks, as well as map inactive areas where bacteria could have developed in stagnant water;
- remote and automated operation of irrigation systems;
- continuous monitoring of quality parameters of water supply and water from rainwater and graywater recovery systems;
- treatment of harvested rainwater and recovered graywater;
- water balance optimization according to the levels of water in rainwater and graywater reservoirs, to the scheduled and learned uses, and to weather forecast.

In particular, recovery and reuse of rainwater and graywater require an advanced water management system to operate effectively and achieve the expected savings without affecting human health (see Fig. 10.4). Specifically, graywater reuse involves the collection of used water from bathroom sinks, bidets, showers and bathtubs, and laundries, whereas rainwater harvesting is commonly linked to roof gutters instead of ground drains to limit water contamination. Another source of reusable water consists in condensation from HVAC systems. Water contaminated with biological agents, such as that from kitchen sinks, dishwashers and toilets, requires extensive depuration thus is usually disposed of in the waste drains and in common sewers. All recovered water must undergo chemical/physical treatment before being safely

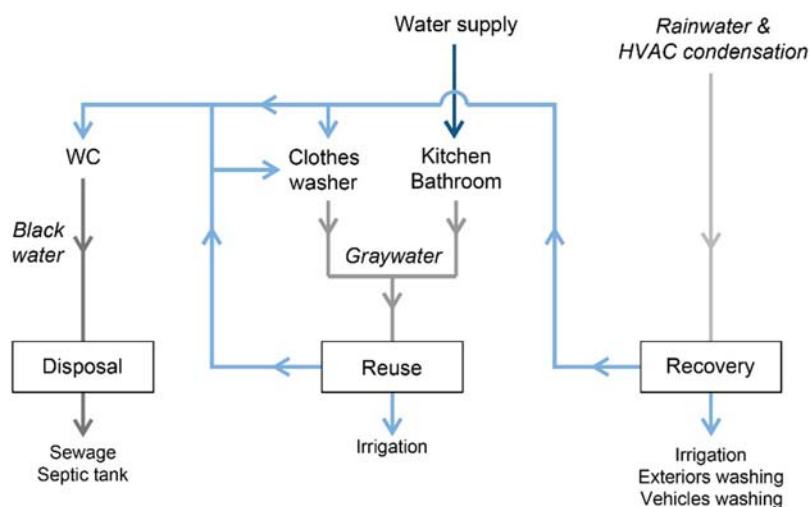


FIGURE 10.4 Water recovery and reuse scheme and use.

reused for nonpotable uses in compliance with local regulations, such as for toilet flushing, landscape irrigation, clothes washing, outdoor washing, fire extinguishing, cooling, and recreational use (Takeuchi & Tanaka, 2020).

Such system requires the preparation of additional plumbing, separate tanks, and different filtration systems for the collection, filtration, and storage of different types of recovered water.

Treatment of rainwater and condensation water consist at least in filtration and disinfection processes. First, physical filtration removes possible suspended solids, through cartridge, sand, activated carbon, or membrane filters. Subsequently, in order to disable possible microorganisms, a disinfection phase occurs, usually through an UV sterilizer, or through chemical treatments based on chlorine or ozone. A typical treatment system for domestic use is composed by a multistage filter (90 and 25 μm cartridge filters to mechanically remove suspended particles and dust, and a 10 μm carbon filter to catch organic molecules) followed by the UV sterilizer which inactivates unwanted organisms that may be still present. The sterilizer contains a quartz UV lamp which emits light in high energy wavelengths (200–400 nm) able to inactivate microorganisms (bacteria, viruses, cysts, etc.), disabling their life functions and stopping their ability to multiply and cause infection or illness.

Graywater has an inherently higher degree of contamination and may contain large PM, therefore must undergo a more intensive filtration treatment which commonly involves different stages up to microfiltration. Normally, graywater from bathroom sinks and showers/tubs is subjected first to coarse filtration, aeration, fine filtration, and membrane ultrafiltration, in this order. First, coarse filtration (2000 μm) removes any suspended solids present, such as fluff, textile fibers, and hair, then the aeration reaction reduces surfactants. Pretreated graywater is then sent to a pressure filter (200 μm), and finally to the ultrafiltration membranes. These are made by hollow fibers of polyethersulfone (PES) with pore size about 0.02 μm : such porosity allows to remove almost all bacteria and viruses—reduction capacity is 4-log for viruses (99.99%) and 9-log for bacteria (99.999999%). Once treated, purified graywater can be stored in a dedicated tank, usually along with harvested rainwater and condensation water, before its intended reuse.

All these functions converge in the BAS connected water management system, which is tasked with tracking the harvesting and filtration rate of graywater, rainwater, and condensation water and manage their use for the different buildings services.

10.4 Control strategies

Controlling and coordinating the different subsystems of buildings and the relative services with the objective of optimizing their overall performances is a rather complex task, that requires specific BAS strategies able to balance several parameters which are normally in competition one with the other, namely, energy consumption, occupants' comfort, and costs. Furthermore, the uncertainty associated with both internal and external environmental factors such as energy loads caused by the users, varying weather conditions and dynamic energy price, limits the effectiveness of basic control solutions (hour-based schedules, single set-point thermostats or on/off light switches) and imposes the need for more advanced management systems. Modern BAS control strategies consist in the instructions and logics employed to elaborate information from sensors and operate all connected systems accordingly, and shall be able to take into account uncertain and dynamic factors which may result in an unexpected deviation from desired performance (Alkhatib et al., 2021). BAS control scheme consists of both hardware elements at the field level (sensors, actuators, communication infrastructure and connected devices) and a software component, which operates at the management and automation levels (see Fig. 10.5). In particular, the automation level consists of controllers implementing control loops to meet configured set points, whereas the management level usually consists of the computer that configures static set points as well as rules and schedules to change these set points (Schmidt & Åhlund, 2018).

Overall, the control system operates by gathering data from connected sensors and adjusting the related building services continually and actively, either by simply reacting after the conditions have changed according to set logics and rules, or by effectively predicting how the situation will develop and anticipating the expected outcome, with increasingly refined methods also based on AI and ML. Methods from the first category are commonly indicated as traditional or classical control strategies and employ models derived from established industrial automation practices. Methods in the second category are instead classified as advanced control strategies (ACS), and leverage the ongoing research on Model Predictive Control (MPC), ML and AI to improve their capability to deal with uncertain, complex and dynamic contexts and to make the system more adaptable to users' needs (Gholamzadehmir, Del Pero, Buffa, Fedrizzi, & Aste, 2020) (Fig. 10.6).

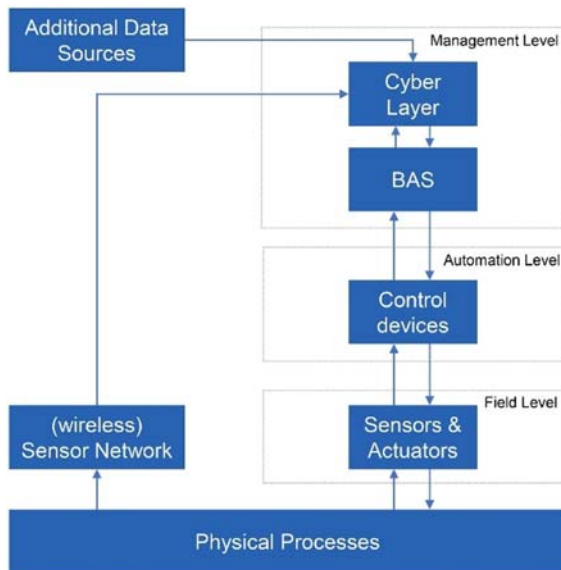


FIGURE 10.5 BAS control scheme.

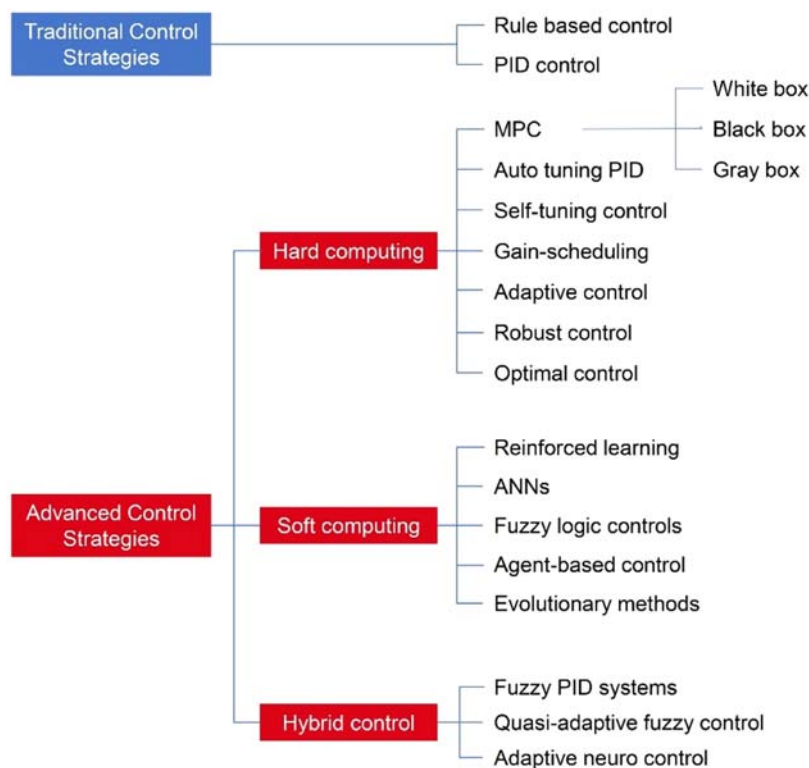


FIGURE 10.6 BAS control strategies.

10.4.1 Traditional control strategies

These conventional control methods are characterized by low cost and simple implementation and can be mainly divided in two subgroups: rule-based control (RBC), also known as on/off methods, and proportional, integral, and derivative (PID) control modes (Behrooz, Mariun, Marhaban, Radzi, & Ramli, 2018).

10.4.1.1 Rule-based control

RBC methods are based on a set of predefined rules to control the system. They use upper and lower set points to control processes within given boundaries and are used mostly in HVAC subsystems for temperature control. Modulation capability is limited as the control can be either one or zero, and therefore performed actions can be as simple as turning a thermostat or switch on or off. Operation requires human made rules and thresholds that define the source of data and how to manipulate that information. These rules should outline unequivocally the triggers and the action that should follow, and usually come in the form of IF/THEN sentences, for example, “IF this event occurs THEN perform this action.” Although simple to set up, this logic has little scalability, meaning that a rule-based system capable of handling 100 different actions would need 100 different written rules, and any system update to add actions would require additional rules. A careful design of the control rules is therefore essential, which is not always granted. RBC is still the standard approach used nowadays in commercial BASs for most building control problems (Gwerder et al., 2010), although the lack of interaction with the external environment (i.e., user/grid/district/city) may preclude the application of high-efficiency control. Furthermore, RBC methods have no learning capability, meaning that more complicated systems would require more complex rules with higher maintenance/update costs, and that incomplete data and control challenges not considered at the design stage would be difficult to handle. RBC depends on the operator knowledge and applies its rules to reduce the energy and operating cost, such as appropriate start/stop time of HVAC, night set-back, precooling, and preheating etc. This alone can provide significant savings when applied correctly; however, the operator has to constantly monitor and adjust the HVAC operation to meet the objectives of reducing energy consumption while maintaining thermal comfort (Afram, Janabi-Sharifi, Fung, & Raahemifar, 2017).

Nonetheless, RBC methods can integrate the prediction of some future boundary conditions, for example, variations in hourly electricity cost, becoming predictive rule-based control (PRBC). Providing the control rules are well defined, PRBC can decrease the energy costs for the building operation (Alimohammadisagvand, Jokisalo, & Sirén, 2018). Predictive rules may include lower and upper thresholds for energy price, PV generation, and thermal loads, allowing to store energy during low-price periods and lower consumption during high-price periods, for instance, running the heat pump either at times of high PV generation to maximize self-consumption or at times of minimum electricity prices to charge the storage tank of the heat pump system (Clauß, Stinner, Sartori, & Georges, 2019).

10.4.1.2 Proportional-integral-derivative control

Differently from RBC, PID control relies on feedback from sensors to decide its course of action. In particular, the PID control loop continuously calculates the “error,” that is, the difference between the desired setpoint (a specific value of temperature, humidity, pressure, etc.) and the value measured by field sensors, then tries to reach its target by applying a mathematical correction based on proportional, integral, and derivative terms, respectively (see Fig. 10.7). After the

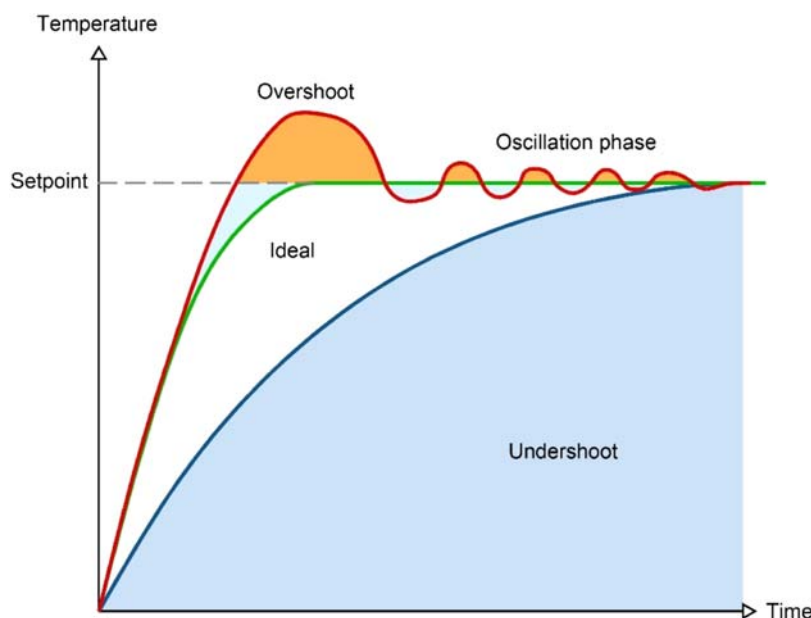


FIGURE 10.7 PID control operation.

change is sensed, adaptations are made, then the process is looped back and repeated. Specifically, the proportional approach is relevant to the present offset and produces an output proportional to the error by comparing the feedback signal with the set point (e.g., first overshooting or undershooting the target value then adjusting the output). The integral approach is instead relevant to the past errors accumulation and removes the error by integrating it over time until its value comes to zero. The derivative approach, finally, is relevant to the future offset considering the rate of changes in the process and increases system response while minimizing overshooting by slowing down the correction factor (Alkhatib et al., 2021). Thermal process dynamics such as temperature and humidity control in buildings can be considered as slow responding processes, therefore a simpler controller with only the proportional approach can be used obtaining an acceptably small offset and good stability. The integral and derivative terms are combined with proportional control in order to cope with sudden load changes in the system, while keeping the zero offset under steady-state conditions.

Before their application, PID controller must be tuned, that is, its control parameters (proportional band/gain, integral gain/reset, derivative gain/rate) must be adjusted to the optimum values for the desired control response and to improve stability by preventing unbounded oscillations around the desired equilibrium point. In particular, tuning is required whenever adapting PID controllers, which are inherently linear and symmetric in their mathematical approach, to nonlinear systems such as HVAC: in case of active heating (via a heating element) and passive cooling (heating off, but no cooling), overshoot can only be corrected slowly—it cannot be forced downward. In this case the PID should be tuned to be overdamped, to prevent or reduce overshoot, though this reduces performance as it increases settling time (Behrooz et al., 2018).

PID controls limits can be overcome by coupling them with more advanced control tools, which include algorithms for self-tuning (Fütterer, Kraus, Schmidt, & Mueller, 2015) and nonlinear control systems, obtaining so-called hybrid control methods, such as fuzzy-PID controllers.

10.4.2 Advanced control strategies

Traditional control strategies have grown increasingly inadequate to cope with the requirements of modern building operation, and today constitute a main bottleneck to the improvements of energy efficiency and the full exploitation of BAS potential. This is mainly due to their incapability of dealing with uncertain or unprecedented energy loads caused by users, weather conditions, or energy supply, as well as their difficulty of balancing the two contrasting objectives of high comfort level and low running cost of the building at the same time. Furthermore, the increasing diffusion of on-site renewable energy sources, distributed generation, and thermal or electrical energy storage solutions requires contemporary buildings to shift from mere energy consumers to interactive actors within the smart grids, by applying more sophisticated energy strategies such as demand response and peak load shaving (Kathirgamanathan, De Rosa, Mangina, & Finn, 2021; Serale, Fiorentini, Capozzoli, Bernardini, & Bemporad, 2018).

In this picture, ACS aim to overcome the limits of traditional controllers which result in many performance and economic penalties such as higher energy consumption, higher operating cost, higher thermal discomfort, and higher equipment wear and tear (Afram et al., 2017).

By employing a range of different approaches and mechanisms, ACS are able in fact to react effectively to variations in any of the building's operation parameters, always guaranteeing the achievement of the optimal solution in terms of minimization of overall system energy input or operating cost while still maintaining the satisfied indoor thermal comfort and healthy environment. ACS constitute therefore the main element to achieve the energy efficiency objectives of BAS needs (Gholamzadehmir et al., 2020).

Differently from conventional control systems such as RBC or PID, which still constitute the vast majority of BAS control strategies applied in building practice, ACS employ advanced mathematical, physical, statistical, and data mining methods to define their operating logics, integrating the ability of self-learning, self-adjusting, and parameters prediction in the control process. ACS have seen impressive research and development efforts in the last decades, which was enabled by the increased implementation of wired and wireless low-cost sensors and embedded controllers in building systems, by the availability of vast amounts of heterogeneous and accurate data on buildings operation, by the advancements in computational power at a decreasing cost, and by the availability of accurate weather predictions, which have allowed control engineers to explore several strategies for optimizing an efficient building control. Numerous studies have shown that adding advanced control strategies to BAS, and to HVAC subsystem in particular, could result in more than 50% reduction in energy consumption and operating cost (Afram et al., 2017).

According to the computational paradigms employed to drive their operation logics, ACS can be distinguished in two main categories, hard computing control strategies, and soft computing control strategies, with some control methods that employ a combination of both (hybrid or fusion control strategies) (Behrooz et al., 2018).

Hard computing control strategies deduce their operation according to a mathematical/analytical model, in which underlying equations are literally and systematically stated, and have rigorous requirements in terms of precision and accuracy of input data. This category includes MPC, auto-tuning PID control, gain-scheduling control, self-tuning control, adaptive control, nonlinear control, optimal control, and robust control methods needs (Gholamzadehmir et al., 2020). Hard computing techniques are based on principles of definiteness and rigidity; hence, they require additional effort in terms of development and computation time when confronted with real-world scenarios characterized by many concurrent uncertain and estimated conditions, which often do not translate to precise solutions and make finding a proper mathematical model for the system difficult (Sakunthala, Kiranmayi, & Nagaraju Mandadi, 2018). Among hard computing approaches, MPC is widely considered the most promising technique because of its ability to integrate disturbances, constraints, and dynamic control and energy conservation strategies into BAS control (Afram & Janabi-Sharifi, 2014).

Soft computing control strategies, also called intelligent control, are instead based on probabilistic reasoning, approximate perception, and imprecise models and allow a degree of interpretation, research, and adjustments in their operation (Sakunthala et al., 2018). Soft computing strategies are therefore better suited to cope with imprecision, uncertainty, and noisy data, from which they can derive approximate or statistical responses and can operate without modeling the system, but only depending on the desired output (e.g., human thermal comfort feelings, consumption, cost, etc.). This category includes reinforcement learning (RL), artificial neural networks (ANN), fuzzy logic (FL) controls, agent-based controls as well as genetic algorithms and other evolutionary methods.

Hybrid control strategies combine both hard and soft control techniques. In particular, soft control techniques are employed at higher levels and hard or traditional control techniques at the lower levels of the control structure. Examples include fuzzy-PID systems, quasi-adaptive fuzzy control, adaptive-neuro control, and others. Hybrid strategies combine both qualities and disadvantages of hard and soft control techniques, requiring large amounts of data for training the soft control component, and extensive expertise for designing and tuning a flexible enough hard control component (Afram et al., 2017).

10.4.3 Model predictive control

Among ACS, MPC is proving particularly promising in terms of energy and cost saving potential and thermal comfort satisfaction, due to its ability to predict the dynamic behavior of connected systems in the future and adjust the response of the relative controllers accordingly (Hazyuk, Ghiaus, & Penhouet, 2014; Serale et al., 2018).

The MPC strategy based on predictive approach is in fact able to factor in effectively the information related to the technical systems as well as future external and internal environmental data that include weather forecast, building load, occupancy, and energy prices (Behrooz et al., 2018) and is particularly suited for the dynamic, slow-moving processes with time delays that include HVAC management, renewable energy generation, or the exploitation of building's thermal mass (Le Dréau & Heiselberg, 2016).

The concept of MPC is already consolidated in the processing industry, where it was introduced in the 1970s in particular to support oil and gas engineering. The development and application of MPC strategies in the building sector is, however, still in its infancy, although first experimental demonstrations and simulations are already showing it vastly outperforming traditional control methods. In particular, simulations and pilot case studies have proved how MPC allows to combine improvements in thermal comfort with simultaneous energy savings up to 50% (Drgoňa, Picard a, & Helsen, 2020; Sturzenegger, Gyalistras, Morari, & Smith, 2016). Additional benefits include decreased greenhouse gases emissions as well as cost reduction and improved grid flexibility via price-responsive and demand-response capabilities of MPC (Bianchini, Casini, Vicino, & Zarrilli, 2016; Borsche, Oldewurtel, & Andersson, 2014). Most studies conducted focused on MPC application on tertiary buildings; however, benefits are documented also for small-scale, residential applications (Fielsch, Grunert, Stursberg, & Kummert, 2017), in particular concerning distributed energy demand flexibility (Corbin & Henze, 2016).

Despite these results, adoption rate of MPC in the actual building practice is being rather slow. This is mainly due to the challenges related to the development, implementation, commissioning, and maintenance of the MPC system and its components, which require extensive interdisciplinary expertise not only in building control but also in energy modeling, optimization algorithms, mathematical and ML programming, data science, as well as a powerful and

elaborate building ICT and BAS infrastructure, which is still often lacking even in contemporary constructions, else the performance will be shy of its potential (Drgoňa et al., 2020).

Advantages of MPC methods for BAS are various due to its flexibility in coping with a number of situations, and include

- use of a system model for anticipatory control actions rather than corrective control;
- integration of a disturbance model for disturbance rejection;
- ability to handle constraints and uncertainties;
- ability to handle time-varying system dynamics and a wide range of operating conditions;
- ability to cope with slow-moving processes with time delays;
- integration of energy conservation strategies in the controller formulation;
- use of a cost function for achievement of multiple objectives;
- use of advanced optimization algorithms for computation of control vectors;
- ability to control the system at both the supervisory and local loop levels (Afram & Janabi-Sharifi, 2014).

Basically, the core of a MPC controller consists of two main technologies: a prediction model to anticipate the dynamic behavior of the control subject, and an optimization solver to find the best control input to set in order to meet the desired result (see Fig. 10.8).

In particular, the prediction model foresees the dynamic response of the outputs of a system as affected by both controlled inputs (the manipulated variables) and uncontrolled inputs (also known as disturbances), as well as constraints enforced by the designer. MPC then uses these predictions to select the optimal sequence of future controlled inputs according to a specific performance index (commonly a cost function to minimize) (Serale et al., 2018).

Concerning the cost function, it can take the form of tracking error, control effort, energy cost, demand cost, power consumption, or a combination of these factors.

Regarding constraints, these can be placed according to system's limitations such as the rate and range of actuators and manipulated variables (e.g., upper and lower limits of zone temperature, supply air flow rate limits, and range and speed limits for damper positioning), or to imposed thresholds concerning comfort or functionality requirements.

Concerning, lastly, the external and internal disturbances acting on the system due to weather, occupant activities, equipment use, and energy supply, these are also modeled, and their effects on the system predicted as well for optimization. This effort results in a control system that is robust to both time-varying disturbances and system parameters and regulates the process tightly within given bounds (Killian & Kozek, 2016).

Time is factored in the MPC flow in three aspects: the prediction horizon, the control horizon, and the time step (or control sampling time). The prediction horizon refers to the length of time for which system output is computed by the MPC, the control horizon denotes the length of time for which the control signal is computed, and finally the time step, also known as sampling time or time interval, is the period during which the control signal remains unchanged (Afram & Janabi-Sharifi, 2014). The MPC algorithm operates by solving an optimal control problem in the present time over the finite prediction horizon, then applying only the first move of the control strategy devised. At the following time interval, it gets new measurements and repeats the optimization process (see Fig. 10.9).

At each time step, the measurements from field sensors, the predictions of the disturbances, and the candidate MPC inputs (e.g., heat supplies) are used as simulation inputs to the building model. This simulation is carried out over the prediction horizon, which typically lies between 8 and 72 hours in building applications. The optimizer evaluates the performance criterion for each simulation run and adapts the candidate MPC inputs until an optimal solution is obtained. Only the very first step of the devised strategy is actually implemented to the building, then the optimization is restarted at the next time interval, getting new measurements and expected disturbances and continuously shifting the prediction horizon forward, an effect called “receding horizon” (Killian & Kozek, 2016).

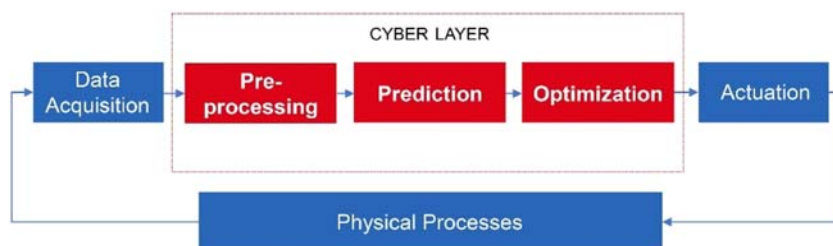


FIGURE 10.8 Operation loop of MPC showing prediction model and optimization solver.

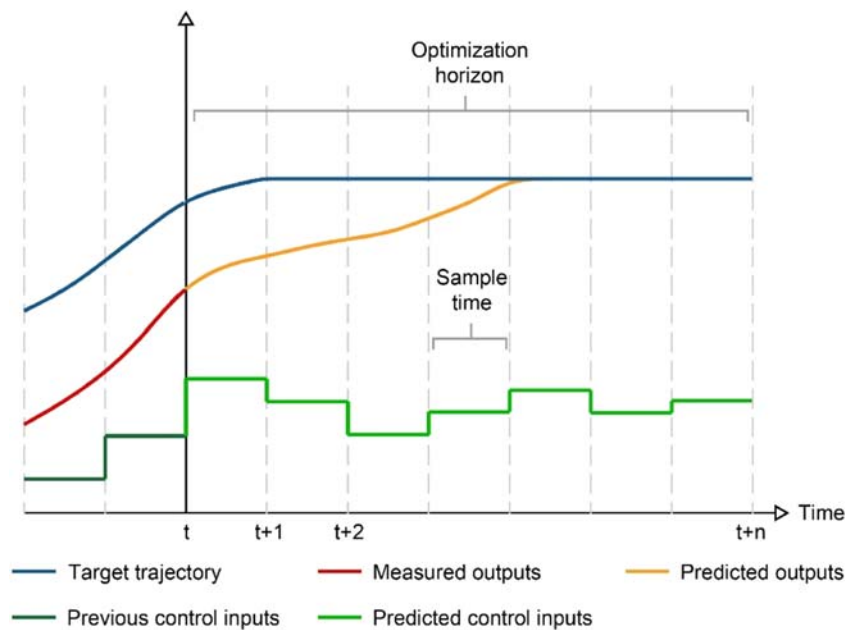


FIGURE 10.9 Time development of MPC actions.

Typically, for slow-moving processes such as temperature changes in HVAC systems, the prediction horizon is 5–48 hours, the control horizon range is 4–5 hours, and the time step is between 1 and 3 hours, with a control horizon generally smaller than or equal to the prediction horizon. Horizon and time steps must be carefully selected depending on the controlled process and its dynamics: for instance, a smaller prediction horizon or a faster sampling time could result in suboptimal performance due to delays in the temperature process, whereas a longer prediction horizon could lead to increased computation time without any further benefit (Afram & Janabi-Sharifi, 2014). Most of the research on predictive control evaluated the prediction horizon of 24 hours ahead, a setup found as best suited to enhance energy saving and thermal control (Luzi, Vaccarini, & Lemma, 2019). On the other hand, the prediction horizon and control horizon may shrink to a few seconds when applied to faster-moving dynamic processes, such as compressor pressure and superheat temperature control. Time-variable horizons are also employed in some applications, for instance, by reducing or increasing the prediction horizon as the time progresses toward the end of the day. Concerning sampling times, these also affect the MPC operation and accuracy, as investigated in literature (Gholamibozanjani et al., 2018); however, 1 hour time intervals are generally considered well suited for most building applications.

For the optimization algorithm to be effective, prerequisites are a reliable modeling of building dynamics, the compliance with technological and thermal constraints, and the exploitation of available predictions of future disturbances.

As stated above, disturbances refer to every noncontrollable input that has an influence on the building system. Common examples are climatic disturbances (e.g., external temperature, relative humidity, wet-bulb temperature, dew-point temperature, solar radiation, wind velocity, ground temperature), occupant behavior-related disturbances (e.g., occupied/unoccupied spaces, variation in the scheduled comfort set points, internal heat gains/loads, adjacent zones set points, used equipment), as well as grid and energy distributor related disturbances [e.g., Time-of-Use (ToU) or real-time prices, peak loads penalties, etc.] (Serale et al., 2018).

Climate disturbances predictions commonly translate to the integration of accurate weather forecast information as inputs to the building simulation. The easiest way to obtain it is from online commercial weather forecast services which are typically based on advanced climate models. Experimental studies achieved 30% energy saving and 41% cost saving by application of weather forecast in MPC (Barzin, Chen, Young, & Farid, 2016). However, the online weather forecast may not accurately represent the actual weather conditions, for instance, being based on data from climate stations far from the considered building or with altogether different terrain. Considering how MPC works, eventual ambient temperature errors may not have a major impact on the thermal comfort and energy performance; however, uncertainties in predicting solar radiation may impact thermal comfort conditions significantly (Mirakhorli, 2016). As an alternative, ML models such as ANN can be trained on weather data collected from the building site, and may be accurate enough for short-term predictions, up to several hours ahead (Wollsen & Jørgensen, 2015), which is the range typically relevant for MPC in buildings. ML can be more effectively employed on recorded measured data to

calculate the effective shift between weather forecast and actual local conditions, in order to factor in the influence of local parameters and apply corrective factors to improve predictions accuracy.

Indoor occupancy disturbances can in turn be modeled either as heat gain profiles, room presences, or occupant count according to simple occupancy schedules, obtaining mixed results due to their inherent variations. More accurate is behavioral modeling, which aims to predict how the occupants will interact with the indoor environment (by opening windows or shades, switching lighting or overriding default set points), which equipment they will operate, which actions they will perform and how they will be dressed (Drgoňa et al., 2020). Occupant presence and actions can be modeled using rule-based approaches, stochastic modeling, or data-driven models such as ML or deep learning (DL) (Carlucci et al., 2020). A key function of occupancy-predictive MPC is that it can switch off the technical systems in an unoccupied period and provide the thermal comfort of users in the occupied period while guaranteeing enough time for low-energy temperature adjustment (Gholamzadehmīr et al., 2020). Studies have shown that occupancy-based MPC HVAC controls can save up to 30% more energy comparing with traditional rule-based controls (Dai, Liu, & Zhang, 2020; Mirakhorli, 2016), and the energy efficiency of appliances and lighting systems can be improved by up to 45% through occupancy adaptation (Ahmadi-Karvigh, Becerik-Gerber, & Soibelman, 2019).

Finally, grid-related disturbances can be modeled by applying the dynamic electricity price to the system with the aim to maximize the energy/cost efficiency at district/city scale. MPC then defines a load schedule for the system to regulate correlation between time of consumption and peak load shifting, shaving, or matching with the grid: under different conditions, the optimizer decides to switch between direct use of on-site generated energy, charge/discharge the energy storage system, or selling/buying energy from the grid (Gholamzadehmīr et al., 2020).

As stated above, a fundamental component of the MPC method is the predictive model of the system itself, which is used to forecast and optimize the future operation of the building together with the current state measurements and the disturbance predictions. In particular, modeling methods are categorized in two different categories according to ASHRAE (American Society of Heating, Refrigerating, & Air-Conditioning Engineers ASHRAE, 2013): the forward approach, also known as classical, physical-based, “white-box” approach or engineering method, and the data-driven approach, also called inverse approach.

Forward approach predicts the building dynamics based on physical rules pertaining the principles of heat transfer and conservation of energy and mass. Each parameter fed to the model is physically meaningful and is obtained from the building geometry, material properties, and systems specifications. Forward approach methods include common energy simulation tools (e.g., EnergyPlus, TRNSYS, ESP-r, and DOE-2) as well as reduced-order models, quasi-steady-state methods, or modified bin methods (Serale et al., 2018).

Data-driven methods, conversely, are based on the collection of historical data and its use in strictly mathematical models to infer predictions on the building’s future state. Mathematical models employed in data-driven methods consist in statistical tools and, more commonly, in data mining algorithms based on ML. ASHRAE further classifies data-driven models in calibrated models, black-box models, and gray-box models.

Calibrated simulation models are similar to those used in forward approach methods and are based on physical rules for predicting the future energy behavior of the building or parts thereof. In addition to white-box models, however, real data from the field are used to further calibrate the model and align it with the real-world results.

Black-box models instead are entirely empirical and infer the rules governing the building’s energy performance by matching the parameter of the model to the historical behavior of the system, without requiring full knowledge of neither the system nor its processes.

Lastly, gray-box models mix elements from both white-box and black-box approaches, as they still represent the physical description of the systems or building, although simplified, but identify and estimate their parameters using data-driven methods.

Each approach to prediction models differs in terms of advantages, disadvantages, and requirements of data and information about the system or building subject to prediction. As such, the selection of the modeling technique to employ in MPC entails an analysis of the scope and objectives foreseen, of the accuracy and reliability expected, and of the resources available in terms of information and computational capacity.

White-box paradigms, being based on equations deriving from physical and chemical laws of conservation, require a deep understanding of the physical behavior of the parameters and operational processes of the system, and of the assumptions taken in developing it. For the model to be accurate, a number of building components have to be modeled with sufficient detail, such as HVAC components (AHUs, chillers, terminals, ducts, and piping works), building envelope, heat loads, and losses. Therefore extensive documentation is required, which is rarely available when intervening on existing buildings or systems and, in new constructions, needs the extraction of hundreds, if not thousands of parameters from project specifications and BIM files and their insertion into the models, a process still largely manual and

tedious (Gao, Koch, & Wu, 2019). On the other hand, the obtained models, if provided with accurate data, provide highly reliable results which are transparent and easily analyzable, meaning that physically meaningful variables can be tracked singularly to gain additional insight or, for instance, for fault detection purposes. White-box models are best at identifying the dynamic relationship between the system and the ambient disturbances and provide much more information about the system dynamic behaviors. However, those models are often too complex to be implemented in real-time MPC systems. Concerning data requirements, white-box systems need little to no historical data from the building operation to carry out their predictions, and employ it for optional fine-tuning and calibration. This makes them best suited for applications at the design stage for buildings and systems yet to be realized, in which therefore no usage data are available. Overall, the white-box approach leads to reliable and interpretable models with little requirements on the sensor data amount and quality, but only if detailed technical documentation and physics-based modeling expertise are available (Drgoňa et al., 2020).

Black-box approaches, either using statistical regression models or ML algorithms such as ANN or SVM, simply correlate the energy consumption or energy index output with the influencing parameters, producing a simpler model capable of high accuracy, even higher than white-box paradigms in the case of ML-based models, and obtainable even without a good understanding of the system physics (Afroz, Shafiullah, Urmee, & Higgins, 2018). However, this type of model relies completely on training data provided, which must be abundant and meaningful, and may in turn lose reliability if future inputs fall beyond the training range (for instance, if incomplete seasonal data were used for training). Generalization capability is also lower compared to white-box models. The black-box approach provides models which can be transferable to different buildings and systems with the necessary adaptations, thus reducing the implementation time. Black-box models, in particular those based on ANN, are particularly suited for the modeling of building and systems with natural ventilation, a problem that is difficult to solve even with a sophisticated computational fluid dynamics (CFD) model, which requires a substantial computational effort and may not be able to capture the effects of natural ventilation accurately, as it would be limited by mesh size and structure, finer details of building components, heat sources, morphology of surrounding buildings, and other obstructions to air movement (Chen, Tong, Zheng, Samuelson, & Norford, 2020). Overall, black-box approaches are the recommended choice whenever extensive historical data are available, as they can provide remarkable results without hard to collect building documentation.

Gray-box methods may finally be the most convenient solution if both information about the building and HVAC design and some historical measurements are available, as they can provide fairly high prediction accuracy even when data are incomplete and uncertain. However, expert knowledge is needed to set the main system dynamics and the overall model structure, and additional effort is also required for gathering and preparing data for training or estimating the missing parameters. Gray-box shares many features of white- and black-box paradigms and therefore entails some advantages and disadvantages of both. However, the gray-box approach is often preferred over the black-box because of the impossibility of a physical interpretation of the results in the latter (Žáčková, Váňa, & Cigler, 2014).

Notwithstanding the prediction model selected, it is always advised to carry out an exhaustive model validation to ensure good MPC performance. Moreover, it is possible to start with a simple initial model to begin the control operations which will be replaced by an improved model in the near future through re-estimated input data and occupants' comfort perception (Rockett & Hathway, 2016).

Nonetheless, the accuracy of any prediction model may deteriorate over operational time, as the building's environment is continuously evolving: occupants' preferences and patterns may change gradually or abruptly; plants and systems degrade and are repaired or replaced; renovations or refurbishments occur; and the weather itself changes with the seasons and among the years. Therefore regular updates to the model are required to ensure satisfactory performance. Concerning white-box approaches, the models need to be maintained by experts with the same knowledge as those who developed them, whereas for data-driven models, tools employed are those commonly associated with the concept drift phenomenon, that is, when the statistical properties of the target variable, which the model is trying to predict, change over time in unforeseen ways causing the predictions to become less accurate (Schmidt & Åhlund, 2018).

10.4.3.1 White-box methods

As stated above, white-box methods model the thermal dynamics and energy behavior of a building or sublevel components by calculation, based on either the physics of buildings or suitable approximations thereof. One of the main advantages of white-box methods is that the system does not require to be physically built or to provide historical data to evaluate its performance, making them suitable for preliminary predictions of energy needs and design of system loads. Historical data from the field may in turn be used to calibrate the white-box model and improve its accuracy (Serale et al., 2018).

White-box methods can be roughly classified into two categories: the detailed comprehensive method and the simplified method (Zhao & Magoulès, 2012).

The detailed comprehensive method employs complex physical functions or thermal dynamics to precisely calculate the energy consumption for all components of the building based on building's and environmental information as the inputs, which include external climate conditions, materials, and characteristics of the building elements, systems specifications, operation modes, and utility rate schedule. Although physics equations and the associated parameters may be developed by expert knowledge based on the building's systems and characteristics, normally established building energy simulation software is employed. These include EnergyPlus, DOE-2, eQUEST, ESP-r, TRNSYS, Modelica, IDA ICE, and others, described in greater detail in Section 5.2. These elaborate simulation tools can be effective and accurate, but have important limitations in their application in MPC. Being based on physical principles, extensive details of building and environmental parameters are required as the input data, leading to less accurate simulations when they are unavailable. Moreover, setup and operation of these tools normally requires tedious expert work, making them difficult to perform and cost inefficient. For whole building simulations, furthermore, models end up entailing thousands of parameters, greatly increasing the computational time required for each prediction in a way that may not be compatible with the MPC operation.

Simplified models have been proposed as alternatives to detailed comprehensive models for specific applications. Among these, steady-state and quasi-steady-state linear approaches allow only basic energy prediction. An example is the degree-day method, based on the degree-day index. However, it is suitable only for small buildings dominated by the envelope-based consumption, that is linearly linked to external temperature, does not take into account the building's thermal mass and is only suitable for heat energy consumption. More accurate is the modified bin method, also known as temperature frequency method, which consists of performing instantaneous heating and cooling energy calculations at many different outdoor dry bulb temperature conditions, then multiplying the results by the number of hours of occurrence of each condition. It gives reasonable monthly and annual building energy estimates in a simpler manner than detailed hourly simulation programs, especially for low mass buildings where internally generated loads dominate or loads are not linearly dependent on outdoor/indoor temperature difference (Zhao & Magoulès, 2012).

Nonetheless, the common approach to developing white-box models is to employ one of the building energy simulation software programs available on the market (Energyplus, TRNSYS, Modelica, etc.), which were initially built for design purposes to simulate energy and mass flows in buildings according to the envelope materials, the weather, the internal loads, and the HVAC systems based on detailed models of building components. However, these are typically not directly suitable for integration into the MPC as a prediction model, for the following main reasons:

- they often focus on a single subsystem, such as the building envelope, the HVAC system, or the on-site energy generation, and struggle to integrate different functions into the same simulation problem;
- they are typically nonequipped to perform optimization problems internally and need external algorithm and tools to process their results;
- simulation output is commonly non-compatible directly with typical supervisory and control sequences for building automation.

In the last 10 years, middleware software and interface protocols have been developed to bridge the communication between the different energy simulation programs and with control-oriented tools, specifically toward most used programming languages in automation control such as MATLAB/Simulink and Python. Platforms such as Building Controls Virtual Test Bed (BCVTB) and the Functional Mock-up Interface (FMI), as well as MATLAB/Simulink toolboxes such as Openbuild or MLE+, allow to interface different simulation programs with each other to complement their functionalities and implement cosimulation, that is, applications in which at least two simulators, each solving an initial-value differential or difference equation, are coupled to exchange data during run time as the simulation progresses. These allow to couple, for instance, the EnergyPlus model of the building with an HVAC system modularly modeled using the Modelica Buildings Library, with a control model for active components developed using MATLAB/Simulink, or with the output of Radiance to integrate illuminance and glare evaluation in the process (Wetter, 2012). In particular, FMI standardizes the interface of models that contain differential, algebraic, and discrete equations, which can thus be encapsulated into a Functional Mock-up Unit (FMU) using dedicated tools, for example, EnergyPlusToFMU. The FMU can then be imported in another environment to be executed, allowing several FMUs to cooperate at run time through a cosimulation environment.

Cosimulation is crucial for MPC operation, as it requires the prediction model to be linked to the optimization process. While some software tools such as Modelica are flexible enough for developing the building model and the optimization algorithm on the same platform, most used software, namely, TRNSYS or EnergyPlus, have instead no

optimization process on-board. BCVTB and FMI allow to couple or translate the simulation results to external optimization tools such as MATLAB algorithms, GenOpt, etc., allowing for instance to couple TRNSYS with a genetic algorithm or EnergyPlus with particle swarm optimization (PSO) algorithm (Corbin, Henze, & May-Ostendorp, 2013).

Finally, cosimulation platforms like BCVTB also allow to exchange data with BACnet compliant BAS components, coupling the simulation programs with actual hardware or to a complete virtual representation of the system that will be controlled to validate the control sequence or conduct model-based fault detection.

10.4.3.2 *Black-box methods*

Black-box models reconstruct the dynamics of the buildings entirely from the measured data, and are particularly suitable for predicting the behavior of processes where a priori deterministic knowledge of the physical relationship between input and output is not univocally defined. They are based on the empirical behaviors of the system or process and aim to mathematically relate input variables to output variables directly. Generated parameters, however, have no physical significance and the equations do not reveal the causal relationship underneath, thus they are not interpretable by building operators. These models are faster to develop and implement compared to other prediction paradigms; therefore they are often adopted as control-oriented models capable of ensuring an accurate system representation (Drgoña et al., 2020). However, black-box models cannot ensure reliable prediction for operating points outside the range covered by the training data, and thus a comprehensive set of input-output data of the system to be modeled is needed under all possible working conditions, which could be challenging especially for large-scale systems such as HVAC systems which operate under a wide range of weather conditions throughout the year. Therefore the ease of development of inverse models comes at the cost of reduced generalization capability compared to white-box models (Afram et al., 2017).

Mathematical methods employed in black-box models to infer the future state of the system include both statistical approaches based on regression from provided data, and data mining approaches that employ ML algorithms. Black-box methods based on ML are deemed more apt than merely statistical approaches to cope with the uncertainties and variables that affect the behavior of buildings, a task that is difficult to formalize. ML methods examples are ANNs, support vector machine (SVM), genetic algorithms (GAs), RL, deep ML, etc. (Boodi, Beddiar, Benamour, Amirat, & Benbouzid, 2018), with SVM and ANN the most widely used in literature (Wang & Srinivasan, 2017).

Statistical models

Concerning statistical models, they typically rely on a regression analysis to devise a relationship linking an output to the contributing inputs. Statistical regression investigates this relationship among different variables in a probabilistic framework. It is an easy-to-use approach for predicting building energy consumption, especially over longer periods (Wei et al., 2018). However, the regress models require extensive historical data for training, and accuracy of short-term predictions is inferior to other black-box methods based on ML. Moreover, statistical regression is poorly suited to select plausible predictors and appropriate time scale to fit energy consumption for buildings under a wide range of environment and weather conditions. Statistical prediction methods employed in literature include principal component analysis (PCA), nonlinear autoregressive exogenous model (NARX), autoregressive integrated moving average (ARIMA), ARIMA with eXternal inputs (ARIMAX), and conditional demand analysis (CDA) (Zhao & Magoulès, 2012).

SVM

Introduced by Vapnik and Cortes in the 1990s, SVM is a kernel-based ML algorithm, obtained by supervised learning, which has good performance for both regression and classification and is suitable for solving nonlinear problems even with a relatively small amount of training data (Shi et al., 2020). SVM solves a nonlinear problem through transforming the nonlinearity between parameters and targets using linear mapping in two steps: first, it projects the nonlinear problem into a high-dimensional space and determines the function $f(x)$ that fits best in the high-dimensional space, second, it applies a kernel function to make the complex nonlinear map a linear problem (Amasyali & El-Gohary, 2018). SVM is considered one of the most robust and accurate algorithms; however, it requires a substantial computational effort: its efficiency can be increased by resorting to least squares SVM (LS-SVM) and parallel SVM, which have been successfully implemented in building energy consumption prediction. LS-SVM, in particular, was demonstrated as quick and having correct learning performance even when the training set is limited (Ahmad et al., 2014). SVM used for regression analysis is called support vector regression (SVR) and has been widely applied to solve regression problems to estimate an underlying relationship between the nonlinear inputs to the continuous real-valued target (Wei et al., 2018). In

addition to predicting energy consumption of single buildings, SVM have also proven effective in learning from consolidated external data to predict energy loads of new buildings with sufficient accuracy, with better turnout compared to neural networks methods (Li, Ren, & Meng, 2010; Zhao & Magoulès, 2011).

Artificial Neural Network

ANN is a ML algorithm inspired by neuroscience study and is characterized by strong capability to represent the relationship between inputs and outputs, even of nonlinear nature, through multiple layers of neurons. The high accuracy to approximate nonlinear systems compared to other ML methods makes ANN the most popular algorithm for MPC application (Afram et al., 2017). In particular, ANN mimics the human brain by using several neurons in multiple layers, which contributes are generally trained by using supervised learning methods. A limit of ANN use in MPC is that nonlinear models generated are challenging to optimize, as the solution may fall in many local minima before reaching the global minimum solution, and the optimization solution may take a long time to converge which may be incompatible with shortest timeframe MPC applications. Global optimization methods such as evolutionary algorithms and simulated annealing can work with nonlinear optimization problems but present convergence and computational complexity issues.

Basically, ANNs are structured as a collection of nodes, the artificial neurons, connected in order to transmit signals from one to another as with biological synapses (see Fig. 10.10). Each artificial neuron that receives signals processes them with a nonlinear function (the activation function) of the sum of its inputs and can in turn signal the output to the other neurons connected to it. Both neurons and connections typically have a weight that increases or decreases the strength of the signal and adjusts as learning proceeds, and neurons may have a threshold such that the output signal is sent only if the aggregate signal crosses that limit. Artificial neurons are aggregated into different layers, and each neuron connects only to the neurons of the adjacent layers. External input data enter the first layer, called input layer, from which signals travel toward the last layer that produces the ultimate results, called the output layer. Between the input and output layers, there can be “hidden” layers. Signals can move only in the direction towards the output layer (feedforward neural network—FNN) or can also move between neurons of the same or previous layers (recurrent neural network—RNN).

There are many different types of ANN structures, with multilayer perceptron (MLP) feedforward structure is the most popular one for control systems applications (Afram et al., 2017). MLP is a feedforward network with an input layer, one or more hidden layers and an output layer. Except for the input nodes, each neuron uses an activation function, commonly sigmoidal, hyperbolic, radial basis, or linear.

MLP networks are commonly trained by the supervised learning technique called back propagation. The network compares the output values with the correct answer expected and computes the related error value via a specific error

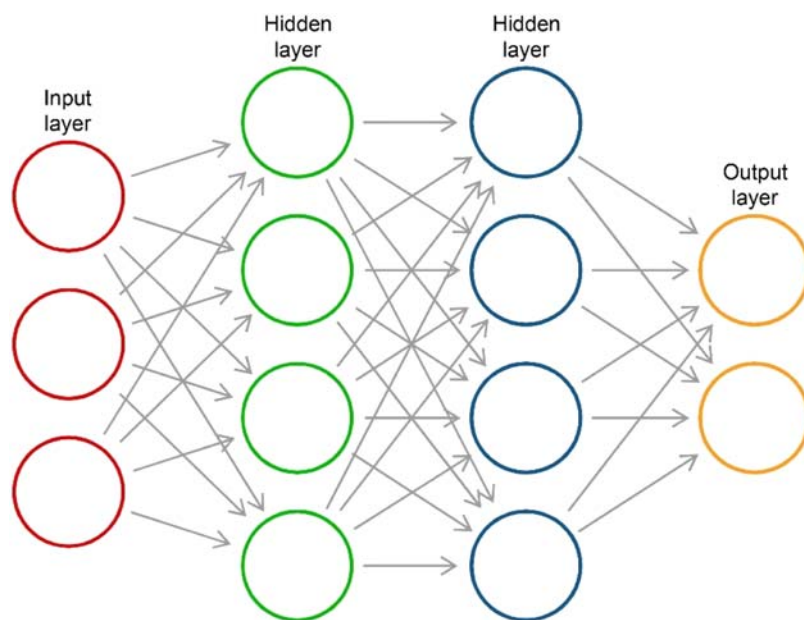


FIGURE 10.10 Artificial neural network (ANN).

function. This error value is then fed back through the network to adjust the weights of each connection in order to reduce the subsequent error values in each training cycle. Over time, the network will converge to some state where the error of the calculations is small enough, the resulting ANN weights are optimal and its predictions are very close to measured data. Measured data are divided into training and validation data sets usually with 70% training data and 30% validation data, and the target model is considered completely learned when it performs equally well on both training and testing data sets.

Nonetheless, since neural networks are purely data-driven, the quality of data will largely determine the quality of the model. A rich data training set is therefore required and should have significant size, diversity, and coverage to encompass most possible working conditions of the controlled system. Otherwise, the model may not produce reasonable predictions when the variable domain of the real-world data provides unprecedented values. Moreover, the operations of space heating, cooling, and natural ventilation measured for model training need to have some randomness, rather than following a fixed schedule, otherwise the model may not be able to discern the real effects of a system operation from the scheduling (either time or threshold) (Chen et al., 2020). In addition to conventional field data measured from the site under normal operation, special data gathering test conditions can be implemented by applying pseudo-random binary sequence (PRBS) to the controlled inputs to enlarge data variance. If no historical data are available, training sets can also be generated from building energy simulation programs.

Concerning data collection for ML, the widespread adoption of increasingly evolved BAS and IoT sensors in all types of buildings in the last years has greatly increased the sheer volume of data produced continuously from different sources. However, all this information may overwhelm the analysis center and pose a serious problem of data heterogeneity, that is, data coming with diverse formats and structures and rather noisy, large-scale, and distributed. This data may be incomplete or redundant and may be come from low-battery or poorly calibrated sensors, be exposed to interferences or be affected by network issues, camera failures, or database crashes. Therefore raw data before becoming useful must undergo a data-cleaning process, which substantially improves their quality by dealing with missing information, discarding noisy and redundant elements and integrating data from various sources. Techniques employed in dealing with noisy data streams include Kalman filters, statistical models, and outlier detection models.

Redundant data can be brought down to a smaller number of features without losing significant information through dimensionality reduction techniques, which include two different strategies: feature selection and feature extraction.

Feature selection aims at discriminating the most related subset of features within a high-dimensional vector and mapping them into a lower dimensional one, thus reducing noise and computational effort on the learning models. Common algorithms used include linear discriminant analysis (LDA), PCA, and independent component analysis (ICA).

Feature extraction methods, instead, work in the discrete, frequency, and time domains. In particular, discrete domain methods include Euclidean-based distances, dynamic time warping, and Levenshtein edit distance calculation. Frequency domain approaches focus instead on the periodic structure of the collected data and employ wavelet transformation and Fourier transform. Lastly, time domains methods mostly refer to mean and standard deviation approaches.

ML algorithms can in turn be applied to dimensionality reduction itself, exploring the internal structure of data in an unsupervised manner using less information, mainly through classification and regression problems. Relevant algorithms include principal component regression (PCR) and K-nearest neighbor (K-NN).

Following preprocessing, to improve the efficiency of subsequent training, all input/output data should be normalized, that is, scaled between (-1) and $(+1)$ values, to give equal weight to all variables and suppress any dominant variables due to magnitude differences in the data. The number of parameters themselves should be carefully selected to ensure comprehensibility, scalability, and accuracy of the models. In fact, too many parameters may become redundant, not adding any new information to the model accuracy but instead increasing its dimensionality and its computational requirements during training, whereas too few parameters, on the other hand, may leave some processes unmodeled. Trial and error, experience and specific algorithms may support the selection of appropriate parameters: for example, Wei et al. used of a combination of domain knowledge, boosting tree algorithms, and wrapper algorithms to reduce 500 total measured parameters down to 11 meaningful ones for the development of four building prediction models (Wei, Kusiak, Li, Tang, & Zeng, 2015).

Deep learning and transfer learning

Deep neural networks (DNN) can be defined as ANNs with additional depth, that is, an increased number of hidden layers between the input and the output layers. In particular, most researchers agree that more than two steps from input to output layers is enough to characterize an ANN as “deep,” and more than 10 identify a “very deep” neural network

(Akinosho et al., 2020). Compared to conventional ANNs, also called “shallow neural networks,” DNN trained through DL can model complex nonlinear relationships and allow greater accuracy in pattern recognition problems, and have seen large application in the last 10 years in the fields of image and object recognition and speech recognition. Multiple hidden layers allow in fact to progressively extract higher level features from the raw input, for instance in image processing lower layers may identify features such as edges, corners, shapes, whereas higher layers can use them to identify the relevant concepts (digits, letters, faces, etc.). As they are commonly characterized by many layers of nonlinear hidden units and a very large output layer, DNN training requires a larger computational effort compared to shallow ANNs. The recent evolution of DNN partly follows the breakthrough in the form of cheap, multiprocessor graphic processing units which excel at the fast matrix and vector multiplications required for DL (Schmidhuber, 2015), and partly the larger availability from various sources of both structured data and unlabeled data, the latter better supported by DNNs. Most DL models are based on RNN and convolutional neural networks (CNNs).

RNNs are best suited for handling sequential data and are therefore mostly applied on process time-dependent information. In RNNs, the connections between the artificial neurons form a directed graph that follows the temporal sequence allowing to model dynamic behavior. Differently from FNN, RNNs allow data connection to move within the same or previous layers of the networks, making the data path, that is, the “depth” of the network, potentially infinite (see Fig. 10.11). RNNs are mostly applied in video and speech processing since they can keep information on a previously processed audio chunk or video frame in order to make predictions of successive data. RNNs are commonly trained using back propagation through time, a variant of back propagation used in MLP training. RNN models have been researched as a viable tool for building energy prediction. For instance, Rahman et al. proposed a RNN model that performed better than a 3-layer MLP model to predict electric load profiles in commercial buildings, proving able to provide surrogates for unknown transient variables and to account for long-term dependencies in electricity consumption (Rahman, Srikumar, & Smith, 2018).

CNNs, in turn, are geared toward image recognition, and are based on feedforward MLP algorithms. In CNNs, the connectivity pattern between the nodes in the hidden layers resemble those in animals’ visual cortex, in which each individual neuron responds to stimuli only in a restricted region of the visual field, but these overlap such that they cover the entire view. This behavior is mimicked by a series of convolutional layers, which convolve the input functions and pass the result to the next layer, gradually shifting the receptive fields, and reducing the number of free parameters (see Fig. 10.12). This allows the network to grow deeper with more agility. In addition to convolutional layers, CNNs also include global or local pooling layers to reduce the dimension of data by combining the output of neuron clusters from one layer into single neurons in the following layer.

A significant advantage of the architecture of DNNs consists in their transferability potential, that is, the possibility of partly reusing and recycling models from an application to another, between different rooms or different buildings altogether (transfer learning). This capability has twofold implications: on the one hand, it diminishes the amount of

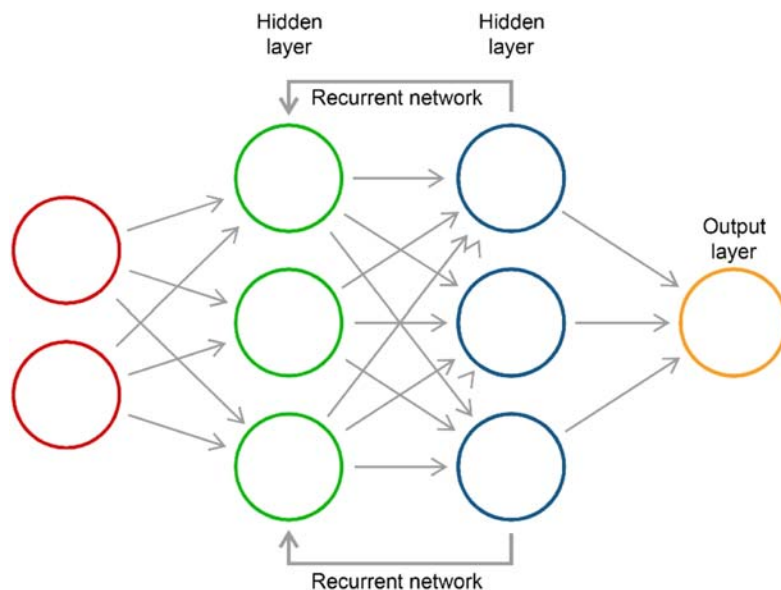


FIGURE 10.11 Recurrent neural network architecture.

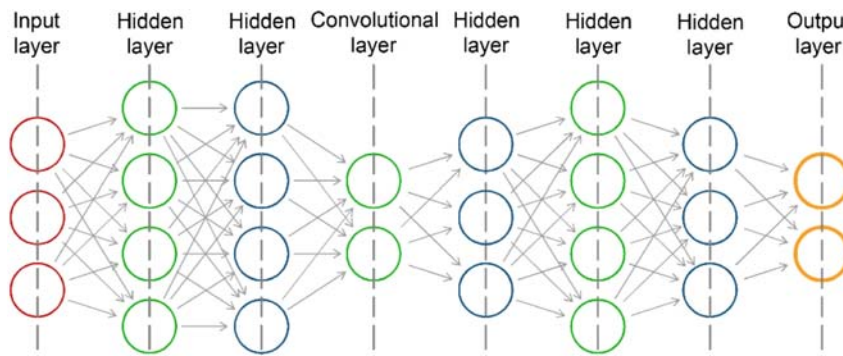


FIGURE 10.12 Convolutional neural network architecture.

work and data needed for ML; on the other hand, it improves the accuracy and real-world applicability of MPC in new buildings in which there is only a limited amount of data for training a new model and data from simulations will inevitably have a discrepancy with the real building operation (Wei et al., 2015). Transfer learning is particularly studied in the field of CNNs for image recognition, in which neural networks can have hundreds of large layers and millions of parameters and model training incurs consequently high computational costs. At the same time, as the underlying problem is recurrent, and since CNNs extract features of the image in a hierarchical order between layers, the first few hidden layers can be reused since they serve the same purpose of identifying lower-level features regardless of the specific problem. In case of image recognition, for instance, being it to distinguish between a dog or a cat or between a car and a bicycle (Shin et al., 2016). Training the last few layers of the CNN instead of the whole network may be sufficient to repurpose that model to a different task, greatly speeding up the training process and reducing the amount of training data required, therefore extending the possibility of employing accurate CNN models substantially over more candidates.

Wei et al. (2015) demonstrated the potential of transfer learning in HVAC MPC by first pretraining a deep MLP network with seven layers and 42,209 trainable parameters with historical multiyear data of a source room in Beijing, then retraining the obtained model with only 15 days of data of a completely different target room in Shanghai. During transfer, most weights of the model were maintained intact and only the first layer with 200 parameters was retrained. Compared to both trained-on-source and trained-on-target models, the transfer model performed up to 10 times better in terms of accuracy. Authors noted that having source and target rooms with different climate zones, materials, and size posed no problems; however, efficiency of transfer learning declines if the operations are in entirely different categories, for example, if the source building has a time-based schedule, and the target building has an occupancy-based schedule.

10.4.3.3 Gray-box methods

Gray-box methods of buildings' operation prediction have been touted by several researchers as an effective compromise between white-box and black-box approaches, as they allow physical interpretation of the parameters of the model and of the related building behavior while making use of building's field data, in a simplified and more effective manner. In fact, white-box physical models normally require extensive modeling effort and documentation and it is generally impossible to leverage the model created during the design process because either the model is unavailable, is inaccurate, or is too complicated to be used in a control environment (large building models may take up to several hours to run). Gray-box models instead use reduced-order models, that is, physical descriptions simplified by means of state space dimensionality reduction or linearization. Model coefficients are in turn identified based on the operation data using statistics or parameter identification methods, allowing to simulate the behavior of building energy systems with reduced requirement of both training data and calculation time.

Most common gray-box method to explain the thermodynamics of a system is the resistance and capacitance network (RC), a simplified, semideterministic physical model characterized by a solid physics representation and computation efficiency. In this model, sometimes also referred to as lumped-capacitance modeling, the electric capacitors represent the thermal capacitance, and the electric resistors between the nodes represent the thermal resistances of the building envelope and indoor elements (see Fig. 10.13). Parameters of resistances and capacitances can be determined from on-site measured data by nonlinear regression methods (Serale et al., 2018). Nonetheless, the development of the RC model requires to establish a simplified physical model and assume bounds and initial values of its parameters

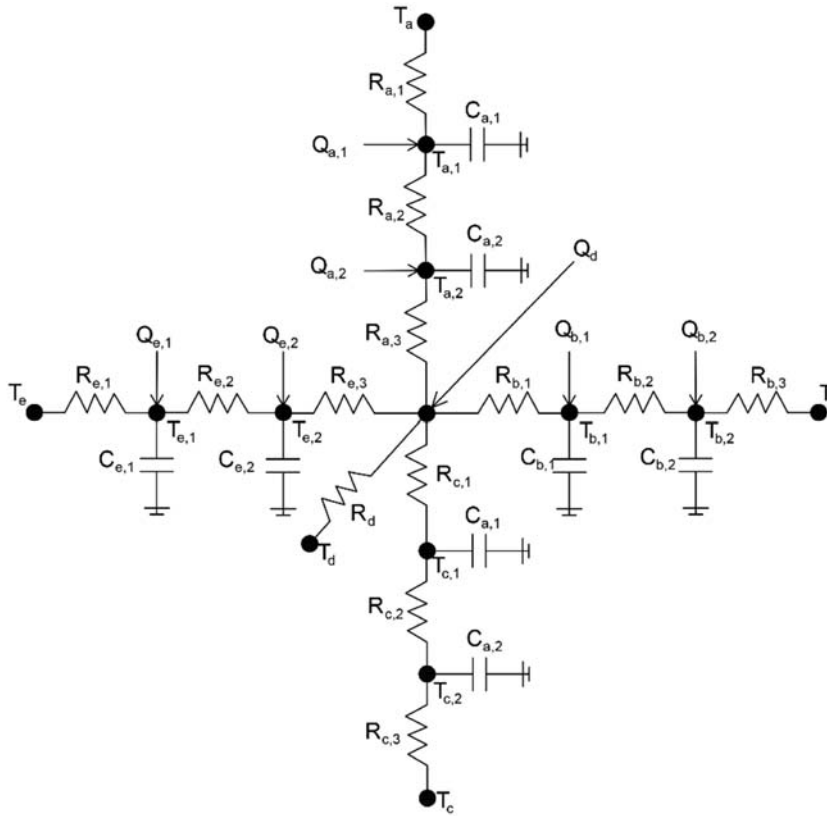


FIGURE 10.13 RC gray-box model.

based on the building geometry and materials, hence considerable expert knowledge and engineering experience are needed. Additionally, the specific model is unlikely to be reusable for other buildings with different geometries and materials (Wang, Li, Chen, Yuan, & Huang, 2019).

In a RC model, the building is partitioned into regions or nodes, typically the air volume of a room or zone or building element layers, each characterized by a uniform temperature. Heat capacitance is calculated for each node as the product of its specific heat capacity and mass, and the heat flux between adjacent nodes is assumed to be linearly proportional to the difference between the regions' temperatures according to their thermal resistance, which includes effects of thermal conduction, convection and linearized radiation. Smaller regions increase the model's accuracy but also its size and computational effort. Using the law of energy conservation, this results in a system of linear ordinary differential equations that describe the evolution of the temperature of each node in the absence of external influences. Influences such as ambient air, solar irradiation, and building systems are then considered as heat fluxes acting on the states, and constitute the major challenge in RC modeling as their physics are often nonlinear and may vary substantially from building to building. Resistance and capacitance parameters can be identified through statistics methods from measured field data of the building: normally 1–2 weeks of data can be sufficient to train the model to sufficient accuracy (Li & Wen, 2014). Statistical models employed to determine the parameters include linear and nonlinear regression, GAs, as well as global and local searching optimization algorithms.

Another example of gray-box model is inverse comprehensive room transfer functions (iCRTF), which is derived from discretization of the state space formulation and creation of linear transfer functions, whose coefficients can be identified based on regression (Blum, Xu, & Norford, 2016).

Several software tools have been developed to assist the development of reduced-order models, such as OpenStudio or Building Resistance-Capacitance Modeling (BRCM) MATLAB Toolbox. OpenStudio is a popular collection of software tools developed to support whole building energy modeling using EnergyPlus and advanced daylight analysis using Radiance and includes modeling and analysis modules and scripting tools that allow EnergyPlus models into a streamlined form more suitable for MPC application. Model reduction process devised by researchers from NREL involves converting the EnergyPlus model into OpenStudio then using scripts to perturb its parameters to generate dozens of alternative energy models, from which new simulation are run to produce a wide range of results to put into a

single database. Linear regression is finally applied on the perturbed parameter space to fit the reduced-order equation, obtaining an accurate, streamlined model with greatly reduced computation time and suitable for MPC optimization as the problem is convex and a global optimum will always be achieved (Cole, Hale, & Edgar, 2013).

Tools such as the BRCM MATLAB Toolbox are instead focused on facilitating the modeling of RC building analogs for MPC by allowing a streamlined generation of (bi-) linear resistance-capacitance type models from basic geometry, construction and building systems data (Sturzenegger, Gyalistras, Semeraro, Morari, & Smith, 2014). BRCM Matlab Toolbox separates the generation of the dynamic thermal model (which describes the heat transfer between rooms, walls, floors, and ceilings) from that of external heat flux models (which describe external influences, for example, solar gains, external air conditions, building systems, internal gains, etc.). The dynamic thermal model is generated from geometry and construction data files which can be either entered by hand or extracted from an EnergyPlus model, enabling the use of common graphical editors to generate the building geometry. Several external heat flux models are instead provided for different physical phenomena and HVAC systems, and must be populated with well-structured input data files (excel or CSV).

10.4.3.4 Control optimization techniques

As introduced above, the prediction of the future behavior of the system of interest, either obtained via white, black or gray-box methods, is just one of the two components of the MPC operation, the other being the decision of which actions to take by solving an optimization problem. In fact, optimization is the primary challenge in building control, as the main objectives, namely, energy consumption and comfort level in the built environment, are typically conflicting.

Optimization is based on an objective function, also called cost function, which represents a target to minimize. More commonly, two or more targets are set, often conflicting with each other: this problem is referred to as multiobjective optimization, and the aim becomes the identification of the best performing trade-off between the objectives. Common approaches for multiobjective optimization include goal attainment, minimax, and Pareto front methods.

Concerning the formulation of the objective function itself, it is affected by several factors, including the building dynamics, the HVAC system, the type and detail of the prediction model, the observability and controllability of the system, and case-specific constraints and requirements. A common example is fully modeling the HVAC system and having the function attempt to minimize the energy use by manipulating the single temperature set points. In other instances, only the building envelope is modeled and the objective is to minimize the inputs from the different HVAC systems, with each system having an associated cost (Picard & Helsen, 2018). In addition to energy use and user comfort, other optimization problems may include more specific objectives, such as the minimization of monetary costs, the minimization of greenhouse gases emissions, or the maximization of the share of local renewable energy.

In particular, the sole minimization of the energy use in a building does not necessarily result in the absolute minimization of the operational costs or of the emissions: in case of volatile electricity prices, for instance, energy can be taken from the grid when cheaper and stored as thermal or electrical energy for later use, resulting in a cost reduction even if some energy is lost for load shifting. The presence of on-site renewable energy sources can also be exploited to either minimize cost by selling the energy when most convenient, or minimize emissions by favoring self-consumption. These objectives may be formulated by transforming the energy use into monetary or emission cost by means of a variable factor, which can be considered as a forecasted disturbance to the model.

Generally speaking, optimization techniques applicable to MPC differ depending on whether the building's problem formulation, model representation, and uncertainty aspects are linear or nonlinear, and can be segmented into two main categories: mathematical programming and metaheuristic algorithms.

Mathematical programming techniques include sequential quadratic programming or mixed-integer linear programming and have been successfully demonstrated in energy and operation management using MPC strategies. These problem solvers are more appropriate for finding a solution to linear or convex problems; therefore their convergence speed is slow when applied to nonlinear or nonconvex ones.

For more complex and nonlinear optimization problems, such as those that take into account stochastic events, uncertainties and disturbance, nature-based heuristics are more appropriate at finding the optimal solution with high convergence speed and efficient constraint handling, as needed for a reliable MPC controller.

A nature-inspired heuristic widely used in building optimization is GA, a stochastic technique inspired from natural selection process. This approach iteratively searches a population of candidate solutions (represented by chromosomes consisting of genes—choices for optimization variables) for those that best fit the specific cost function, and refines the next generation by mixing the chromosomes (i.e., the optimization parameters) of the fittest members. GAs are explained in more detail in Section 6.4.2.1.

Another popular heuristic for optimization is simulated annealing, which primary operation consists of a local search to minimize a problem-specific cost function. To avoid getting trapped in local optima before converging to the global optimum, simulated annealing sometimes proposes a candidate solution that increases the value of the cost function instead of decreasing it, and this uphill move is accepted or rejected according to a configurable acceptance probability (Schmidt & Åhlund, 2018).

A common optimization approach is PSO, which is based on a population of candidate solutions. A gravitational algorithm iteratively updates the distribution of the solutions (particles) according to simple rules of attraction and inertia. PSO can only be used to solve single-objective optimization problems, whereas multiobjective particle swarm optimization (MOPSO) can solve the multiobjective optimization problems by allowing to specify the trade-off between conflicting objectives, for example, saving energy and addressing comfort aspects.

In presence of conflicting objective functions, the multiobjective optimization problem typically produces a set of nondominated (Pareto optimal) solutions instead of a single optimal one. In these cases, strength Pareto evolutionary algorithm (SPEA) has advantage in searching global solution while MOPSO is applicable in searching for optimal local solutions. Finally, strength MOPSO (S-MOPSO), which combines SPEA and MOPSO algorithms, is considered effective in finding optimal solutions of nonlinear multiobjective models (Afram et al., 2017).

10.4.4 Reinforced learning

RL is a branch of ML that is specialized in solving control or sequential decision making problems and is considered a promising method to apply in building controls. RL is data driven and can be either model based or model-free, with the second avoiding the tedious work of developing and calibrating a detailed model, as is required by MPC. Additionally, RL could leverage the recent and rapid developments in the ML field, such as DL and feature encoding, to make better control decisions. In fact, the major challenge of model-based control systems is that they are labor-intensive and require expertise to develop and cannot be reused. While it might be cost-effective to develop and calibrate a model for a car or an airplane that can be generalized and used for many cars and airplanes, every building and its energy systems is unique, so it is difficult to generalize a standard building energy model for various buildings.

Main consolidated ML techniques are supervised learning, in which instantaneous feedback is provided to the algorithm that will immediately know how accurate its prediction is compared with the label data, and unsupervised learning, in which no feedback is provided to the algorithm and the dataset is unlabeled. RL lies in between these approaches by receiving delayed feedback, and is mathematically based on Markov decision process (Wang & Hong, 2020).

Specifically, RL consists of an agent that interacts with a definite environment, and learns what actions to take depending on its state (see Fig. 10.14). The agent learns tentatively and is rewarded for taking desirable actions, which typically involves a significant amount of trial and error as it learns what actions result in the highest reward.

In a typical RL algorithm, the agent interacts with its environment in discrete time steps, or states. The agent commonly has a policy which determines what actions it will take, and the goal is to find the optimum policy within the set of possible policies. Specifically, the agent first observes the state of the environment, then selects an action to perform and assesses the new state obtained and the reward achieved. The agent now updates its current policy according to the reward and repeats the loop on the new state. In addition, the agent also considers the expected future rewards it will obtain if it follows its current policy, with specific variables making it more or less forward thinking.

In fact, the control agent could not simply select the action corresponding to the highest reward; instead, it needs to consider the delayed future rewards corresponding to the new state. For instance, the action of precooling might lead to



FIGURE 10.14 Reinforcement learning training loop.

higher immediate energy consumption, but in the long term, the new state saves utility costs. The strength of RL lies in its ability to optimize the trade-off between short-term and long-term benefits.

In model-based algorithms, the agent learns a model of the environment based on observing how the state of the environment changes when certain actions are taken. These observations are used to estimate the environments transition and rewards. Once the algorithm learns a model of the environment, it can be combined with a planning algorithm to decide what actions to take. However, learning an accurate model is time-consuming and requires expertise. In fact, model-based RL is not an alternative to MPC, but rather a black-box method within the established MPC flow.

More interestingly, model-free RL skips the process of having to learn a model. Instead, it aims at learning a policy from the interaction with the environment, via trial and error, with the aim of approximating the optimum policy. Many of the routinely used RL algorithms are model-free, such as Q-learning and State–action–reward–state–action (SARSA). Crucially, model-free approaches are generally less computationally expensive than model-based ones.

Nonetheless, training an RL controller is data- and time-demanding, even if size has reduced with advancements in RL techniques. Research found that 3 years of training data can be adequate to guarantee that RL controllers outperform rule-based controllers (Yang, Nagy, Goffin, & Schlueter, 2015). Furthermore, many RL algorithms, such as Q-learning, represent the values of each state-action pair in a look up table (Q table). This approach works well for problems where the state-action space is small. However, when the number of states and actions increase, the size of the table quickly becomes exceedingly large (Mason & Grijalva, 2019). As the size of the state-action space grows, the learning time to converge to an optimal policy also grows and each additional state or action variable added increases the problem size exponentially. A widely adopted solution is to replace the Q table with a function approximator, most commonly a DNN. This technique, known as deep reinforcement learning (DRL), can manage larger state-action spaces, thus bringing more possibilities when working with a huge number of variables (Lissa et al., 2021). In particular, the main advantage of DRL method over the conventional RL method is that the application of the DNN makes it possible to achieve high level control for extremely complex problems, such as with continuous state spaces or action spaces, without the tabular constraints. In DRL, a more generalized regression model is established instead of maintaining a concrete Q table to store all the possible action values, allowing more robust and flexible strategies against unseen states in the case of continuous control (Du et al., 2021).

As RL controllers learn the optimal policy by testing new policies and evaluating the outcomes, it is possible that some tested policies might lead to an undesirable outcome, such as too cold or too hot temperatures. This would result in an initial exploration period where the RL agent would evaluate different policies, many of which would have an unacceptably high energy cost associated with it. A consolidated approach is to pretrain the controller to make it safe and robust enough to be implemented in real buildings. This can be used with simulators rather than real buildings, or by referencing to common practices or industry standards in this field as the optimal policy. Additionally, the controller can be pretrained using the optimal policy resulting from other optimization methods, such as PSO or model-based convex optimization, or even MPC itself. As the simulator or the model-based optimization is used only for pretraining, either the simulator or the model does not need to be very accurate, because RL will further improve the policy by fine-tuning it when implemented in physical systems (Wang & Hong, 2020).

In research, RL has been successfully applied to many areas of building energy management, including HVAC control, with Q-learning as the most used algorithm. Typically, the environment states for the RL algorithm include factors such as time of day, outdoor temperature, indoor temperature, weather forecast and occupancy, and potential actions include temperature set points, air flow control, heating control and cooling control. The RL algorithm also needs some sort of reward to operate, which is usually calculated based on energy cost, thermal comfort, or a combination of both. Literature reports numerous successful applications of RL to HVAC control with a variety of RL algorithms. Most studies report energy savings in the range of 10% when compared to rule-based approaches. There is also a recent trend to apply DRL to HVAC control, which has outperformed traditional tabular RL. This trend is unsurprising given the recent success and attention that DL has received. Concerning water heating, in turn, many of the studies report reductions of around 20% when compared to the baseline.

A promising application of RL controllers is to manage home energy services such as appliances, lighting, PV, battery, etc., which itself is a complex problem with multiple factors that must be managed to reduce the overall energy consumption. The states for the RL algorithm when exploring building energy management in a more holistic manner generally consist of the time of day, temperature information, and the current usage state of the various appliances, as well as electricity prices, grid load, and information in relation to PV panels such as solar irradiance. The actions available to the RL agent mainly include switching a device or appliance on or off, and charging or discharging the battery. Studies reported an average 50% reduction of energy cost, up to 72% when implementing RL with a model-based controller, with better savings in HEMSs equipped with batteries and PV systems (Mason & Grijalva, 2019).

Concerning DRL approach to HEMS control, a study that included PV self-consumption optimization and a dynamic setpoint definition for indoor temperature, demonstrated energy savings of up to 16%, 10.2% of load shifting via PV self-consumption optimization, and 99% of temperatures falling within the specified set-points range (Lissa et al., 2021).

10.5 Advanced human interfaces

User interface is an often-overlooked aspect of BAS, although its relevance is substantial in representing the bridge between the occupants' needs and requests and the building controls. Depending on the functions of the BAS, the type of user involved and the degree of control allowed, different interfaces may be implemented within the same system. For instance, multitenant office buildings may provide a central control interface, password protected, and accessible only by authorized technicians and maintenance officers, paired with simpler input units where occupants may have limited control over specific functions (e.g., room thermostats, lighting, blinds control), whereas in a single residential unit the homeowner would have control on all subsystems.

The main control interface sits at the top level of the BAS, that is, the management level, and usually consists of PCs connected via an Ethernet network, although the system is usually accessible via web server to allow remote management and maintenance. These operator workstations can communicate with, interrogate and control any of the controllers and devices on the network. Main functions provided at the management level include system programming of controllers and sequences, monitor and control field point and set points, display of system information and reports, system scheduling, archive and analysis of historical data, alerts, visualization of trends logs and charts for optimization and diagnostic purposes. The BAS system is usually managed by a server and operator workstation using standard operating systems, specific BAS software applications, web access, and graphic interfaces.

In particular, modern BAS software tools integrate powerful graphics capabilities and integrated editors, which allow to create the desired GUI from simple vector drawings to photorealistic images and 3D models imported from BIM files. Middleware tools such as JavaScript or HTML5/CCS3 graphics packages can also be used to further customize the behavior of each graphic, introducing for instance animations to highlight changes in the system or make navigation easier, for example, by creating a floor plan view with color-coded temperatures, pressure, humidity, or usage levels for each zone.

In addition to the operator workstations, simpler control interfaces can be built into controllers and remote devices. These usually consist in smaller LCD displays with a button or touch interface, and allow specific inputs from occupants within the strategies and logics set at the higher management level. Both management and occupant level interfaces can also be replicated on mobile apps to allow operation from smartphones or tablets as well (Casini, 2020) (Fig. 10.15).

Finally, BAS interfaces have seen the recent introduction of advanced user interfaces based on informal conversation with the system via text or voice (chatbot or voice interface) or even via specific gestures as detected via computer vision algorithms. These UI are also called “human interfaces” for their more intuitive and easier operation.

Thanks to the developments in AI, BASs can now be operated via voice control (voice interface) or written text (chatbot), this way allowing both to greatly simplify the user interface and to delegate numerous operational activities directly to the machine with substantial time savings. With a chatbot or voice interface, in fact, a simple textual or



FIGURE 10.15 Touch-based BAS interfaces.

spoken request effectively replaces the entire process of opening different software tools, checking data, finding results and crossing them, and finally obtaining the answer or the action requested.

In particular, through voice control it is possible to query the BAS to obtain certain information or ask to perform a certain action.

Requested information may concern the retrieval of the readings from a sensor (light, temperature, etc.), of the production and consumption values of a given day, of the on/off status of a device or open/closed status of an envelope element, or the diagnosis on the operation of a machine, a forecast on consumption or costs, or the result of a possible scenario.

The action to be taken may concern, instead, the on/off switching of devices, the opening or closing of doors, windows and curtains, the variation of the intensity levels of the equipment, the activation of programmed cycles or scenarios, up to scheduling a meeting, booking a service, purchasing goods, sending a message or email, etc.

The system can also be programmed to provide users with proactive notifications such as suggestions or alarms.

Regardless of the type of voice request from the user, these systems are based on a process of understanding human language and on the execution of the intent contained in the message. This process is made possible through software expressly designed to automate regular Q&A queries and menial tasks a human would typically do, by having moderately complex conversations with users and following informal instructions provided by text or voice instead of task-specific commands.

These software employ AI techniques of natural language understanding (NLU), NLP, and natural language generation (NLG) which enable computers to identify valuable information from everyday speech and determine the intent, the task or action requested, and the entities, or parameters and keywords needed to complete the task, up to the communication of results to the user.

Traditionally computers have not been capable of extracting knowledge from of natural-human language (that used in spoken conversations, text messages, books, emails, social media posts, etc.) because information is presented as unstructured data, as opposed to structured data of the sort found in data tables and spreadsheets. NLP enables computers to process and extract meaning from language to an impressive extent, capitalizing on advancements in AI, Big Data, and ML by training its models with vast amounts of language data until sufficient usability is reached, then improving them by learning from actual use cases.

Once NLP has figured out the meaning of the user input and converted it into code, the computer can carry out its task, then present the results to the user by employing NLG to take the processed data and transform it into language that sounds natural, as if a human was writing or speaking.

Both NLP and NLG are based on algorithms to extract rules from unstructured language data and convert the data into a format that machines can understand by using analytical techniques such as syntactic analysis (assessing language according to grammatical rules) and semantic analysis (getting at the meaning conveyed by the language) (Marr, 2020).

Chatbots and voice interfaces are both underpinned by these technologies and differ in the way they interact with the user: the former employs a written chat interface to communicate with the user like an instant messenger app, the latter is instead entirely voice based, responding to spoken language queries and answering the same way.

Voice interface has the advantages of being more natural thus requiring less effort, of allowing to free both hands and vision potentially for doing another activity in parallel, also helping disabled people, and of being more efficient than writing on a keyboard (we can speak up to 200 words per minute opposed to 60 in case of writing on a keyboard). It is also particularly suited for languages that are easier to speak than type, such as Chinese.

Since the 2010s, the use of vocal interface systems for BAS has greatly expanded, thanks to the availability on the market of numerous smart vocal assistants (VA), built into smartphones, personal computers, or dedicated home speakers, such as Apple Siri (2010), IBM Watson Assistant (2011), Amazon Alexa (2014), Microsoft Cortana (2014), and Google Assistant (2016), that provide users with a great variety of services (Adamopoulou & Moussiades, 2020). These VA can in fact be easily integrated and used to interact via voice command with all the functions of the BAS, also providing the possibility to use the other, non-BAS specific services they offer.

Vocal interface system can be developed using programming languages like Java and Python or NLU cloud platforms powered by ML such as Google DialogFlow, Facebook wit.ai, Microsoft Azure LUIS, IBM Watson Conversation, Amazon Lex, and SAP Conversation AI. The VA is trained to recognize a series of predefined phrases in which intent can be expressed by the user, in order to be able to respond correctly even when faced with different alternatives in language. In addition, VA, thanks to ML, is able to continuously learn from users new ways of understanding a certain request, becoming able over time to respond even without the user having to pronounce predetermined sentences.

By inserting so-called “implicit” sentences during the training phase, such as “I’m cold” or “I’m hot,” it is also possible to have a more natural dialog with the VA: it will understand what to do even when the user pronounces sentences



FIGURE 10.16 Data flows of a vocal interface system.

without explicit parameters or references to the action to be performed. For example, upon hearing the voice command “I’m cold,” the system will respond by asking the user if they want the temperature to be raised.

Once developed, the VA can be easily integrated into a smart speaker and activated via an explicit keyword, such as “talk to BAS,” to be added to that of activation of the speaker itself (such as Hi Google, or Hey Cortana, etc.).

The information flow provides that the user’s voice request addressed to the smart speaker is sent to a cloud-based bot service where it is interpreted and structured, to extract intent and contextual variables (see Fig. 10.16). The command is then transmitted through a cloud gateway to the BAS actuator to perform the requested action. A feedback of the action performed is finally sent to the end user also via smart speaker to confirm the user.

10.6 Smart Home

The concept of smart home, smart house or, more broadly, of home automation refers to the deployment of advanced BAS technologies in the residential, single-family sector. Specifically, a Smart Home can be defined as a residence that has a system (composed of a range of smart devices) or several systems that are network connected, can be controlled remotely or automated, and provide a range of services such as enhanced entertainment (e.g., a smart TV, streaming and audio system), security (e.g., a system of cameras, sensors, controls and locks), and energy efficiency (e.g., a HEMS) (4E Energy Efficient End-Use Equipment Technology Collaboration Programme, 2018). Traditionally, residential application of BAS has lagged behind larger office and commercial real estate, in which the high cost and complexity of automation systems could be mitigated by centralized installations and offset by the scale of economic savings achievable. Furthermore, tertiary applications could make do with limited systems flexibility, as they were deployed with specific users and activities in mind in a more strictly controlled environment such as office complexes or large retail, whereas home automation would need closer tailoring on the single user’s needs.

The recent advancements of BAS technology in terms of ease of programming, advanced control functions and reduced cost of electronics, as well as the wider availability on the market of cheap, unobtrusive, and easy to set-up IoT devices, have greatly expanded the market and the adoption of smart home technologies, which have become a substantial component of the whole BAS sector. In the United States alone, the smart home sector has experienced a CAGR of 31% between 2015 and 2017, jumping from 17 million to 29 million connected homes in just 2 years, and today accounts for the majority of the global market share, with the EU behind at 22.5 million connected households in 2017, or 9.9% of European households (Del Rio, Sovacool, Bergman, & Makuch, 2020). Worldwide, the Smart Home market is expected to grow from US\$78.3 billion in 2020 to US\$135.3 billion by 2025, at a CAGR of 11.6% (Markets & Markets, 2020).

The growth of the smart home market is expected to be significantly driven by the increasing availability of IoT technologies (switches, timers, sensors, remote controllers, and IoT integrated home appliances) that find convenience in relying on the dwellers’ smartphones as their control center and user interface, promising easy and remote monitoring and operation of a wealth of house functions at one’s fingertips. In particular, consumer preference mainly goes for home security (video doorbells and surveillance systems), voice-assisted technologies (such as Alexa and Google Home), and centralized home entertainment control, with increasing adoption of IoT HVAC controllers and HEMS as well. Traditional home automation systems on the market, such as MyHOME by bTicino, Chorus by Gewiss or By-me by Vimar, have instead relied on consolidated BAS standards such as BUS paired cable distribution and central servers, although with cloud and mobile app functionalities. Such systems are inherently more reliable and secure compared to wireless IoT systems, but require extensive wiring and professional installers for their application. This has discouraged retrofit interventions and poses questions about their scalability and compatibility with current and future third-party products.

Home automation can be implemented at different levels of sophistication, depending on the degree of integration sought between the different house services (Mocrii, Chen, & Musilek, 2018). This is partly true for larger BAS, as reported in this chapter, but is particularly important for smart homes. Indeed, on the one hand there are a multitude of consumer IoT systems available on the market that focus on automating a single home service and which main appeal

is their seamless plug-and-play installation by the users themselves. On the other hand, in addition to the piecemeal adoption of smart home systems independent from each other, the development or programming of an overarching architecture is needed to integrate and leverage data and abilities of connected devices and achieve system-wide benefits in terms of user convenience, energy, and cost savings and increased comfort.

According to the American Council for an Energy-Efficient Economy (ACEEE), typical smart home technology features can be summarized as follows (“Skip” Laitner, McDonnell, & Ehrhardt-Martinez, 2014):

- network connectivity: it can use networks to send data to and receive data from household members, other devices and other entities such as energy providers;
- automation: it can be set to turn on, turn down or adjust home services in response to preset settings or learning based on household preferences;
- context awareness: it can recognize household members and situational contexts via sensors and other technologies;
- adaptiveness: it can change settings or offerings in response to household members;
- interactive: it can provide alerts and notifications and can be voice controlled;
- remote controllability: it can be controlled remotely by use of network connection via a smartphone or web app;
- ability to be personalized: it can be tailored to needs and desires;
- anticipation: it can anticipate these desires or needs without conscious meditation.

Smart homes are considered a viable measure to reduce energy consumption of both existing and future residential building stock. Smart home enabled energy savings could be in the region of 20%–30% of household energy use, with increasing potential as technologies are optimized, developed and linked with the implementation of further energy efficiency opportunities (see Table 10.10). As an illustration, the potential energy savings in the UK could be more than 3 Mtoe per year with a smart home penetration share of 30%. Correspondingly, savings in Japan could be in the region of 2.6–3.9 Mtoe per year. Energy savings in the United States could be around 15.7–23.5 Mtoe per year and could grow in excess of 30 Mtoe with 40% deployment (4E Energy Efficient End-Use Equipment Technology Collaboration Programme, 2018).

TABLE 10.10 Residential buildings: possible benefits of digital technology (IEA, 2019).

Technology	Description	Possible benefits
Smart thermostat	Heating and cooling controlled remotely (or automatically) and temperature adjusted according to preferences or sensor inputs	5%–20% less energy use for heating or cooling
Smart zoning	Individual rooms or zones heated or cooled to specific temperatures at specific times	10% less energy use for heating or cooling
Smart window control	Controls amount of light let through and can block heat or cold	10%–20% less energy use for heating or cooling
Smart lighting (including occupancy control)	Remote control of lighting, automation, adjustment to occupancy	1%–10% less home energy use; 30%–40% less lighting energy use
Smart plugs	Turns unconnected products into connected devices	1%–5% less home energy use
Home energy management system	Enhances control and automation of energy-using appliances and equipment	8%–20% less home energy use
Extensive system of management and automation optimized for energy efficiency	Combination of technologies providing measurement, monitoring, dynamic benchmarking, information displays, management, control, automation, zoning, occupancy systems, maintenance management, etc.	30% less home energy use
Smart district heating	Artificial intelligence combined with sensors to optimize district heating use in apartment blocks	~ 10% less apartment block energy use ~ 20% more apartment block peak energy savings

At the same time, smart home technologies will be responsible for a growing share of residential energy use. For example, IEA assesses that 50% of household electricity demand for appliances by 2040 is expected to come from connected devices, as connected devices generally need to be on or at higher power modes for extended periods of time to maintain connectivity, increasing their energy consumption, and offer new functions and services (e.g., preheating homes or running automated security routines) which may lead to intensified use and increased energy demand (IEA, 2017). A key issue of concern is the standby energy consumption of smart home devices needed for network connectivity. If left unchecked, the energy demand of network connected devices in homes and offices could grow from 616 TWh/year in 2013 to 1140 TWh/year by 2025, although policies and programmes to reduce network standby power energy consumption have been put in place in several jurisdictions (e.g., EU, United States, and South Korea) (IEA, 2014).

More generally, the acquisition, transmission, and storage of data and remote software updates consume a lot of energy. Other challenges affecting IoT system performance include reliable power supply for IoT sensors and devices, efficient power and energy storage technologies, energy requirements for data routing, and availability of low-power communication stack (Lawal & Rafsanjani, 2021).

10.6.1 Smart home services

Smart home devices currently available on the market cover a wide range of applications with different capabilities, costs, and achievable benefits. IoT systems allow, in addition to monitoring, to operate appliances and electrical equipment, manage HVAC and lighting, or control individual power outlets (see Fig. 10.17). Security applications include IP cameras, video doorbells, and smart locks for access control (see Table 10.11).

Home security and safety is one of the fastest growing trends for home automation. IoT smoke or CO₂ sensors (Nest, Netatmo) are widespread smart home services, as they allow a cheap and effortless retrofit in existing dwellings which often lack these type of sensors as they are not required by building codes. CO₂ sensors in particular can signal when it is time to open the windows and reduce unneeded HVAC loads. Remote video cameras are also increasingly diffused and allow recording and streaming of both indoor and outdoor video feed on the house premises. Main manufacturers on the market include Arlo, Ring, Netatmo, and Google Nest. These cameras can also feature AI capabilities and are able to distinguish people, pets and objects, follow detected agents, record directional audio, and issue alerts automatically on the preferred communication device. Recorded video is automatically tagged with detected sounds and movements to allow quick search of specific events. Some products also feature built-in speakers to allow communication between devices. Similar to IoT cameras, smart doorbells are wireless and battery operated and are able to stream live audio and video, detect motion, and issue alerts. Indoor surveillance drones are also entering the market to cover any gap and identify potential risks. Additionally, smart locks enable another layer of security control by managing and sharing access. These devices are compatible with standard European or Yale cylinders and can be operated with the smartphone or with proprietary smart keys via BLE or NFC communication, each customizable and activable or deactivable via a dedicated app (for instance to deactivate lost keys or to assign special privileges to guests, family members, or maintenance staff). Some products also include biometric identification (fingerprint reader or retina scanner). Other features include voice activation, geofencing, and auto-locking features. Similarly, smart garage door controllers enable remote operation and status monitoring, issue alerts when vehicles and people come and go, and allow basic automation features.

Concerning smart appliances, these are available from most major manufacturers of either large or small domestic devices. Smart appliances were defined in the EU Ecodesign Preparatory Study for Smart Appliances as appliances that are communication enabled. This communication platform can be used to offer multiple classes of functionalities like demand side flexibility, that is, the capability to receive, interpret, and act on a signal received from an energy provider and adjust its operation according with the settings chosen by the energy consumer. Kitchen appliances such as dishwasher, clothes washer/drier, refrigerator, stove, oven, or tabletop cookers also allow scheduling and automation of daily routines (Marikyan, Papagiannidis, & Alamanos, 2019). Smart refrigerators feature multiple internal wide-angle camera with AI functions that identify and inventory the fridge contents and show them on the outer screen, without requiring to open the door, or even remotely on the phone or on the house TV (Samsung Family Hub), or have a transparent window display to show what's inside and relevant information on top (LG InstaView). Other features include instant access to recipes and step-by-step guides, meal planners according to the food present in the refrigerator, creation of shopping lists and automated order of food via e-shops. Clothes washers and driers can learn the users' preferred laundry cycles and automatically regulate time and detergent according to the soil level detected or to pictures of the clothes taken via the app (Candy Snap&Wash) (see Fig. 10.18). Washes and drying

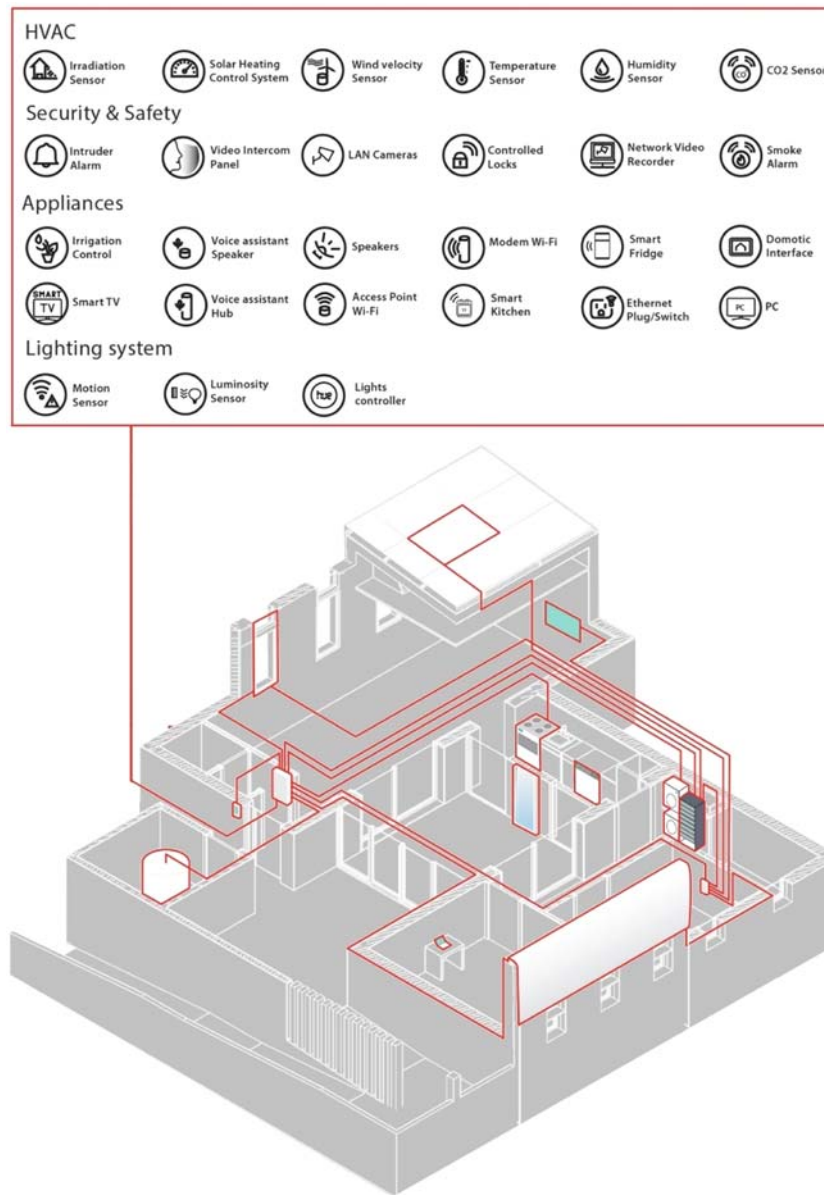


FIGURE 10.17 Example of smart home connected services.

cycles can be scheduled and interrogated remotely via smartphone. Connected ovens can be preheated and monitored remotely (Candy Connected Oven), and cooking time and temperature adjusted via voice command (see Fig. 10.18). Air dressers can be remotely started and paused and issue notifications and cycle recommendations according to the color and fabric of the garments.

In addition to connected devices, most home appliances can be enhanced with smart plugs and load monitors that are able to measure their power consumption and to control their operation in real-time (Stojkoska & Trivodaliev, 2017). This way any “dumb” device that’s plugged-in can gain remote control, scheduling and energy monitoring capabilities: using a mobile app, a coffee maker switches on at sunrise, a fan can be scheduled to turn on at noon, or a lamp can be synchronized with the sunset so the owner never comes home to a dark house. Existing lighting systems can be enhanced with smart switches to gain remote control and scheduling as well. Smart plugs are connected between the power outlet and the actual device or can be integrated in the power outlet itself (smart power outlets). Energy consumption data can be checked in real time, stored for later analysis or exported as CSV or xls files, and can be integrated with energy price information to perform some basic cost control. Main manufacturers of smart plugs, switches, and outlets include Wiz (see Fig. 10.19), Belkin Wemo, Parce, Dome, Leviton, Sylvania, and iHome.

TABLE 10.11 Main IoT home devices.

Smart functions	IoT products
<i>Monitoring of indoor/outdoor environmental parameters</i> Remote information on air quality, lighting, air temperature, humidity, noise levels	NetAtmo, Nest, Baranidesign
<i>Electric</i> Monitoring of energy consumption and on/off control for individual appliances/outlets/lights	Wemo, Parce, Dome, Leviton, Sylvania, iHome, Kasa, Wyze, Wiz
<i>HVAC</i> Monitoring of indoor/outdoor environmental parameters and energy consumption, remote control. Learning-based self-programming and optimization. Automatic operation based on the presence/absence of people (geofencing).	Nest, NetAtmo, Ecobee, Wyze
<i>Lighting</i> Remote information and control of lighting equipment Programmable lighting scenarios (guests, party, home theater, etc.). Routine switch on to simulate occupancy of the premises (vacation mode) Centralized lighting power off when the system recognizes the absence of users	Philips HUE, Signify Interact, Wiz, GE Link, Osram Smart + , Wyze Bulb, Lixf Mini
<i>Appliances</i> Remote monitoring and control of home appliances (kitchen, laundry, vacuum cleaners), self-reporting on cycles status, self-programming according to detected food, stain level, fabric, etc.	LG InstaView, Samsung SmartHome, Candy simpli-Fy, Whirlpool Smart Appliances
<i>Water</i> Leak and flood detection and automated water shut-off. Monitoring of hot and cold water consumption. Monitoring of environmental conditions and of soil humidity and nutrition and automatic or remote control of irrigation.	Dome, Belkin Phyn Plus
<i>Home security</i> Home boundaries, check in on live video and audio feed, events reporting, control other smart devices Remote locks control, access, and permissions remote control	Wyze, Nest, Ring, Arlo, Netatmo, August Smartlock, Yale

**FIGURE 10.18** Candy smart washing machine (left) and oven (right). Courtesy of Candy.**FIGURE 10.19** Smart bulbs, smart plug, and smart presence detector by Wiz. Courtesy of Signify.

Smart thermostats are another product with growing adoption rates, pioneered by Google Nest in 2011 and today available from manufacturers that include Honeywell, Ecobee, and Wyze. Whereas a programmable thermostat can help reduce energy consumption by turning the HVAC system on when you anticipate being home and off when you do not, a smart thermostat goes beyond simple scheduling by enabling more sophisticated schedules for every day of the week, giving complete, remote control over the HVAC system, including hot water production. These are usually linked to the home's Wi-Fi net and are equipped with microphones to enable voice commands and summon Home assistants. Their main feature is ML algorithms to learn from users' patterns and preferences quickly, and after a short period become able to anticipate their needs with a sufficient degree of accuracy. Motion sensors and geofencing based on tracking the occupants' smartphones also trigger home/away modes, and IoT weather stations or IAQ sensors can be factored in as well. Multizone climate control can be enabled by integrating the central thermostat with wireless, battery-powered room sensors. In addition to improve thermal comfort, smart thermostats have proven remarkable energy savings, up to 10% for heating, 16% for cooling, 16% in electricity and 22% in gas consumption ([4E Energy Efficient End-Use Equipment Technology Collaboration Programme, 2018](#)).

Concerning smart lighting systems, as reported in Section 10.3.3, available products from major lighting companies such as Philips Hue, General Electric Link, WiZ (see [Fig. 10.19](#)) or Osram Smart + , allow user control via smartphone of brightness, CCT and RGB color of selected lamps and light bulbs that plug into existing sockets, as well as allowing personalized scheduling and scenarios.

Concerning home energy systems (energy meters, on-site renewable energy sources, EV chargers or energy storage), these can be integrated in the smart home with a variety of devices to unlock more sophisticated capabilities and benefits, including those described in Section 10.3.1. A fundamental component of the smart home is the smart meter, which acts as the interface between the house and the electricity grid and allows bidirectional flow of information, enabling advanced functions such as demand side management, energy sell back to the grid or demand response (see [Section 12.2.1](#)).

Energy portals are smartphones or web applications that deliver energy consumption information, which was usually imperceptible to the consumer, in a more user-friendly way, providing a more detailed and direct feedback than traditional bills from energy utilities. They collect energy consumption information from smart meters, smart power outlets, smart appliances, and other smart products within the household to allow real-time energy monitoring, as well as enabling users to act on the information given and remotely control appliances while providing immediate feedback on actions, suggestions on potential savings and comparisons with similar consumers ([Serrenho & Bertoldi, 2019](#)).

10.6.2 Connected homes

Similarly to larger BAS applications, all single smart home services can work sufficiently even if siloed from each other, but their integration and intercommunication into a single control center can unlock the greatest potential in terms of enhanced home automation and management.

The most straightforward way of integrating different IoT devices is by connecting them to the same smart home application, the main ones being Amazon Alexa Smart Home, Apple HomeKit, Samsung SmartThings or Google Home, with open-source or third-party alternatives available as well (Home Assistant, Tado, Homee). These platforms support the vast majority of IoT devices on the market, and focus on enabling voice command on all connected systems through their own voice assistants (Alexa, Siri, Bixby or Google Assistant, respectively) and smart speakers/smart hubs. These apps can provide a basic degree of automation, for instance, by triggering alerts if the smart locks have been left open or by switching the lights off if the occupants have gone to bed. More advanced interaction between services can be implemented with user defined scenarios (Alexa Routines or HomeKit Scenes), in which multiple connected devices to work in combination following a defined voice command or event (for instance, a "leaving the home" scenario may lock the door, turn the lights off, lower the thermostat and close the shades).

Smart home functionality can be further expanded behind the single control app by developing ad-hoc scripts or taking advantage of specific apps such as If This Then That, which allow to create interactions between different apps and devices in a trigger-action-query logic. Examples include flashing the lights when the doorbell rings, opening the windows when a CO₂ threshold is met or closing them if rain is forecast, unlocking smart locks if a fire is detected, and several others.

In addition to these consumer-grade implementations, suitable for DOY retrofit, more sophisticated and advanced smart homes can be achieved when constructing the building from the ground up or in deep renovation interventions. In these cases, it is possible to employ conventional, wired BAS devices as well as IoT wireless ones, allowing faster, stabler and more secure connection, as well as installing connected sensors and actuators even in more complex building components, such as windows, central HVAC systems, domestic MEP grids, integrated renewable energy sources, etc.

Indeed, the preparation of dedicated conduits for BUS wiring in home renovation has become an established good practice among contractors.

Several smart home demonstration projects, often sponsored by manufacturers or tech consortiums, have been shown in the years to highlight technology progress and showcase the latest products. Notable examples include the Fraunhofer inHaus Center opened in Duisburg in 2001 as a lighthouse project for exploring and testing new system solutions and products from the smart home segment in a residential environment, that has been continuously upgraded ever since. The first T-Com Haus from Deutsche Telekom was opened in Berlin in 2005 to offer consumer and journalists insights on connecting various home appliances and controlling them by means of different input devices.

An interesting testbed for pushing the boundaries of Smart Home solutions has been the Solar Decathlon competition, in which university teams from all over the world compete in designing, constructing and testing solar powered, highly efficient house prototypes where BAS and HEMS prove determinant in achieving the severe performance targets set by the organizers. A remarkable example of smart solar house was ReStart4Smart by Sapienza University of Rome which competed in Solar Decathlon Middle East 2018 (Baghi, Ma, Robinson, & Boehme, 2021). This prototype featured an innovative BAS system which coupled advanced monitoring and control of IEQ parameters with a sophisticated EMS to balance energy generation, house energy storage, and energy grid exchanges with occupants' thermal and visual comfort and daily routines. In particular, the house BAS system was based on a central control server (Ilevia Eve X1) that allowed multiprotocol connection of multiple cabled and wireless devices via Ethernet, Wi-Fi, ZigBee, KNX, Modbus, and direct connection. This allowed control of façade elements (windows and shades), building systems (electrical, energy storage, HVAC, lighting) and home appliances (RGB lighting, smart kitchen, EV charger, entertainment system) either via determined schedules, dynamic algorithms enhanced by ML as well as with direct user command with a bespoke mobile apps or vocal commands to the Cortana Virtual Assistant. CCTV system with integrated face recognition enabled to automatically set home scenarios that reflect the user's taste. The face recognition service moreover acted as a safety system, monitoring the number and the identity of the people inside the house and issuing an alert whenever an unidentified person tries to get inside. Together with the highly performing building geometry, envelope, and systems, during the competition the BAS allowed to reduce energy consumed by HVAC and lighting to less than half than the total PV production of the house, and to only 75% of that when factoring in all house loads (EV charging, home appliances use, etc.), confirming the prototype as a positive energy house (Casini, 2020).

Within the energy management possibilities enabled by smart homes, virtual assistants are being recognized for their potential to boost energy awareness of occupants, improving their behavior and allowing more involved interaction. Several utilities in the United States, Canada, and the UK are now leveraging home virtual assistants to deliver information to customers on their energy use, account balances, electricity outages, as well as allowing customers to make payments. They can be an effective interface for reducing energy consumption as well, with some energy companies using them to provide consumers with energy efficiency tips. Although in these first applications much of the advice to users tends to be generic, more sophisticated uses are viable, for instance providing consumers with tailored information about available energy efficiency rebates, helping them to exploit ToU tariffs better, allow direct access to a households' smart devices as part of a demand-response program (see Section 12.3.4), or even enable remote energy audits. In the UK, Octopus Energy began in 2019 to offer ToU tariffs through Amazon's Alexa virtual assistant, allowing customers to ask when electricity is cheaper to plan their energy use accordingly.

Moreover, smart homes show promising potential in enabling assistive technologies for more fragile dwellers, such as the elderly or those with physical or mental disabilities. In particular, home automation can be effective in increasing accessibility of home services, for instance, by automating the operation of doors, windows and blinds via motors and actuators that replace human efforts. VAs enable informal interaction with the house services even for those with little familiarity with graphical interfaces and allow remote command from the bed or the wheelchair. Control systems can be integrated with mobility aids, allowing, for instance, to open doors or switch lights automatically when the wheelchair approaches, thanks to integrated NFC or BLE transponders. Hearing impaired users can benefit from specific IoT combinations, such as making the smart lights flash or change color when the phone or doorbell rings.

Smart accessibility and assistance are extremely promising in view of the current trends in population demographics, the growing requirements for support, social and health care for older people and the pressing need to find solutions that provide high quality care without increasing costs. Smart home technologies would allow most older people to continue living in their own homes, as they usually desire, and maintain existing links with family and friends, enabling them to stay socially active (Ghorayeb, Comber, & Gooberman-Hill, 2021). At the same time, this would relieve burden on healthcare and eldercare structures by shifting some care aspects from the hospital to the home (telemedicine).

Furthermore, smart home sensors and wearable devices can be effectively used in combination with ML algorithms to unobtrusively recognize the human activities, such as meal preparation, eating, sleeping, and personal hygiene, as

well as detect possible anomalies as irregular durations and deviated patterns of activities. The recognition of the performed activities and related anomalies can provide important information to health providers about their patient's medical condition, which can be useful in timely identification of emergencies or prevention of many health-related risks. For instance, risk situations such as falls, people not moving or not leaving the bed or bathroom for unusually long periods may trigger warnings to relatives and caregivers. On a wider scope, daily activity monitoring may reveal and track early signs of mental illness: for instance, people suffering from dementia, such as Alzheimer disease, tend to forget the subtasks within an activity or can take unusual duration to perform an activity (Fahad & Tahir, 2021).

Finally, smart home systems are also considered a promising technology for prevention and monitoring of infectious diseases and epidemics, as showed with the COVID 19 epidemic in 2020. In particular, voice commands can reduce physical contact with switches, remotes, faucets, and knobs, which have been demonstrated as a vehicle of infection spread, even in households between family members. Personal sanitization can be achieved via UV floor mats for shoes and UV light boxes for everyday objects such as keys and phones, which can be connected to the home automation system and therefore to personal routines. In the event of personal quarantine, the smart home can double as a monitoring environment to track infection signals without risking contact with healthcare practitioners: patient's vital signals can be tracked with wearable sensors (thermometer, pulse oximeters, heart monitors) as well as with smart home sensors (IR cameras, microphone, motion sensors) (Gupta, Bhatt, Gupta, & Tosun, 2020).

10.7 Conclusion and future trends

BASs aim at controlling, integrating, and automating the operation of most, if not all, building services, including power systems, HVAC, lighting, active envelope components, access control, safety and security systems, transportation, and more, while allowing different degrees of interaction with the building's occupants. Due to their proven efficacy in optimizing building's operations, the implementation of such smart systems in assets of any size and use represents a cost-effective solution to enable healthier and more comfortable spaces with a lower energy use and carbon impact, permitting adjustments to the needs of users and allowing the actual operational behavior to closely match that simulated in the design phase. Worldwide, advanced BAS applications grow by the day and are today an essential feature of high-end developments and retrofits for tertiary, residential or industrial use. More advanced BASs can employ AI and ML algorithms to greatly optimize the building management using weather forecasts, occupancy, usage, energy prices prediction, and patterns identified in consumer behavior. Moreover, such systems and technologies are today becoming more and more necessary in a scenario where energy systems will be characterized by larger share of renewables, distributed supply, and energy flexibility that is also managed on the demand side (EV infrastructure, on-site electricity generation, energy storage).

Within BASs, smart home is a particularly interesting area of development, with multiple IoT-based devices currently available on the market that cover a wide range of applications: in addition to monitoring, it is possible to operate appliances and electrical equipment, manage HVAC and lighting, control individual power outlets, manage home security with IP cameras, video doorbells, and smart locks for access control. Human interfaces (touchscreen, mobile apps, and vocal commands) provide even inexperienced occupants with intuitive controls and clear information dashboards, with the added benefit of bridging the information deficit of users and inducing virtuous behavior in the management of house equipment. Sensors equipped smart homes also enable assistive technologies for more fragile dwellers, such as the elderly or those with physical or mental disabilities, allowing to provide cure and assistance without transferring patients to nursing homes or healthcare facilities. Continuous data streams from IR cameras, microphones, motion sensors, and wearable devices (thermometer, pulse oximeters, heart monitors) can be fed to ML algorithms to can track vital signals, detect possible anomalies as irregular durations and deviated patterns of activities or risk situations, triggering warnings or alarms.

Nonetheless, an important aspect that needs to be considered with the increasing adoption of BAS and IoT in buildings and infrastructures is their expected service lifetime: although structures and buildings are designed to last for decades (25, 50, 100 years or more), digital technologies therein typically evolve in months and become obsolete in few years. In addition to lower performance and maintenance issues, a major risk of nonupdated legacy systems is to leave smart buildings and infrastructures exposed to cyberattacks. The only way to address this is by planning for constant updates of those systems. However, in smart buildings the main focus is often devoted to the application (e.g., controlling an HVAC system) with digital security aspects being neglected. On the contrary, those systems should be implemented by joint teams with distinct expertise in plant, automation, and cybersecurity. The latter constitutes an important topic of the growing market of building automation, that urges to be supported by appropriate regulations.

The ever-increasing digital complexity and connectivity of BAS in smart buildings raises in fact serious concerns about their protection from unauthorized digital access, and risks must be mitigated by implementing security procedures, system management, and constant updates, in particular as the advent of 5G promises to radically increase the numbers and data flows of IoT devices, with billions more expected to be connected by 2025. In addition to protection from cyberattacks, privacy issues arise from the diffusion of Internet connected devices, monitoring solutions, and IoT systems capable of tracking and recording actions and behavior of people, which in some cases may not even be aware that they are observed. Therefore comprehensive data protection strategies must be implemented both by design, ensuring that installed devices have a built-in security strategy, and by management, ensuring adequate data permitting policies and regular patching procedures.

These issues become even more prominent when dealing with retrofits of BAS and IoT features into legacy systems, a common occurrence as most buildings in the world were built before the advent of home automation and ICT in general and in some countries even before HVAC systems and similar advanced technological systems. This adds even more complexity and constraints because the introduction of these new technologies into existing (usually inhabited or in-use) buildings and infrastructures usually poses additional security and interoperability problems.

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Advanced facility management

11.1 Building facility management

Building facility management (BFM) is a complex activity that involves multiple disciplines and integrates people, places, processes, and technology to ensure the functionality of the built environment (Atkin & Brooks, 2014; Lewis, 1999; Roper & Payant, 2014).

BFM involves “the approach, analysis, and optimization of all processes, relating to the building or other real estates that can be used for business needs of the organization, except the core-business of the organization itself” and can include several functions according to the organization type, such as operations, maintenance and repair, real estate acquisition and disposal, general administrative services, space planning, allocation and management, etc. (Gao & Pishdad-Bozorgi, 2019; German Facility Management Association, 2018).

The growing complexity of modern facilities has increases the responsibilities and significances of management over time. According to ISO 41011, Facility Management (FM) can be defined “as an organizational function which integrates people, place and process within the built environment for the purpose of improving quality of life and productivity of business.”

FM is the aspect of management that focuses on how to develop, maintain and improve the physical assets needed to support and add value to the business processes of organizations, as well as create and maintain a physical workplace that provides optimal support to the people and work of the organizations (Drion, Melissen, & Wood, 2012). Scopes of FM pertain facilitating resources use, enhancing organizational effectiveness, and improving living and working spaces for social or economic activities. Compared with other life-cycle phases of any asset, FM usually lasts for the longest period, roughly 30–50 years if not more, and is imperative to realize a facility’s designated functions. The efficiency and effectiveness of FM can significantly affect operations cost, energy consumption, indoor comfort, and emissions. Only in the US market, the cost of inadequate interoperability in the capital facilities industry was estimated is \$15.8 billion per year, 57.8% of which borne by owners and operators during facility operation and maintenance (O&M) (NIST, 2004). These costs arise from inefficient business process management, redundant FM systems, the cost of training on those systems, productivity loss, rework costs, and other issues (Pishdad-Bozorgi, Gao, Eastman, Patrick, & Self, 2018).

Among the various tasks delegated to the facility manager, the most relevant is certainly to keep the building operating and to ensure all the equipment and systems function properly. In particular, facility O&M “encompasses a broad spectrum of services, competencies, processes, and tools required to assure the built environment will perform the functions for which a facility was designed and constructed” (Sapp, 2017).

In fact, the costs of O&M represent 50%–70% of the total annual facility operating costs (Rondeau, Brown, & Lapides, 2006) and approximately 85% of the total expenses throughout the life cycle of a building is incurred during O&M phase (Koch, Neges, König, & Abramovici, 2014; Wong, Ge, & He, 2018).

Main activities of O&M include maintenance and repair, energy management, emergency management, change/relocation management, security, hazardous waste management, ICT management, and others. Specifically, maintenance and repair refer to all works necessary to maintain the expected useful life of an asset, and represent the combination of all technical, administrative and managerial actions carried out to retain or restore a building item (architectural components or MEP systems) in order to maintain its functionality, quality characteristics, efficiency and economic value over time. Along the building life cycle, maintenance and repair therefore play an essential role in ensuring the conservation over time of the building’s performance as established in the design phase in terms of comfort, safety and energy efficiency and in containing management costs in the operational phase. In particular, an effective maintenance can help to:

- prevent premature decay and degradation;
- maintain structural stability and safety;

- prevent unnecessary damage from the weather or from general usage;
- optimize performance;
- inform plans for renovation, refurbishment or retrofitting;
- determine the causes of defects and so help prevent reoccurrence or repetition;
- ensure continued compliance with statutory requirements.

Maintenance should be considered thoroughly, as it plays a major role in ensuring the performance of facilities and, in recent decades, the maintenance costs of existing buildings have been increasing rapidly. Currently, most of the maintenance activities consist in corrective actions executed in emergency conditions. Such attitude is severely limited, and the maintenance role is increasingly recognized as a strategic element for any O&M activity. Rather than reacting to failures, there is a need for supporting more planned maintenance approaches. Therefore, to improve the efficiency of building maintenance management (BMM) and minimize the maintenance costs, optimal planning of schedule and costs for maintenance work should be implemented in time, and advanced management tools are needed, including building automation systems (BAS), building information modeling (BIM) integrated facilities management software, reality capture technology (e.g., 3D laser scanning, point clouds), the Internet of Things (IoT) (e.g., radio-frequency identification (RFID) and sensor network technologies) and geographic information system, extended reality tools and digital building twins (DBTs) (Love & Matthews, 2019; Silvestri, Forcina, Introna, Santolamazza, & Cesarotti, 2020; Wong et al., 2018).

11.1.1 Building maintenance policies

Maintenance policies regard all the activities related to the development of a regularly scheduled work program to guarantee satisfactory equipment operation and prevent major issues. These activities include the choice of the optimal maintenance strategy and job planning and scheduling. According to the objectives and methods of intervention, maintenance activities can be divided into either proactive or reactive activities (Chen & Tang, 2019) (see Fig. 11.1). The former aim to intervene on the asset before the failure occurs, the latter include interventions carried out following the detection of a malfunction.

Reactive maintenance, also called corrective maintenance or failure maintenance, was the first historically to be applied and includes the activities performed following the detection of a failure or upon the occurrence of a breakdown and aimed at bringing an entity back to a state in which it can perform the required function. Corrective maintenance also includes so-called interim interventions aimed at mitigating the disservice while waiting for the actual maintenance intervention to be carried out and, based on determined maintenance logics, budget and available resources, it can be started with a certain delay with respect to the detection of the failure (deferred maintenance). Corrective maintenance is the one that involves the highest costs both in terms of expenses for the intervention and of damage due to the unexpected shutdown of the system. For this reason, over time it has been increasingly replaced by a preventive approach aimed at reducing the probability of failure or the degradation of the operation of a given entity.

Proactive, or preventive, maintenance includes different types of maintenance: time-based (or cyclical), condition-based and predictive.

Time-based maintenance is a preventive maintenance strategy which foresees, on the basis of experience, to perform interventions according to predetermined time intervals, with the aim of avoiding service interruption, or if it is inevitable, minimize its impact by planning beforehand. Although this approach is substantially better than the reactive, it is far from optimal. In this type of strategy, the trend is to ensure safety and service maintenance by over-maintaining the asset, thus causing an unnecessary economic cost (Ahmad & Kamaruddin, 2012).

Condition-based maintenance, also known as diagnosis-based maintenance, consists of anticipating a maintenance activity based on evidence of degradation and deviation from the normal behavior of the asset. These anomalies are detected thanks to the maturity of technologies such as IoT and cloud computing, which can be applied to monitor

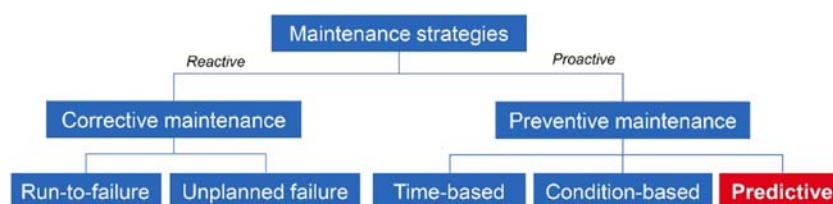


FIGURE 11.1 Main reactive and proactive maintenance strategies.

continuously the condition of the asset. Condition-based approaches can be enhanced by AI algorithms to diagnose condition based on detailed status data (Ahmad & Kamaruddin, 2012).

Predictive maintenance, or prognosis maintenance, is a type of preventive maintenance that is carried out following the identification of one or more parameters that are measured and processed using appropriate mathematical models to calculate the remaining time before failure. A variation of the measurements made with respect to the state of normal operation will indicate the increase in degradation and, ultimately, will allow to predict the time of the fault. Predictive maintenance aims to predict what will happen, and when, by learning from historical maintenance records, observing real-time data, and predicting future events. Predictive maintenance is currently the most advanced technique from a technological point of view, and indeed leverages the installation of an IoT sensors for monitoring and real-time transfer of a huge amount of data which, processed by a computerized maintenance management system (CMMS) system, are able to extrapolate appropriate models of the time remaining before the occurrence of a fault.

11.1.2 Computer-aided facility management

Building maintenance requires the analysis and integration of several types of information and knowledge, such as maintenance records, work orders, or causes and knock-on effects, continuously generated by different subjects and sources. To avoid inappropriate decisions and consequent extra costs, a well-integrated data system is therefore necessary for FM companies to manage the constant changes occurring in the facility (Silvestri et al., 2020).

FM information systems include CMMS and computer-aided facility management (CAFM). While both CMMS and CAFM help manage and record a database of daily maintenance operations (e.g., asset management, inventory control, service request generation, work order management) from an organization, CAFM provides extra functions like reactive maintenance and planned preventative maintenance management, space and move management, resource scheduling, etc. (Wong et al., 2018).

CAFM software assist facilities managers with planning, managing, reporting and tracking maintenance operations. It is usually a mixture of computer-aided design (CAD) and/or specific facilities management relational database software (Wong et al., 2018).

Facilities management software tools were first developed in the late 1980s and became popular in a variety of sectors including healthcare, government, education, commercial organizations and industry. Many CAFM solutions are now web-based and offer a wide variety of features including facilities orientated scheduling and analysis techniques.

CAFM programs can help facility managers in ensuring every asset is fully utilized at the lowest cost through all stages of the building's life cycle, and support technical and administrative tasks as well as the strategic processes required for planning and management.

These tools commonly include a variety of functions and features which can be tailored to the exact requirements of the organization, which may include the following:

- strategic planning, by assisting in determining space requirements, equipment layouts, construction costs, environmental constraints, and other critical planning functions;
- space inventory and organization, by defining and standardizing space attributes and elements and by preparing asset inventories, including floor plans, locations, dimensions, cost, usage, energy consumption, age, construction data, contact details, key pieces of equipment and essential infrastructure, fire and safety properties, etc.;
- operations, by monitoring and managing building;
- maintenance and repairs, by scheduling and monitoring routine operations and preventive interventions;
- forecasting, by predicting future requirements for space, utilities, or equipment, and evaluating and planning changes accordingly.

More advanced, integrated CAFM programs feature intelligent interfaces, evolved functionalities and connection to analysis packages. Functions common to most integrated CAFM systems include the following:

- interactive relational databases that focus on the functional requirements of facility managers;
- interactive graphics with standard CAD engines that enable basic alterations to layouts, plans and other visual documents;
- data management tools that allow to use existing data and to export relevant information for analytics.

More and more CAFM systems expand their operation by connecting to the BIM model of the asset. Indeed, BIM can provide a fully-populated dataset to feed into the CAFM tool and to edit in-program to enable planning modifications and maintain the FM model throughout the building life cycle.

The introduction of project and life cycle management functionalities within CAFM systems will further support facility managers, allowing the following benefits (Krystyna Araszkiewicz, 2017):

- early project engagement;
- contribution toward materials and products used, instead of delegating procurement;
- enhanced asset intelligence through integrated product information portals;
- smarter assets;
- cross sharing of information across disciplines;
- a single source of truthful data;
- assessment of the performance of the project pre-handover;
- comprehension of the intended operation of the project for maximum efficiency.

Main CAFM programs available on the market include Planon, SpaceIQ, Collective view, ioffice, Trimble ManhattanONE, facilityquest, or Accruent vx Maintain. These tools provide interfaces, dashboards and databases to track, streamline, integrate and optimize the full workflow related to facility and asset management, including reactive and preventive maintenance, work orders and contractors management, expenses and cost control, invoicing, and reconciliation.

Most advanced software, in particular, integrate CAFM and maintenance scheduling through CMMS with additional functional domains that pertain real estate and lease management, space management, project management as well as human resources management. This multifunctional approach takes the name of integrated workplace management system (IWMS) and has the main objective of enabling alignment of real estate and work teams to any change in working styles and requirements. IWMS programs have seen increased recognition during the COVID-19 epidemic emergency, in which mobile working, increased flexibility and the rethinking of consolidated office spaces and routines have created or accelerated new challenges for those responsible for managing and maintaining the workplace.

One of the main features of IWMS is space management and planning, which consists in measuring space efficiency to capture actual utilization, in planning and managing single-person and large-scale, project-based moves, as well as implementing scheduling and reservation of workspaces such as desks, cubicles, office and meeting rooms. Space management is closely tied to FM and maintenance, as it allows to collimate systems utilization and stress loads, preventive maintenance and planned downtime with the new possibilities offered by office hoteling, that is, the dynamic scheduling of flexible services according to the specific daily needs of workers, instead of conventional fixed-desk-per-employee scenarios.

11.1.3 BIM-enhanced facility management

An effective BMM must be able to coordinate in an integrated way numerous information of different nature such as systems operating data, environmental parameters, costs, state of conservation of materials and structural elements, project documents, data sheets, manuals, contracts, authorizations, inspection results, maintenance reports and records, etc. Typically, such information includes 2D drawings, spreadsheets, bar graphs, and field reports in both electronic and paper formats from various locations, systems and involved agents.

Traditionally these different information sets, assuming they are fully available, are stored and analyzed independently of each other, thus preventing fully informed decisions to be made. The lack of integration makes the correlation between the various information difficult, if not impossible, resulting in an excessive waste of resources in research and data analysis. This inevitably leads to inefficient maintenance, shifted toward a corrective rather than preventive approach with a consequent increase in management costs. Situations of deferred maintenance occur regularly, which in the end lead to increased overall costs of managing and operating facilities, increased incidence of unplanned, more costly and emergency repairs, breakdown of buildings and equipment requiring significant capital expenditures, disruption of normal building operation, decreased user productivity, increased risk of voiding warranties of equipment and building components.

In this picture, BIM can be a convenient tool to significantly improve the operation and maintenance phase of buildings (Aziz, Nawawi, & Ariff, 2016; Krystyna Araszkiewicz, 2017; Matarneh, Danso-Amoako, Al-Bizri, Gaterell, & Matarneh, 2019).

BIM can be useful in two ways. On the one hand, the data-rich nature of BIM enables to factor maintenance needs in right from the design phase by immediately inserting all the information that will be relevant for the management of the building, thereby already addressing digital schedule and cost management for the later stage of the project life cycle according to a so-called 7D BIM approach (Hu, Tian, Li, & Zhang, 2018) (see Section 4.2.3.5).

In 7D BIM, every information pertaining FM is collated at a single place within the BIM model. This can greatly improve the quality of service during the entire life cycle of a project. By leveraging 7D BIM, one can ensure that every element of the project stays in its best shape, from building handover until its decommission, with several benefits including optimized asset and FM from design stage to demolition, simplified and easy replacement of parts and repairs, as well as streamlined maintenance process for contractors and subcontractors (Chen & Tang, 2019; Nicał & Wodyński, 2016).

On the other hand, BIM technology has the potential to deliver remarkable value to owners and facility managers by offering them a powerful tool to easily retrieve information from the virtual model of the facility and locate building components, and to significantly ease understanding of displayed information (FM-enabled BIM) (Hu et al., 2018).

Indeed, the inherent complexity of FM can greatly benefit from semantic data encapsulated within BIM at the design and construction stages of a building life cycle. A BIM developed to LOD 500 is recommended for FM, as it contains geometry and information precise enough to support operations and maintenance activities including workflows, inventory, maintenance, production capacity, safety protocols, etc.

In particular, one of the most common problems for facility managers is information accessibility, meaning that they usually do not have easy and quick access to information required to process work orders. This can be effectively addressed by leveraging BIM to integrate the fragmented FM information from different building management systems and to provide an intuitive information access interface. The term “FM-enabled BIM” refers to a BIM model containing the FM information required for auto-populating CAFM systems (Pishdad-Bozorgi et al., 2018).

Facility managers can take advantage of BIM both as a knowledge collection tool and as a repository to document and keep track of evolving maintenance information, to support decision-making during the whole operational life of any facility. Compared to traditional CAFM databases, BIM integration allows much quicker and intuitive retrieval of information, analysis of relevant data and extraction of knowledge and insights to plan maintenance work and to perform repairs. Moreover, the inherent multidisciplinary and collaborative nature of BIM platforms is well suited for FM, and maintenance operation in particular, as it helps different stakeholders to access and share information in real-time, clarify roles and responsibilities, and communicate between business partners.

The benefits of using BIM in FM include providing valuable “as-built” information, records of maintenance, details of warranty and service, quality measurement, assessment and monitoring, space making and energy monitoring, emergency procedures, personnel safety (Wetzel & Thabet, 2015), retrofit planning, reduced errors, fast-tracked project delivery time, reduced implementation costs, and the provision of feedback to eliminate design-related performance issues (Aziz et al., 2016). BIM offers object-based 3D visualization data, which is important for FM data management as data acquisition and identification is faster and more efficient for object-based FM systems with the support of BIM.

To tailor BIM for use by facility managers or owners, project teams should define early on which FM information to include in the BIM models, then establish a systematic process gathering it during the design and construction phases. Conversely, facility managers should preemptively identify the required data for FM activities and define the desired levels of detail. This information transfer can be streamlined by using the Construction Operations Building Information Exchange (COBie) format, which provides a standard for capturing and recording project handover data created during design, construction, and commissioning. As an added measure to improve security and reliability of maintenance data, the BIM model can be set up within a blockchain platform at the moment of handover to the owner or building operator (see Section 9.1.5). This way, the model becomes a certified database of building and maintenance information, ensuring all data imported and extracted is tinker-free and providing a truthful trace of all operations conducted on the asset in its life cycle.

Once the required information is ready-to-use, it must be made available and accessible to facility managers when needed and presented intuitively to maintenance personnel. This can be achieved by adopting barcodes, RFID, and extended reality (XR) along with BIM to facilitate maintenance and repair activities.

Finally, BIM can constitute the foundation on which to create the digital twin (DT) of the building, that is, a virtual replica of that physical entity and its subsystems which is continuously updated by live data collected from the IoT sensors distributed within the real object. An accomplished DT allows to both gather project data, collect real-time information from operating systems, implement predictive maintenance, and simulate what-if scenarios for maintenance and operation optioneering (see Section 11.4).

11.2 Predictive building maintenance

In the last decade, thanks to the advancement in IoT and machine learning (ML), the concept of predictive maintenance has gained big prominence in the industrial sector, and has recently started appearing in BFM as well.

The wider availability of inexpensive, integrated and connected IoT devices allows, in particular, to connect building machines and their subcomponents not only to monitor process data and parameters for BAS integration, but also to collect information related to the physical health aspects of the machine such as vibration, pressure, temperature, acoustics, viscosity and flow rate of fluids and many others. Through AI and ML algorithms, all this information can now be effectively leveraged for early fault detection, fault identification, health assessment of machines, as well as to predict accurately the future state of the system.

Predictive maintenance, also referred to as “smart maintenance,” “data-driven maintenance” or “Maintenance 4.0,” differs substantially from preventive maintenance, which scope is simply to schedule the maintenance activity in advance to avoid machine failures. Instead, in predictive maintenance activities are scheduled based on collected data from sensors and analysis with the aim of avoiding unnecessary equipment replacement, reduce machine downtime, find the root cause the fault, and ultimately save costs and improve efficiency. Through data analysis, predictive maintenance aims not only to know what happened (descriptive maintenance) or why it happened (diagnostic maintenance), but also to predict the future outcomes such as the type of failure and the expected time to complete failure. In particular, predictive maintenance requires the identification of one or more parameters to measure and process, using appropriate mathematical and ML models, in order to identify the remaining time before failure. Various methodologies can be used, including tribological analyses on lubricants, vibration measurement, thermography, analysis of absorbed currents, detection of anomalous vibrations, and many others. Any measured variation compared to the expected state of normal operation may indicate an increase in parts degradation and, ultimately, allow to predict the time of the fault with sufficient accuracy and anticipation. Broadly speaking, the forecasts can be of two main types: cross-sectional forecasting and time series forecasting.

Cross-sectional forecasting is the estimation of parameters of which no measurements exist, by using measures on other variables that have been observed. This type of analysis looks at data collected at a single point in time, rather than over a period of time. Examples of this approach include the following:

- the measurement of the electric current that passes through an electronic component to assess its condition;
- the use of thermography to detect the temperature raise caused by increased friction on the parts subject to wear;
- the chemical analysis of lubricant oil for metallic particles that may indicate a principle of wear in the engine parts;
- the measurement of vibrations that may signal a misalignment, imbalance or a damaged bearing;
- the use of thermography, again, to check of the tightening of the electrical cable terminals which, if loose, produce heat due to the Joule effect.

Time series forecasting, instead, refers to the estimation of how parameters change over time, measuring them until that time instant (t) and predicting their value at the future time instant ($t + dt$). Typically, measurements are collected at regular intervals, and processed each time to predict the future values. A common example is the prediction of the time of residual charge of battery-operated devices, which is estimated based on the consumption rate up to that time, thus on the way the device has been used. In time series, it is possible to identify trends, namely a long-term increase or decrease in values; seasonal phenomena, which determine changes in values over a period of time that is always repeating the same duration; or cyclical phenomena, that cause increases and decreases in values with fluctuations that do not always have the same duration, that is, they are not periodic.

Overall, predictive maintenance is carried out entailing the following main activities:

- measurement in real-time of physical quantities of interest;
- prediction of these measurable parameters, and the calculation of nonmeasurable ones, at a future instant in time;
- identification of eventual anomalies or faults in the predicted system status;
- schedule of preventive and corrective activities before the system reaches the critical condition.

In particular, the prediction and identification steps require the application of advanced mathematical models to ensure sufficient accuracy of the process, that is, preventing failures to go undetected and at the same time avoiding unnecessary interventions on correctly functioning parts. Mathematical models employed in predictive analytics mainly rely on statistical regression techniques, which focus on establishing a function to represent the interactions between the different variables in consideration. Several regression models can be employed, ranging from simple linear regression to more advanced methods such as autoregressive moving-average or autoregressive-integrated moving-average. However, developing these mathematical models requires both extensive knowledge of mathematics and maintenance experience to effectively connect failure causes, solutions and indicators. Moreover, these models are usually case-specific and hardly generalizable to similar group of problems, are not able to learn from processes behavior, and do not include feedback loops and efficiency assessment techniques, preventing their continuous improvement over time (Nemeth, Ansari, Sih, Haslhofer, & Schindler, 2018).

Limitations of these mathematical models make ML a preferred choice to carry out accurate predictive analytics, especially in high-dimensional problems in which disturbances, interactions and boundary conditions are difficult to model and a stochastic approach is recommended, as is the case with more complex building facilities and machines (Susto, Schirru, Pampuri, McLoone, & Beghi, 2015).

In particular, ML-based predictive maintenance models can be developed using the following two main methods: supervised learning, where information on the occurrence of failures is present in the modeling dataset, and unsupervised learning, where logistic and/or process information is available, but no maintenance data exists. ML methods are explained in greater detail in Section 9.6. For predictive maintenance applications, supervised solutions are preferable, and shall include in their training dataset details on fault history, maintenance and repair history and actual machine conditions, to ensure the algorithms learns the normal operating scheme and which factors may indicate or directly cause malfunctions (Paolanti et al., 2018).

Notwithstanding the learning method employed, models' accuracy is strictly dependent on quality and quantity of data provided, first for the training phase then for the actual application in predictive maintenance. In particular, the methods envisaged for data acquisition influence directly the approach to take for predicting failure detection and maintenance solutions.

Data useful for predictive maintenance can be mainly gathered from system integrated sensors, which have seen a remarkable evolution in recent years, becoming smaller, cheaper, more reliable and crucially easier to integrate in systems thanks to battery power and wireless connections. Physical parameter of interest that can be collected by sensors include vibration, humidity, temperature, noise, as well as electrical resistance and current absorption. Sensors for predictive maintenance may as well overlap with those already in place for BAS functioning (see Section 10.2), however the latter are commonly installed with the main scope of energy efficiency and reduced communication costs (Aggarwal, 2013), hence additional or different elements may be required even if a complete BAS is in place.

Data from sensors is collected with two main techniques, namely push-based and pull-based acquisition, and should always be stored in an organized logfile for subsequent analysis and retrieval. Pull-based data acquisition requires the programmer to define a query, which can be automated at a desired frequency, and send it to the system, that will then return the matched value from the sensor reading. In push-based data acquisition systems, instead, the system will autonomously communicate its readings whenever these deviate from a predetermined state or behavior (see Fig. 11.2).

Pull-based acquisition allows both real-time data collection as well as interval data acquisition. In real-time collection, data is continuously produced and processed with no appreciable delay, with the objective of predicting or detecting any state change that may infer current or future malfunctions. This system produces significant amounts of data, and therefore requires substantial investment in term of computing power, communication infrastructure and data storage to effectively process them. The predictive maintenance system, or the ML model in training, would be presented with a considerable amount of information, which would often be mostly useless. Interval data acquisition, in turn, links data transfer to specific conditions, which commonly consist in a time interval. Although this reduces pressure on the communication and computing infrastructure, the time intervals must be specified carefully based on the monitored process to prevent some relevant data to go undetected and cause delays in failure detection.

Push-based acquisition is instead based on the definition of the specific behaviors of the real-world system that the user needs to observe. Sensor readings are issued whenever these predetermined conditions are met, typically when the threshold of "normal" operation is crossed. For instance, the system can establish a range for the normal operating temperatures of a machine part, and signal only extreme temperatures with more than 5°C deviation above or beyond optimum values, which may indicate a possible failure (Sittón-Candanedo et al., 2018). This acquisition system is useful when different kinds of data shall be issued to more than one system, for instance, if certain data pertain the BAS control and other the predictive maintenance system.

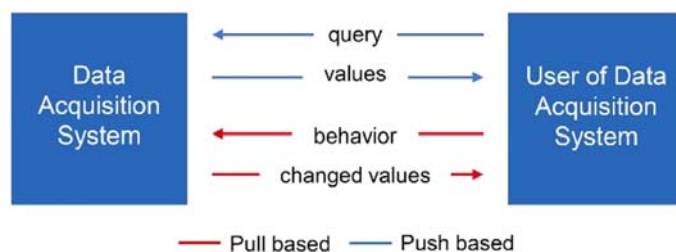


FIGURE 11.2 Pull- and push-based data acquisition systems.

Quality data from sensors allow the predictive maintenance system to monitor and predict the current and future state of any process or machine, and identify any deviation or trend that may signal future malfunctions. The following step is therefore to feed this information to the decision model, which in turn is tasked with the systematic prioritization of alerts and with the definition of maintenance activities to undertake. The multicriteria decision model must be integrated with specific operational and management constraints (regarding for instance downtime cost, environmental factors, budget targets, risk disposition, as well as current service plan, availability of spare parts and maintenance resources) to allow to automatically prioritize the predicted machine failures according to a dynamic strategy and prescribe maintenance interventions accordingly (Nemeth et al., 2018).

A recent example of predictive maintenance is the service provided by Thyssenkrupp, which made its foray into the digital realm by connecting its elevators to IoT sensors to provide the company's global service engineers real-time data to improve operational efficiency. By combining IoT data with ML algorithms, Thyssenkrupp's service claims to predict future failures, fix problems before they arise and increase overall elevator reliability. The convenience of the service is increased by its remote capabilities: mixed reality (MR) video-streaming allows on-site service technicians to connect with remote specialists, informed by the predictive maintenance model, for support in diagnosing and repairing any issue.

11.3 Extended reality in building operation

As reported, O&M of buildings and infrastructure is a crucial aspect of the construction industry. Since these facilities are designed and built to last for many years, this constitutes the longest period of its life cycle and accounts for most of the total life-cycle cost. The application of XR technology in building and systems maintenance show promising results in enhancing human performance in carrying out technical maintenance tasks, as well as improving the administration of maintenance operations and supporting strategic decision-making (Palmarini, Erkoyuncu, Roy, & Torabmostaedi, 2018).

11.3.1 Virtual reality in maintenance

Virtual reality (VR) application in the O&M phase of a building's life cycle concerns the following three main areas:

1. maintainability design, to improve its effectiveness by enabling multidisciplinary experts to enhance their comprehension of products and reducing the cost of reworks;
2. maintenance training for technicians and managers by complementing or replacing traditional 2D based and text-based lessons and exercises;
3. teleoperated maintenance in cases of interventions in dangerous or difficult to reach locations.

Concerning maintainability design, VR helps all stakeholders to vividly simulate the maintenance of every piece of equipment or product in a perfectly replicated environment, allowing to conduct design reviews and predict maintenance-related design flaws effectively. In addition to the design team, VR accessibility allows facility managers, technicians, and maintenance engineers to step into the project, simulate routine operations and provide useful insights already in early-stage design. Through interacting with the virtual prototypes in the immersive environment, they can have a more explicit comprehension of the practical maintenance scenario of the product before it comes into service. VR interactive data related to maintenance processes can be further gathered and utilized by embedded algorithms to make quantitative and qualitative maintainability evaluations. VR has been successfully used in maintenance design to help evaluate parts accessibility, ergonomics, environment factors such as heat or radiation, fatigue, and other human factors (Guo et al., 2018).

Regarding training, VR maintenance exercises can greatly facilitate the subsequent process of on-site tasks. It is demonstrated that the immersive environment allows for a more involved, distraction-free learning of procedure and operations. Related cognitive benefits involve both working memory development (information encoding) and retrieval (information recalling), with VR trained groups able to outperform subjects trained with conventional 2D and text instructions in both operation time and maintenance accuracy (Shi, Du, & Worthy, 2020). In particular, several studies have indicated that haptic feedback from VR systems can better improve users' situational awareness and performance for maintenance applications. Although research of VR studies focuses on the pursuit of realistically stereoscopic visual effects, as 80% of the external information processed by the brain comes from vision, whether VR can accurately simulate the haptic feedback in the real maintenance process is also very important since maintenance is a process of close human-machine interaction most implemented by the human hand (Guo et al., 2020). Studies showed that haptic

feedback is more efficient than visual feedback in improving the performance of maintenance workers, which can help correct the operation trajectory, and is very helpful for the enhancement of situational awareness in telemanipulation tasks, reducing the completion time and improving the quality of operation (Oosterhout et al., 2019).

Finally, VR can greatly improve the accuracy of teleoperated maintenance interventions, such as those performed in hazardous or hard to reach environments (offshore platforms, nuclear plants, underwater facilities, or emergency interventions). In most cases, these operations can be carried out with teleoperated vehicles (see Section 8.2.4) or with robots equipped with articulated arms and manipulators which have reached remarkable levels of dexterity and precision of movement. The application of VR allows the robot operator the best involvement in the task by projecting 360 degrees video feed from on-board cameras and closely mimicking commands imparted by VR controllers but also vocal, thought and eye-based control. Most advanced applications of VR teleoperation involve full body suits used to control biomorphic robots, as in VR exoskeletons (see Section 8.2.3.6).

11.3.2 Augmented reality in maintenance

Augmented reality (AR) allows users to enhance their real-world field of view with real-time superimposed digital information, which may report relevant data on that specific asset or even step-by-step instructions on how to repair a component. This makes AR particularly suitable for supporting both maintenance training and interventions in buildings and infrastructure, as it allows real-time retrieval of relevant information and their seamless integration into the actual task at hand, along with enabling collaborative support and remote assistance by experts or coworkers for improved decision-making on-site.

In particular, AR solutions can be integrated in the following maintenance and repair operations:

- maintenance and repair training, by giving indications contextual to the task and allowing close communication with teachers via see-through collaboration;
- preventive maintenance, by providing real-time assembly instructions, compliance checklists and detailed walk-through for unfamiliar procedures;
- corrective maintenance, by retrieving service manual instructions and allowing remote assistance;
- maintenance scheduling, by enabling real-time access to data for monitoring, control and analytics via virtual performance panels and dashboards.

AR solutions can be implemented with either handheld displays (HHS) such as smartphones, tablets or dedicated devices such as Trimble SiteVision (see Fig. 11.3), or head mounted displays (HMD) like smart goggles. Smartphone/tablet apps (XOi, XMReality, Reflekt Remote, and others) do not require any dedicated hardware and superimpose graphics and text on the video feed of the devices' cameras. However, hands-on devices are cumbersome for manual work as the worker's hands are occupied and their attention has to shift continuously from the task to the handheld screen, and remote support is equally suboptimal. Instead, more advanced AR solutions employ HMDs such as Google Glass, Epson Moverio, Vuzix M-Series or Realwear HMT-1, which can also be integrated in PPEs such as hard-hats and crucially allow information retrieval and remote collaboration while leaving hands on the tools and attention on the task.



FIGURE 11.3 AR visualization of concealed utilities with Trimble SiteVision. *Courtesy of Trimble.*

Both HHS and HMD AR devices are self-contained and allow the mobility required for on-site training, service, and maintenance.

Various software allows to create and deliver data with AR (UpSkill Skylight, ScopeAR Worklink), with approaches ranging from displaying text bullet points to interactive 3D animations. Simplest AR interfaces overlay virtual arrows and text to the real environment. Overlaying text information does not obstruct the field of view and text contents are easier to create and update, but are less intuitive and therefore more suitable for improving maintenance performance of already skilled operators. Another effective way of overlaying information is through 2D/3D static models with information relevant to perform inspections or other operations. To improve accessibility, virtual animations can be overlaid on the real environment at each phase. According to the experience of the users, AR guidance can support them in every single step or just give more top-level information. By incorporating machine vision and object recognition technology, real-time feedback on the operation can be provided by checking the position and orientation of the components and showing warning messages to correct the procedure and minimize mistakes or reworks. By transforming conventional paper manuals into electronic multimedia content and seamlessly integrating them into the workflow via HMDs, operators would not need to divert their attention and can focus their concentration on the task at hand. This way, AR can reduce unwanted eye and head movements, improve spatial perception and increase productivity, as alternating the attention between the object to maintain and the instructions consumes valuable time and reduces focus (Palmarini et al., 2018). Furthermore, nowadays complex systems are commonly embedded with an array of sensors to provide information about the functionalities and perform initial diagnosis. Instead of accessing this data on a dedicated PC, AR can enhance this process by displaying valuable information and diagnosis results closer to the object to be maintained.

One of the more widespread applications of AR is for remote maintenance, that is, the collaboration between an expert and a maintainer that are in two physically different locations, also known as “collaborative maintenance” or “remote assistance.” Particularly in view of current technology complexity, traditional remote assistance made over-the-phone is not a convenient solution anymore. AR-based collaboration software such as VSight instead allow transferring information from expert to technician in real-time in a “see-what-I-see” remote cooperation. Experts and coworkers can see the field view via the technician’s device and directly transfer voice instructions, documents or even superimpose their annotations on the worker’s display, enabling otherwise insufficiently qualified persons to accomplish complex activities by themselves, thus minimizing waiting times for more expert team, as well as systems downtime (Röltgen & Dumitrescu, 2020).

In maintenance training, AR has the great advantage of allowing the trainee to interact with the real-world objects and access the virtual information for guidance simultaneously, easily accomplishing the mapping between the training instructions and the real task without the need to use external separate training material such as user manuals. According to Fitts’s model of skill acquisition, AR enables the trainee to learn the basics about the task by observing the augmented instructions and to develop behavior and movement patterns when performing the instructed subtask repeatedly, raising their skills right from initial trials (Webel, Bockholt, Engelke, Peveri, & Preusche, 2011). Another advantage of AR-based training is that the trainee has real tactile feedback when performing the training task, since they can interact with real objects.

11.3.3 Mixed reality in maintenance

Compared to AR, MR technology allows for a further integration between the real world and the virtual information, in which the latter can recognize and adapt to the former allowing for seamless blending of 2D and 3D data with real objects and spaces. MR is implemented with specific HMDs such as Microsoft HoloLens or Magic Leap that feature stereo cameras and IR sensors to recognize and reconstruct the surrounding 3D environment continuously, allowing placement of virtual objects and graphics within the scene with the utmost accuracy (see Fig. 11.4). This capacity makes MR the best suited technology to support maintenance and repair operations in the building and infrastructure sector. In particular, MR can perform all activities that require AR integration and have been described above, including remote collaboration, with much improved precision and contextual interaction. In addition to visualizing maintenance-related data such as the service request, work order information, real-time IoT readings of the asset being serviced, documentation or knowledge base items, MR can highlight parts and operations in their correct order (screws, switches, levers, valves, etc.) and virtually expand the 3D image of the machine to display how it is built and its components. Using a MR integrated cooperation platform such as Microsoft Dynamics 365 Remote Assist, a remote connected expert can see the live, first-person view taken by the HMD, freeze any scene of this video feed and create annotations and 3D



FIGURE 11.4 Visualization of context aware information in maintenance via MR. *Photo by the author.*

holograms which are then integrated into the real-world view of the person wearing the device, anchored to their position irrespective of head movements (Vorraber, Gasser, Webb, Neubacher, & Url, 2020).

Furthermore, the improved spatial awareness allows the device to estimate the location and orientation of the user within the 3D BIM model or DT of the building, enabling first-person navigation aids (arrows, directions) inside the real scale model with the possibility of displaying or interrogating all relevant data, including MEP systems, building components, and data from sensors and IoT devices.

Localization is performed via GNSS positioning and/or by comparing the user's perspective to BIM based on deep learning computation, which is commonly stream-processed in graphics processing unit-enabled servers via Internet protocol. Once the viewer is correctly positioned and oriented in the virtual space, spatial mapping visually fits the object of interest (superimposed text, elements-to-build, concealed pipes) onto the MR image using the 3D sensing capability of MR device (Baek, Ha, & Kim, 2019). MR navigation is also particularly useful to locate the target for maintenance and repair operations (electrical cabinets, air handling units, pipes manifolds) and guide the technician to the location even if they are unfamiliar with the premises.

The ability to precisely superimpose data from the BIM model that would otherwise be concealed, such as wall integrated conduits or overhead ducts, allows spot interventions without wasting time and resources on probing. In particular, this provides a valuable solution to damage prevention and maintenance for underground infrastructure, which excavation operations often have a high risk of inadvertently damaging the existing subsurface utilities, causing financial loss or even accidental deaths (Palmarini et al., 2018).

A workflow proposed by Bentley Systems with the ContextCapture tool exploits photographic reconstruction of the real world to generate a 3D mesh in which 2D pipe maps are projected and aligned based on visible surface features such as manholes, valve access covers, drains. On site, the pipe-augmented 3D mesh is geolocated with the physical world by selecting common control points (doors, lampposts), then turned off to show only the pipe augmentations in the aligned position. This way it is possible to identify pipes and manholes to service and to trace precise excavation

markers minimizing impact on the surroundings. At the same time, the user can visually spot discrepancies between the augmentation and the actual location of surface assets and propose modifications to the pipe database by adjusting the virtual pipes position directly on-site.

11.4 Digital twin

With the increasing diffusion of BIM and IoT devices, the future of building O&M is represented by the DT technology, which promises to revolutionize the way buildings are managed and maintained by transforming them into a rich ecosystem of data and insights (Opoku, Perera, Osei-Kyei, & Rashidi, 2021; Ozturk, 2021).

The term “digital twin” refers to a digital replica of a physical entity—a product, a service, a process, or even a living being—which is continuously informed by live data collected from sensors within the real structure it replicates, thus pairing the virtual and physical worlds with the two-way dynamic mapping between the physical object and its digital model (see Fig. 11.5) (Jones, Snider, Nassehi, Yon, & Hicks, 2020).

Rather than a traditional 3D model, the DT consists in an information model, or better in a common data reference that’s created during a project-planning stage and spans every phase of an asset’s life cycle, from design to manufacturing and construction to O&M—even to its future use or reuse. If the data flow is only unidirectional, that is, the virtual model only represents the physical one without affecting it, it is instead considered a “digital shadow” (Sepasgozar, 2021). The DT model consists of three main parts: the physical products in the real world, the virtual products in the virtual space, and the data and information connection that tie those together.

Objective of the DT technology is to provide an accurate and up to date virtual model for any physical entity, on which to simulate entity behaviors, monitor the ongoing status, recognize internal and external complexities, detect abnormal patterns, reflect system performance, predict future trends and optimize operation. Predictions and what-if scenarios can be conducted on the DT to see what might happen if adjustments are made that might be too expensive, dangerous, or uncertain to try out in a real-world scenario. By altering the variables under which the DT is operating, the changes can be observed in the digital world without putting money or safety at risk, allowing a much larger space for trial and error and experimentation. Although both DT and abstract simulation can execute replications in cyberspace, they are not the same as DT relies on actual, real-time data from its physical counterpart, whereas simulation is based on the study of mathematical models.

Data and information exchange is at the base of the two-way dynamic mapping in the DTs to create a cyber-physical closed-loop: on the one hand, real data gathered in the physical part is sent to the virtual part for processing and analyzing, on the other hand, the virtual model can simulate real-world behavior by a variety of physical-based and data mining based algorithms and output actionable insights to dynamically adapt the physical system to the changing environment (Pan & Zhang, 2021).

Ideally, the DT would be identical to its physical counterpart and access the complete, real-time dataset of all information on the object/system. Realistically, as the object/system increases in complexity, the DT may be identical in only relevant areas, and have only the real-time data necessary to support any desired simulations. The level of accuracy and flexibility of the DT depends on its level of detail and how comprehensive the available data is. Indeed, the DT may not necessarily be a realistic representation and mirror everything about the physical asset, but rather a fit for purpose, relevant abstraction with a level of fidelity according to the primary use cases. Indeed, a DT for one project may be more simplistic with editable data, while another may enable a fully mature use with enhanced simulations. Main levels of DT sophistication are reported below, with each one requiring a greater degree of maturity and digital transformation but also offering increased value:

- *Descriptive twin*, which provides a live, editable version of design and construction data;
- *Informative twin*, which integrates additional operational and sensory data;
- *Predictive twin*, which leverages operational data for insights;
- *Comprehensive twin*, which allows simulation for future what-if scenarios;
- *Autonomous twin*, which gains the ability to learn and act on behalf of users.

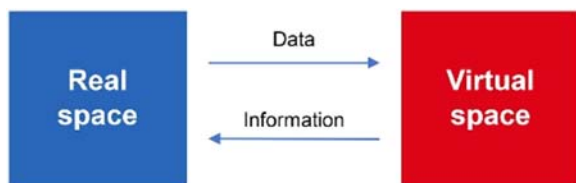


FIGURE 11.5 Digital twin paradigm.

DTs allow for the simulation of many options before taking physical action in the real world to identify the strengths and weaknesses of each plan (what-if scenarios). The DT could also be created based on a prototype of its physical counterpart, and provide feedback as the product is further developed; the DT could even serve as a prototype itself before any physical version is built.

When discussing DTs, there are three distinct environments where they are active, namely DT prototype, DT instance and DT aggregate/environment (Sepasgozar, 2021). The DT prototype describes the prototype of a physical system and contains the information sets necessary to describe and produce a physical version that duplicates or twins the physical version; however, it often does not provide a bi-directional information flow so it is more correctly referred to as a digital shadow. The DT instance describes a specific corresponding physical system that the prototypical DT remains linked to throughout the life of that specific physical system, including geometric dimensioning and tolerancing. The DT aggregate/environment is an integrated, multidomain physical application space for operating on DTs used for a variety of purposes, including the use of the DT for predicting future behavior and performance of a system or for interrogating their current and historical performance. Multiple systems can be compared in a DT environment to find patterns where the system does not meet the design criteria so future systems can be modified accordingly.

The concept of DT is not new, as product and process engineering teams have used 3D CAD models, asset models and process simulations to ensure and validate manufacturability for more than 30 years. In particular, DTs have primarily been used in the manufacturing sector, allowing for the product to be tested at all stages of the design process to ensure the design is feasible, safe, efficient and reliable (Schleich, Anwer, Mathieu, & Wartack, 2017; Tao, Qi, Wang, & Nee, 2019; Tao, Zhang, & Nee, 2019).

The “twin” concept itself can be traced back to NASA in the 1960s during the first trips to the moon, when NASA built exact replicas of everything that was launched into space. During production, these replicas were prototypes of the actual objects, and after the objects were on their way to remote destinations, they became a living, analog twin of the equipment in use: all modifications made by the astronauts on their way into space were also made to the twin. For instance, during the ill-fated Apollo 13 mission where there was a serious malfunction in the service module 2 days into the journey, simulations were made and validated on the analog twin on earth before mission control sent instructions to the astronauts.

In their modern adoption, DTs started as basic CAD documentation of the physical world in the late 1900s and became a representation much closer to reality with the transition to BIM processes that gave the ability to assign parametric data to objects and therefore make the representations move beyond just a physical description, but a functional representation as well. The recent growth of IoT technologies has finally allowed to live stream data from the objects and systems in the physical world to a remote location, analyze the data, and react to modify conditions of the physical object in its actual location.

The modern concept of DT has been introduced by Grieves and Vickers at the University of Michigan in 2002 referring it as the conceptual ideal for product lifecycle management. In 2012 NASA defined the DT of spacecraft as “an integrated multiphysics, multiscale, probabilistic simulation of an as-built vehicle or system that uses the best available physical models, sensor updates, fleet history, etc., to mirror the life of its corresponding flying twin” (Glaessgen & Stargel, 2013).

In the last years, several factors, most concerning the availability of enabling tools for DT data, services, modeling and connection to the physical world, have led to their increased popularity for many fields where they allow the mapping, fusion, and coevolution between the physical and virtual spaces. DT applications can now be found in smart city, construction, healthcare, agriculture, cargo shipping, oil&gas, automobile, aerospace, manufacturing, electricity, etc. In particular, current DT technology has become increasingly desirable due to the improved robustness of the models, with a focus on how they support specific business outcomes, and most of all in the application of advanced Big Data analytics, ML and AI to extract insight of unprecedented relevance (Liu, Fang, Dong, & Xu, 2021).

Indeed, DT can provide many strategic benefits. By combining sensory data acquisition with AI augmented analytics, DT can be used for monitoring, diagnostics, prognostics, and optimization of a multitude of processes. Decision-making of a wide spectrum of operations can be supported by the DT with the assessment of ongoing states, the diagnosis of historical problems, and the prediction of future trends. DTs add value to the traditional analytical approaches by improving situational awareness and enabling better responses to changing conditions, particularly for resource optimization and preventive maintenance. They can reduce operational and potentially capital expenses by optimizing the performance and extending the life of the object they represent while in operation. Through simulation and VR tools, DT improves the understandings of complex physical entities and processes and can be used for the training of users, operators, maintainers, and service providers (Errandonea, Beltrán, & Arrizabalaga, 2020).

Currently, the manufacturing industry is the sector in which most research on the implementation of DTs is concentrated, followed by industries related to the extraction of gas and oil, management of wind turbines, or offshore

infrastructure, in which DTs allow great benefits in terms of reduced maintenance and downtimes in facilities often remote or difficult to access. Construction and FM are also promising application sectors, as DT technology has expanded dramatically in the last years to include large elements such as buildings, factories or even entire cities, thanks to the advances in the fields of ICT, IoT sensors, virtual visualization, cloud computing, AI and ML, and interoperability (Lu & Brilakis, 2019; Teng et al., 2021).

DTs are entering mainstream recognition, having been indicated among Gartner's top 10 strategic technology trends for 2017, 2018, and 2019. In fact, it is expected that by 2021, half of large industrial companies will use DTs, resulting in those organizations gaining a 10% improvement in effectiveness, and by 2022, over two-thirds of companies that have implemented IoT will have deployed at least one DT in production. With an estimated 21 billion connected sensors and endpoints by 2020, DTs will exist for billions of things in the near future. Recent research by analysts Markets and Markets has found that the value of the market for DT solutions is set to grow from \$3.8 billion in 2019 to \$35.8 billion by 2025, with the largest adopters being the healthcare, automotive, aerospace, and defense sectors.

Therefore, DTs are already becoming a business imperative, covering the entire life cycle of an asset or process, and forming the foundation for subsequent products and services development. For complex, expensive industrial or business equipment, services or processes, improving utilization by reducing asset downtime and lowering overall maintenance costs is itself an extremely valuable application of DTs. At the same time, DTs provide engineers with insights in the real-world usage of the products they designed with all the benefits that brings: lifetime maintenance and performance history, as well as consumer insights, behavior data and preferences can be gathered to improve or develop products and services in a more data-driven way. DT can also remove information silos, inefficiencies, uncertainties, errors and the huge resources required for working with models, and enable cheaper virtual prototyping.

Applications of DTs are manifold and encompass a variety of industrial sectors (Raj & Evangeline, 2020).

In the manufacturing field, for example, SAP and Dassault relied on DT to reduce the deviation between functional requirement and actual performance. For civil engineering, Dassault used its 3D Experience Platform to build a "DT Singapore" to support urban planning, construction, and services. Intellectsoft is exploring the DT applications on construction site to detect potential problems and prevent dangerous operations. Concerning renewable energy facilities, Doosan partnered with Microsoft and Bentley Systems to develop DTs of its wind farms, allowing operators to remotely monitor equipment performance and predict energy generation based on weather conditions. This solution uses Azure DTs to combine real-time and historical IoT, weather, and other operational data with physics and ML-based models to accurately predict production output for each turbine in the farm, allowing to proactively adjust the pitch and performance of individual turbines, maximize energy production, and generate insights that will improve the future designs. Similarly, General Electric (GE) built a digital wind farm based on its Predix platform by creating a DT for every wind turbine, to optimize maintenance strategy, improve reliability, and increase energy production (Qi et al., 2021). These cloud-based virtual representations use data captured from their real counterparts to let engineers digitally play out different scenarios, such as running an aircraft engine longer and in a hotter or wetter environment than its current conditions, obtaining insights to maximize output and spot problems before they lead to an unplanned outage. In addition to using physical sensors on the machines, DTs can employ virtual sensors which have ability to guess fairly precisely a value (such as temperature or pressure) by using other data from sensors and smart algorithms based on historical data or models. For instance, GE engineers have developed a DT of the yaw motors of the Haliade 150-6 turbine which estimates, through virtual sensors, the temperature at various parts of the motors using algorithms built on Predix and a modelling approach developed by Ansys. At the office, engineers can monitor how the motors perform under different strains over time and learn more about operating them at peak efficiency, whereas in the field they are able to use an app with a dashboard connected to the twin to monitor the motors' temperature and decide whether to pull back on the power or push the motors further. In addition to wind turbines, GE has heavily invested in integrating DTs also in the designing, manufacturing and maintaining processes of their engines, power generation, oil and gas and medical imaging equipment. Claimed benefits include improved reliability of up to 99% in less than 2 years, reduced reactive maintenance by 40% in less than 1 year and avoided \$11million in lost productivity costs. For instance, GE Trip Optimizer is a DT for locomotives which simulates the most efficient speed and acceleration profile of the train based on weather conditions, topography of the train tracks and scheduled arrival time, enabling fuel savings of 3%–17%, or up to 120,000 L per engine annually.

11.4.1 Digital twin structure

For the implementation of the DT, several programs are available that rely on dedicated platforms, the most advanced of which are Johnson Control's OpenBlue DT, Autodesk Tandem and Microsoft's Azure DTs.

In particular, Azure DTs is an IoT platform that claims to simplify and accelerate the creation of IoT connected solutions, enabling digital representations of real-world things, places, business processes, and people and providing insights that help optimize operations and costs and develop better products. Core capabilities of Azure DTs include the following:

- solutions to ingest CAD drawings to visualize and analyze data in the context of indoor maps and floor plans (Azure Maps Creator);
- a dedicated open modeling language, Digital Twins Definition Language (DTDL), to easily create custom models of intelligent environments, as well as premade models and converter tools for vertical standards to help accelerate development;
- a live, scalable and secure execution environment that uses data from IoT and other sources, from which to extract insights in the context of the modeled world by querying data on a wide range of conditions and relationships;
- Azure IoT Hub to easily connect assets such as IoT and Azure IoT Edge devices, as well as existing business systems such as enterprise resource planning and customer relationship management, to Azure DTs to extract relevant insights across the entire environment;
- integration with other Azure services, including the ability to send data to Azure Data Lake for long-term storage, to Azure Synapse Analytics for analytics services and ML, as well as to Azure Time Series Insights for time series data integration and historian analytics.

The continuous update of data and information between physical and virtual systems is fundamental to allow DT dynamic behavior, and only the integration of data from sensors and machines, historical data and computer-based models enables directional analysis and visualization of the results. For the implementation of the DT, a logical structure that models the relationships between the different physical elements and the data they can express is therefore necessary. Specifically, the DT is founded on an ontology-based approach to information creation for defining relationships between the subcomponents of the physical entity to be replicated. An ontology is the explicit formal specification of the concepts in the domain and of the relations among them, which constitute the building blocks of conceptual models used for DTs (Guerriero, Kubicki, & Rezgui, 2020).

Main existing ontologies that deal with describing the built environment include Building Topology Ontology (BOT), ifcOWL, BIMSO, Cbim, and RealEstateCore.

For instance, Azure DTs models are represented in DTDL, an open modeling language based on JSON-LD and RDF, by which developers can define the schema of the entities they expect to use in their graphs or topologies. DTDL enables developers to freely describe twins in terms of their state properties, telemetry events, commands, components, and relationships. By itself, DTDL is a blank canvas which can model any entity, therefore to accelerate development time for the DT it is possible to employ premade ontologies specific to that DT domain, which allows to bootstrap solution building, as well as seamless integration between DTDL-based solutions from different vendors.

To streamline the creation of DTs for smart buildings solutions, Microsoft partnered with the RealEstateCore Consortium (a Swedish consortium of real estate owners, software houses, and research institutions) to deliver a DTDL-based ontology (or set of models) for the real estate industry, which provides common ground for modeling smart buildings while leveraging industry standards to prevent unnecessary reinvention. RealEstateCore is a popular domain ontology used to model and control buildings, that has already been deployed across sizeable real estate portfolios and has gone through several revisions based on real-world feedback and learning. It also bridges with other building industry standards such as Brick Schema, Project Haystack, W3C Building Topology Ontology (W3C BOT). As the original RealEstateCore ontology was represented using the W3C Web Ontology Language (OWL), it has been converted into the DTDL syntax used in Azure DT using the universal OWL2DTDL tool. RealEstateCore ontology consists of a primary set of interfaces (Space, Asset, LogicalDevice, Capability) and a secondary set of additional interfaces (Agent, Building Component, Collection, Document, Event, Role) connected by a number of relationship types (isPartOf, locatedIn, servedBy, etc.) (see Table 11.1 and Fig. 11.6).

Different DT programs are based on Azure DT technology. One of the most relevant is WillowTwin, a software solution that deploys DTs for the built world to collect, organize, and analyze data, using the DT platform to model tens of thousands of assets and establish a live execution environment based on the real-time data from spaces, devices, and the relationships between them. WillowTwin ingests BIM models to create its DT spatial graph, gathers data from across a built asset (including design information, asset data, manuals, warranty info, etc.) then creates relationships with live data coming from the BAS through BACnet gateways. This way, Willow enables users to find information based on the spatial layout of the objects in a building, leveraging the new contextual storage nodes capability of Azure IoT, allowing precise and relevant insights into building performance. Moreover, WillowTwin's fault rule engine can determine when issues need to be fixed in office spaces or when building machinery needs to be taken offline for

TABLE 11.1 RealEstateCore ontology.

Main set of interfaces	
Asset	An object which is placed inside of a building, but is not an integral part of that building's structure (e.g., architectural elements, furniture, equipment, systems).
LogicalDevice	Electronic equipment or software that communicates and interacts with the DT platform. Logical devices can include integrated circuits inside of a HVAC unit, virtual servers, etc. Logical devices can have capability instances that describe their input/output capabilities, and can be embedded within Asset entities to denote the capabilities of the asset.
Capability	A capability indicates the capacity of an entity, be it a Space, an Asset, or a LogicalDevice, to produce or ingest data. Specific subclasses specialize this behavior: Sensor entities harvest data from the real world, actuator entities accept commands from a DT platform, and Parameter entities configure some capability or system.
Space	A contiguous part of the physical world that has a 3D spatial extent and that can contain subspaces. For example, a Region can contain many pieces of Land, which in turn can contain many Buildings, which in turn can contain Levels and Rooms.
Additional base interfaces	
Agent	Any basic types of stakeholder that can have roles or perform activities, for example, people, companies, departments.
Building Component	A part that constitutes a piece of a building's structural makeup, for example, Facade, Wall, Slab, RoofInnner, etc.
Collection	An administrative grouping of entities that are addressed and treated as a unit for some purpose. These entities may have some spatial arrangement (e.g., an Apartment is typically contiguous), however that is not a requirement (see, e.g., a distributed campus consisting of spatially disjoint plots or buildings).
Document	A formal piece of written, printed or electronic matter that provides information or evidence or that serves as an official record, for example, Lease Contracts, Building Specification, Warranty, Drawing, etc.
Event	A spatiotemporally indexed entity with participants, something which occurs somewhere, and that has or takes some time, for example a Lease or Rent.
Role	A role that is held by some agent, for example a person could hold a Sales Representative role, or an organization could hold a Maintenance Responsibility role
Relationship types	
isPartOf, hasPart	A simplified set of topological relations to connect sub- and superentities within the top-level interface tree. "isPartOf" and "hasPart" are defined to operate on entities of the same type, for example Spaces have only Spaces as parts, Assets have only Assets as parts, etc.
hasCapability	Indicates that a Space, Asset or LogicalDevice has the ability to produces or ingest data represented by sensors, actuators or parameters, for example a VAV air damper "hasCapability" relationship to an TemperatureSensor. The inverse relationship is "isCapabilityOf."
includedIn	Indicates that an entity is included in some Collection, for example a Building is included in a RealEstate, or a Room is included in an Apartment. The inverse relationship is "includes."
locatedIn	Indicates that a given Asset is physically located in a Space. There is no inverse of this one.
hosts	Indicates that a given Asset hosts a logical device; for example an IoT camera "hosts" an IoT Edge runtime. Inverse of "hostedBy," which indicates the physical hardware asset that a given logical device is hosted and executed on.
serves	The coverage or impact area of a given Asset or Sensor/Actuator. For example, an air-treatment unit might serve several Rooms or a full Building. Note that Assets can also service one another, for example an air-treatment Asset might serve an air diffuser Asset. The inverse relationship is "servedBy."
feeds	Indicates that a given equipment is feeding something to another equipment or space, like electricity, water or air. For example, an AHU equipment "feeds" air to a VAV equipment. Inverse relationship is "isFedBy."
hasBuildingComponent	Parthood traversal property linking Buildings to the Building Components that they are made up of, for example, a Building "hasBuildingComponent" a Facade or Wall which are of type "BuildingComponent." The inverse relationship is "componentOfBuilding"

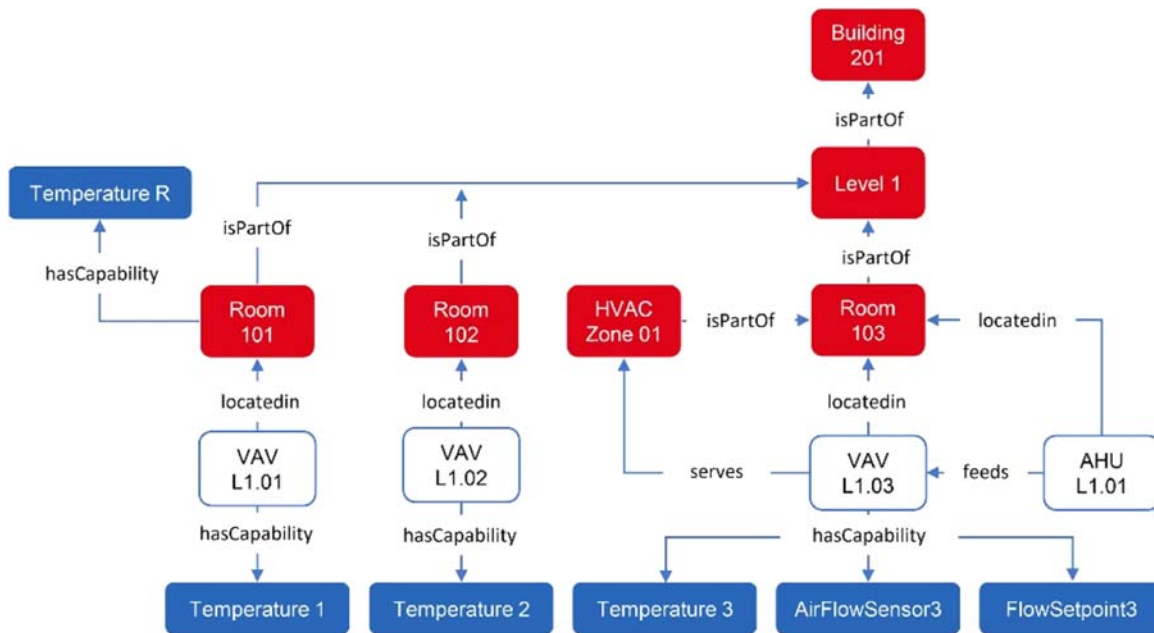


FIGURE 11.6 Example of a subgraph of an Azure Digital Twins instance based on RealEstateCore ontology.

maintenance. Finally, WillowTwin is also commonly deployed to manage energy utilization, to handover buildings from contractor to building operator, to analyze building performance across real estate portfolios, and to manage fault detection and maintenance.

11.4.2 Digital building twin

Extending the DT technology to buildings can enable a new way to build, operate, and experience the built environment (Opoku et al., 2021; Ozturk, 2021).

In particular, the DBT can simultaneously allow the augmented visualization of the digital model and the monitoring, management and the advanced maintenance of the real building (Arup, 2019).

As for augmented visualization, the DBT allows remote access through any device to perform 3D visualization of the building model, horizontal and vertical sectioning, navigation in first person or with VR, measurement of angles and distances, query of individual elements, search for spaces or objects by category, collection of objects in clusters, view and download of documents (floor plans, data sheets), as well as the modification in sync with the BIM model of the building.

Concerning building management, the DBT allows continuous monitoring of all parameters inside and outside the building (temperature, air quality, illumination, etc.) and of the operating status of all equipment (on-off, consumption/production, power use, open-closed, hours of operation, etc.), the remote control of systems, equipment and technical elements (windows, curtains) manually or on the basis of a logic (time schedule, limit conditions, attendance, etc.), as well as the simulation of comfort parameters and consumption of determined scenarios based on variations in the surrounding conditions (climate, thermostat, operating times of the equipment) to be applied to the real building (see Fig. 11.7).

Regarding maintenance, the DBT allows to inspect each individual element by simply browsing the virtual model, to automatically create the list of scheduled maintenance interventions, to plan predictive maintenance interventions on the basis of actual operating parameters and analysis of deviations, to receive alerts and suggestions from the system, to maintain a historical archive of revisions, malfunctions, component statistics, to have a repository of technical data sheets, manuals, certificates, to automatically generate purchase orders to suppliers, and to integrate maintenance with MR (see Fig. 11.8) (Lu, Xie, Parlikad, & Schooling, 2020).

DBTs rely on processing taking place both in the cloud and at the edge. The data that informs the model is collected at the edge by scanners, sensors, or humans working on terminals, while the model simulation runs in the cloud, meaning it can be accessed and used from anywhere (Aheleroff, Xu, Zhong, & Lu., 2021).

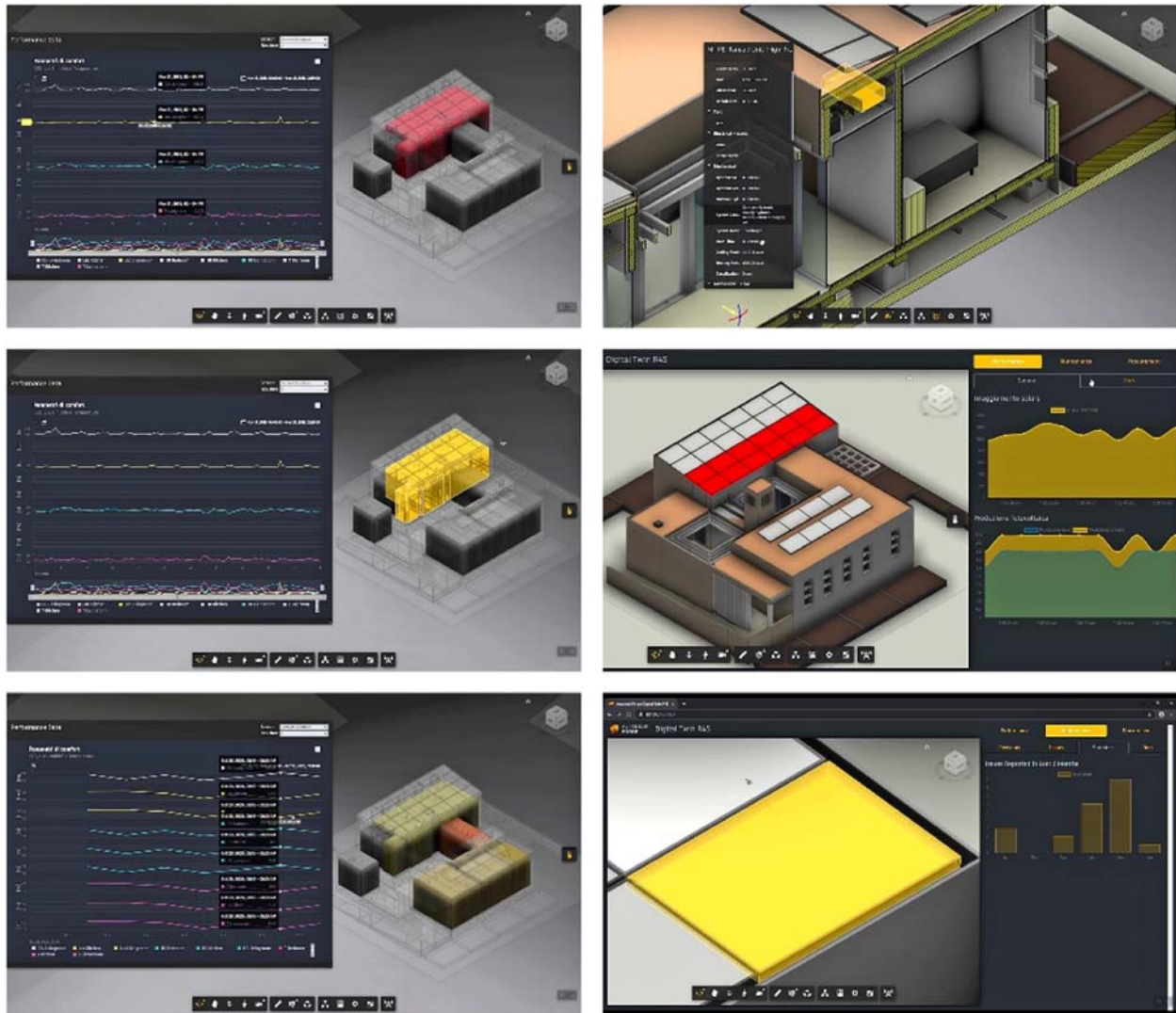


FIGURE 11.7 Example of control and monitoring via the DBT. Credit: Marco Micheli.

The system for the DBT is best planned from the beginning rather than imposed on a project at a late stage, defining the data required, how it is generated, received and stored, who has access to the data, and the types of digital models required. Once this framework is in place, the technology to enable the physical asset to capture the real-time flow of data is selected. The implementation of the DBT can start small with a single system and be expanded over time, or can start as a series of smaller, system-specific DTs that are assembled to create the full picture of an asset (Lim, Zheng, & Chen, 2020). Several technologies are necessary to create a functioning DBT:

- a BIM model with sufficient detail (LOD 500);
- an ontology to create the semantic model of the building;
- a viewer tool for cloud visualization;
- a database for data collection;
- IoT sensors installed in the building;
- connection systems between construction elements and model elements;
- external support systems for data analysis.

The starting point for developing the DBT is a LOD 500 BIM model of the building. This is converted into a DBT through the creation of a semantic model of the building, able to classify the different components and define the relationships between them, which can be performed using different ontological standards, also known as Open Modeling

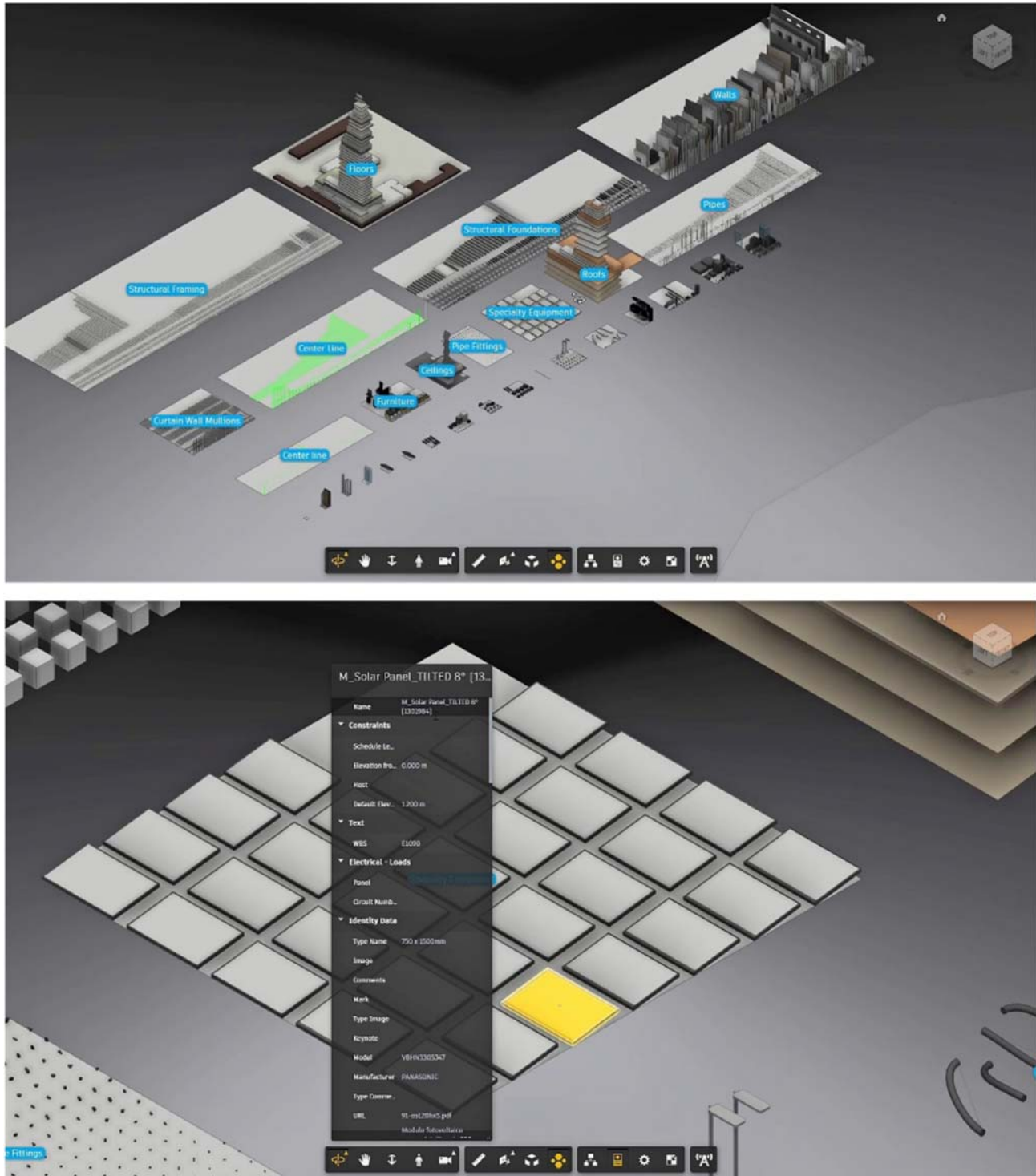


FIGURE 11.8 Example of listing and interrogation of all building components via its digital twin. *Credit: Marco Micheli.*

Languages (BOT, OWL, bSDD, DTDL). The semantic model underlying the DT allows to act on real elements directly from the digital model and vice versa. Once converted, the DBT can be used within a “Live Execution Environment” (LEE) and be viewed within a cloud viewer such as Autodesk Forge. Through the Open Modeling Language, the DBT can also be connected with IoT objects that send real-time data through cloud services such as Azure IoT Hub or AWS

IoT Core. Data can be stored in databases such as CosmosDB or MongoDB. Furthermore, the DBT can be connected to data analysis services to extract value from the historical data of each node within the DT.

Once developed, the DBT contains all the information necessary for the management and maintenance of the building, integrated and constantly updated by the connected sensors that monitor in real-time its state of health, operating conditions, and any anomalies and potential risk situations, providing valuable information for keeping it in perfect working order. The DBT also allows for high fidelity simulation using data from the building systems, maintenance history and all available historical data to identify any possible problems in safety or reliability.

DTs can observe imminent risks, such as equipment failure, enabling operators to proactively mitigate problems and reduce both unexpected maintenance shutdowns and scheduled but unnecessary maintenance procedures. The DT can predict the life span of various plant components in different scenarios, allowing informed decision-making and optioneering, resulting in a reduction in the number of interventions, times and costs.

Applied at the design stage, prototype DTs also allow to explore a wider range of potential solutions that may have never been considered traditionally, for instance to predict the suitability of new materials. DT technology was recently used to test and determine the viability of building a 29-storey apartment tower from sustainable timber in Melbourne, a material which had not been tested in buildings of this height before.

Among the most relevant applications of DT in buildings, IBM Watson Headquarters in Munich has shown how the DT can be used in a cognitive building to control the heating, ventilation, and air conditioning (HVAC) systems and monitor indoor climate conditions. In the building, there are 600 room sensors (e.g., temperature readings, light sensors, and occupancy monitoring), 250 smart meters, and 169 HVAC machines. Based on the collected data, this DBT can help engineers regulate energy consumptions and detect potential use cases, and provide technicians with guided services, maintenance procedures, and knowledge of climate control.

Brookfield Properties, one of the world's largest commercial office landlords, partnered with Willow to create a digital replica of their One Manhattan West property and all the systems within it using the WillowTwin DBT program. This allowed to unlock cost savings, energy optimizations, and value-added services, as well as enabling a fault detection & diagnostics solution for smart maintenance.

Elevator manufacturer Thyssenkrupp developed a DBT of its Innovation Test Tower in Rottweil, Germany, using the WillowTwin platform. The tower is a 246 m high test laboratory built to try and showcase new technologies as well as an active office building. The DBT takes in live data from IoT sensors that monitor the building's systems (lighting, elevators, HVAC, etc.), along with data about the way space is being used and occupied, and stores it perpetually in Azure, along with all construction and design information, like warranty details, equipment operating manuals, and maintenance logs, making it all available in real-time.

WillowTwin uses the spatial intelligence coming from Azure DTs in conjunction with other services, including Azure Time Series Insights for data display and information, Azure Stream Analytics, Azure Blob for data storage, Azure Synapse Analytics for data modeling, and Azure Spark for anomalies detection (see Fig. 11.9). The Willow Connector plugs directly into the BAS and structures and cleans data, sending it into the Azure DTs environment for processing, and finally the results are delivered as actionable, easy-to-understand insights through a client portal.

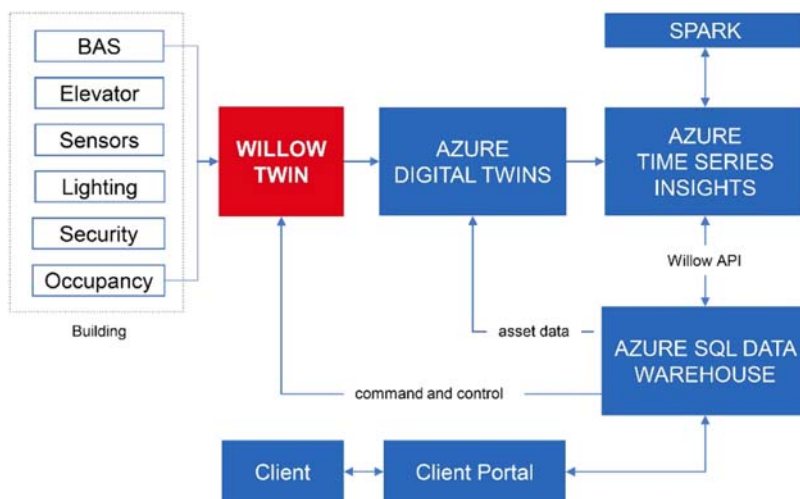


FIGURE 11.9 Willow Twin platform and Azure Digital Twins services.

Building managers and service professionals can access via mobile a multifunctional dashboard that delivers insights alongside the current state of the building's essential systems, including water, heat, electric, and gas usage. Eventual service issues, such as a water pump that stops operating properly, can be visualized via the 3D model of the building that can be enlarged or rotated to locate a digital representation of the physical unit and access a thorough listing of the unit's specifications, operating history, maintenance record, and service manual. The same tower also showcases Thyssenkrupp MAX, a predictive elevator maintenance solution built on Azure that claims to reduce elevator downtime by half and is already used with more than 120,000 elevators worldwide. MAX also feeds information to Willow Twin about elevator occupancy and usage, and operators use that data to enhance the performance and availability of the elevators.

In addition to maintenance, facility managers can use the DBT to streamline everyday tasks and optimize energy usage: WillowTwin connects to Outlook meeting schedules and knows exactly which rooms will be used during the day, delivering air conditioning or heating only to those rooms and asking the cleaners to skip the unused rooms. Furthermore, the DBT generates analytics that show how different departments are using space and how many people are moving through various parts of the building over the course of the day, providing useful insights for daily management and crucial information in case of an emergency, to help first responders pinpoint their efforts.

Finally, the availability of a complete DBT of a functioning office building provides a suitable laboratory for testing new technologies and gathering real-world data and insights. Engineers can constantly reconfigure the virtual space to test different usage scenarios and see what may work best for the people in the building without having to install any physical assets for testing.

Finally, Bentley Systems built a DT of the Microsoft HQ inside Frasers Tower in Singapore on its Bentley iTwin platform—leveraging Azure DTs, Azure IoT Hub, and Azure Time Series Insights—using both historical and real-time data from IoT sensors to create an exact digital replica of the physical building. The building management team uses the information to dynamically allocate space, increase utilization, reduce costs, improve competitiveness, and enhance collaboration and productivity.

A DBT was developed for One Sydney Harbour, a residential development by RPBW, using the models, 2D drawings, specifications and product tech data approved for construction. This allowed to identify and address unresolved design details and errors to a much finer level of detail than would have been achieved through a purely traditional approach, and in a much shorter time frame.

11.5 Conclusion and future trends

Building maintenance represents a strategic activity to ensure the building performs as expected over time and to reduce both operating management costs and those due to maintenance interventions or downtimes and to disruptions created by failures and breakdown.

Thanks to 7D BIM, that is, the 3D model enriched with all data and information required for the O&M stage of a built asset, facility managers can now take advantage of data-rich, living building models for data-driven proactive maintenance, warranty planning, and predictive daily operations. As BIM and IoT devices grow in diffusion, the future of both building operation and maintenance leads to the DT technology, which promises to revolutionize the way buildings are managed and maintained by transforming them into a comprehensive ecosystem of data and insights. In fact, a DT provides an accurate and up to date virtual model the whole building that allows to continuously monitor the ongoing status of the physical twin, simulate entity behaviors, recognize internal and external complexities, detect abnormal patterns, reflect system performance, and predict future trends to optimize operation. It allows to carry out simulations and what-if scenarios to predict the outcome of any adjustment that might be inconvenient to try out in the real world, allowing a larger space for trial and error and for experimentation. DTs can be integrated with AI and ML functions to become more intelligent and autonomous in their decision-making. Aptly trained AI algorithms monitor continuously the status and parameters of all relevant building components, allowing to identify with sufficient anticipation failures and disservices and, therefore, enabling managers to schedule interventions timely to minimize downtime and disruption.

An interesting and substantial support to maintenance activity can also come from AR and MR, technologies that are able to provide users with instructions, sensor data or superimposed technical schemes right in their field of view as well as allowing hands-free communication. Furthermore, integrated cooperation platforms allow remote connected colleagues and experts to see the live, first-person view taken by the MR headset and collaborate actively with the technician, sharing annotations and 3D holograms directly into the real-world view of the person wearing the device. This way, even advanced maintenance operations can be performed by nonspecialized technicians or even unexperienced

users. Further advantages of XR in maintenance include improved training and the possibility of step-by-step indoor navigation, useful for visitors or emergency responders such as firefighters.

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Chapter 12

Smart buildings and smart cities

12.1 Smart city

The smart city (SC) concept emerged in the early 2000s as a combination of ideas about how information and communication technologies might improve the functioning of cities (Batty et al., 2012).

Although several cities worldwide are already labeling themselves as SCs, currently this paradigm is still considered a work in progress. In summary, the SC concept combines, builds on, and expands earlier urban paradigms such as the digital city, virtual city, ubiquitous city, intelligent city, creative city, knowledge city, hybrid city, information city, and wired city. Such SC would be a city capable of improving its citizens' life quality, offering a lasting opportunity for cultural, economic, and social growth in a healthy, safe, stimulating and dynamic environment, with buildings and infrastructures representing the key element for achieving these objectives (Albino, Berardi, & Dangelico, 2015; Zheng, Yuan, Zhu, Zhang, & Shao, 2020). According to the European Union (Casini, 2017; EU Directorate general for internal policies, 2014; Giffinger, Fertner, & Kramar, 2007), a SC is a city that guarantees:

- economic competitiveness, innovation, enterprise, economic image and brands spirit, productivity, job market flexibility, international integration, transformation capacity;
- social interaction of citizens, high qualification level, long-term training, social and ethnic plurality, flexibility, creativity, cosmopolitanism and mental opening, participation to public life;
- collaborative administration functioning and services, participation to decisional processes, public and social services, transparent government activity, politics strategies, and perspectives;
- availability of information and communication technologies and modern and sustainable transportation systems, local and international accessibility, availability of IT infrastructures, sustainable, innovative, and safe transportation systems;
- high environmental quality, attractiveness of natural conditions, pollution, environment protection, sustainable management of resources;
- high quality of life, culture, health and safety, social structures, health conditions, individual security, dwellings quality, educational structures, touristic attractiveness, social cohesion.

A SC is characterized by a strategic approach to sustainability, citizen well-being, and economic development, through the integration of technology and ICT-based solutions, based on multistakeholder, municipally based partnerships. SC initiatives can be classified into the main six domains (or axes, or dimensions) of economy, environment, living, mobility, people, and governance (EU Directorate general for internal policies, 2014; Lu, Chen, & Yu, 2019; Zheng, Yuan, Zhu, Zhang, & Shao, 2020) (Fig. 12.1).

Smart economy refers to e-business and e-commerce, and to those economic opportunities that are enabled by digitalization, including manufacturing and service delivery, innovation, and new products, services, or business models. Smart environment encompasses energy (including smart energy grids, metering, control and monitoring improved by

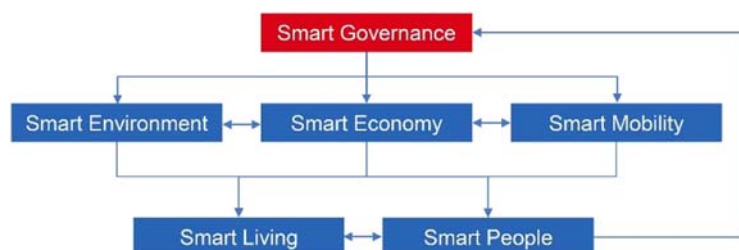


FIGURE 12.1 The six dimensions of the smart city model.

IT, as well as renewable energy sources), water management, green buildings and urban planning, urban services (waste management, drainage systems, public lighting), and efficiency, as well as reuse and substitution of resources to improve environmental conditions. Smart living refers to initiatives that leverage digitalization to improve citizens' lifestyle, providing a safe, attractive and healthy city, also by means of an easier access to healthcare. Smart mobility encompasses initiatives that improve transportation and logistics by using ICT. Smart people is concerned with promoting creativity and fostering innovation to improve agile working, human resources, capacity management, and access to education and training. Finally, smart governance regards the use of digital technology to improve democratic processes and public services (e-government) and to support and facilitate better policy making and decision making.

Over the last decades, the SC concept has evolved: there has been a paradigm shift from an initially ICT technology-driven focus, mainly aimed at maximizing efficiency of the hard urban infrastructure (i.e., transport, communications, waste, energy, water, etc.), to adopting a more comprehensive and inclusive approach, centered on the role of people and the soft infrastructure (i.e., institutions, citizen engagement, social innovation, knowledge economy, justice, etc.).

In particular, smart governance tools such as digital democracy, open governance, citizen empowerment, and participated urbanism are considered fundamental in SC development (Meijer, & Bolívar, 2016). Digital democracy is based on the implementation of ICT and social media to support political and governmental processes, by producing a wider participation of citizens and a more transparent administration. For example, *Apps for Democracy*, a not-for-profit organization, is an open community platform developed for submitting non-emergency service proposals to the city of Washington D.C. The first edition of Apps for Democracy yielded 47 apps in 30 days—an estimated \$2,300,000 value to the city at a cost of \$50,000 (Apps For Democracy: An Innovation Contest). The City of San Francisco uses Urban EcoMap, an Internet-based tool that provides citizens with information on carbon emissions from transportation, energy, and waste among neighborhoods, organized by zip codes, helping them to make sustainability part of their decision making.

Open governance refers to availability to citizens of information, data, and governmental processes to promote their participation and collaboration in the city's decision-making processes, and to the facilitation of proactive and open communication between the citizens and government. Open governance aims to make the urban administrations more responsible to their citizens and thus increase their legitimacy.

Citizen empowerment promotes citizens' awareness of their contribution to decision-making processes and to changes in the city. Provided with communication and participation opportunities, citizens feel called to contribute to the city with their own time, energy, and ideas.

Lastly, participating urbanism entails the use of ICT to enable citizens to collect and share data, ideas and proposals with the city's government. Indeed, community members may as well be experts in the related urban situations and have knowledge and solutions for multiple issues, and through participating urbanism these local knowledge and human resources can be exploited effectively, rather than imposing the change from above.

In this framework for change, technological innovation is vital to find new ways to manage resources and deliver services. Reaching the strategic goals of SCs is only possible by systematically integrating technologies such as renewable energies, advanced materials, innovative transportation systems, ICT, broadband, geolocation systems, Internet of Things (IoT), smartphones and tablets, social networks, city apps and urban data, artificial intelligence (AI) and machine learning (ML), and digital twin (DT) (Ahad, Paiva, Tripathi, & Feroz, 2020; JRC, 2019b; McKinsey, 2018).

In particular, SCs are built on an intelligent urban infrastructure of connected devices, with ubiquitous communications services and sensor technologies across the urban fabric providing municipal officers with new insight into how cities operate. Indeed, much of the SC potential relies on the ability to leverage the data from these devices and other embedded technologies to drive a new range of services (Zheng et al., 2020).

Smart cities are becoming one of the most important testing grounds for IoT, enabling any element of the city architecture to become a potential source of data and a means of fine-grained control, thereby opening up a host of new opportunities for city management and services (Camero & Alba, 2019; IRENA, 2019g; Jiang, 2020; Lu et al., 2019).

In this picture, SC designers, infrastructure stakeholders, coordinators, and policymakers have to develop more secure networked relationships, interoperable data exchange models, and efficient sharing economy platforms in areas such as banking, healthcare, and transportation, for example, as well as improve the quality of services, and efficiently manage diverse urban activities for the benefit of smart citizens. Blockchain technology is considered a suitable choice for enabling numerous use cases in this respect as it can empower SCs to overcome numerous problems pertaining to infrastructural elements in a broad sense, such as the technological, social, and financial environment, and the lack of integration between these elements (IRENA, 2019e; Majeed, Khan, Yaqoob, Ahsan Kazmi, & Salah, 2021; Treiblmaier, Rejeb, & Strebing, 2020).

The inherent security toward hacking, data theft or tampering and the provision of a single, shared source of truth for any information or transaction therein, as described in [Section 9.1.5](#), make blockchain a driver for overcoming current technological limits and concerns in sensitive SC services that include smart healthcare, smart logistics and supply chains, smart mobility, smart energy, smart administration, e-voting, smart factories, smart homes as well as smart education ([McKinsey, 2018](#)).

All these innovations can be harnessed to the policy objectives that are common to almost all SC strategies, that is, to combine sustainability targets, improvements in services to citizens, and development of the local economy in order to provide employment and attract new businesses and new talent. Within this effort, sustainability programs can cover a wide range of ambitions, including reduced energy consumption, increases in local renewable power generation, improvements in waste recycling and water consumption, and changes in transportation patterns, and city services can concern public safety, health and social care, education, waste management, street lighting, and efficient transportation systems. Economy can finally be stimulated the right way by a combination of regulatory and code constraints and, at the same time, tailored incentives to sustain the transition to value-added entrepreneurial activities.

Spurred by emerging city challenges regarding economic development, resource utilization, quality of life, time, cost, and sustainable future, and inspired by international initiatives such as IBM Smart Planet, i-Japan 2015 Strategy, and the Europe 2020 strategy, in the last years SC has become a global phenomenon increasingly embraced by city leaders all over the world, heralding innovative projects and laying out a vision for how cities can use technology to meet sustainability goals, boost local economies, and improve services.

Parallel to cities initiatives, several legislations plans and projects have been developed to support and enforce the change towards smarter cities and buildings: at city level, ISO/TC268 for “Sustainable cities and communities” is responsible for the ISO 37100 series of standards to help cities define their sustainability objectives and put strategies in place to achieve them. This core standard is joined by a series of standards on city indicators including ISO 37120 (indicators for city services and quality of life) and the two upcoming standards ISO 37122 (indicators for smart cities) and ISO 37123 (indicators for resilient cities). ISO/TR 37150 introduced indicators such as global city indicators, green city index series, and SC realized by ICT. Moreover, some legislations are being developed to enhance the existing indicators, such as ISO/NP 37122 “Sustainable Development in Communities- Indicators for Smart Cities” ([Al Dakheel, Del Pero, Aste, & Leonforte, 2020; Sharifi, 2019](#)).

Globally, the market for SCs amounted to USD 410.8 billion in 2020 and is expected to double in size to 820.7 billion by 2025, at a Compound Annual Growth Rate (CAGR) of 14.8% ([MarketsandMarkets, 2020](#)). This growth will be mainly driven by the increasing demand for public safety, rising urban population, and growing government initiatives. In particular, smart transportation segment already accounts for the largest market size in 2020 and is expected to grow at an impressive CAGR during the forecast period, whereas technologies such as video surveillance, DNA phenotyping, and real-time license plate and facial recognition are increasingly used for public safety. SC investments are coming from tech companies such as IBM, Microsoft, and Cisco, and the established megaprojects of Masdar City in the Emirates, Songdo International Business District in South Korea, Hudson Yards in New York City, and India’s Delhi Mumbai Industrial Corridor are gaining global attention as SC testbeds.

While many of the drivers and technologies being deployed are common across the world, there are also considerable differences between regions and countries in terms of the economic and political context, the history and future of urbanization, and the levels of existing and planned infrastructure investment. The SC concept itself is also evolving as many more cities, national governments, and technology and service providers join the discussions. SC strategies show growing emphasis on resilience and climate adaptation, renewed focus on making these developments relevant to citizens’ daily lives, desire for more data-driven policymaking and operational control, as well as recognition of the need for shared standards to help drive SC programs to the next stage.

More than 85% of urban projects focus on the use of IoT and smart sensors throughout the city, in connection with citizens’ devices, to produce digitalized services and improve the efficiency of services. These technologies can provide an unprecedented volume of data points and greatly reduce the cost of gathering information about usage patterns, allowing city governments, employers, and residents to find new ways to optimize existing systems, for instance by encouraging people to use transit during off-hours, to change routes, to use energy and water at different times of day, and to reduce strains on the healthcare system through preventive self-care. Used effectively, SC functionalities can improve significantly quality-of-life indicators such as time saved from traffic or interactions with government, health and safety outcomes, environmental impact, and social connectedness and civic participation. Studies conducted on representative urban areas have found SC initiatives can reduce fatalities by 8%–10%, accelerate emergency response times by 20%–35%, shave the average commute time by 15%–20%, reduce the disease burden by 8%–15%, lower greenhouse gas (GHG) emissions by 10%–15%, and reduce water consumption by 20%–30% ([McKinsey, 2018](#)).

SC digital models can today exploit and benefit from data collection and processing using different technologies of communication, networking, and computing, which in turn lead to the innovation of smart services across different sectors including health, transportation, security, and more (Ahad et al., 2020; Camero & Alba, 2019; Jiang, 2020; JRC, 2019b; McKinsey, 2018).

A SC typically operates on four layers of smartness that build on each other (McKinsey, 2018; Silva, Khan, & Han, 2018; Zygiaris, 2013). The base layer is the physical and social infrastructure, shared with conventional cities as well. The first smart layer is the technology base, which includes the critical mass of IoT sensors and devices connected by high-speed communication networks, as well as open data portals, and citizens' own smartphones. These allow constant readings of variables such as traffic flow, energy consumption, air quality, and many other aspects of daily life and make this information available for decision making. With the rapid build-out of IoT, in fact, billions of inanimate objects have become "smart," that is, have been outfitted with sensors and actuators and connected to the Internet, with examples including RFID tags in packages to track cargo shipments, GNSS receivers to guide drivers to their destinations, and smart thermostats to turn off heat and air conditioning when rooms are unoccupied. As the costs of IoT sensors, processing power, and cloud storage fell, adoption grew in all industrial sectors, achieving a total connected devices of 20.4 billion expected by 2020.

The second layer consists of the SC specific applications. Technology providers and app developers are tasked with creating the tools needed for translating raw data into alerts, insight, and ultimately action. Tools are available in multiple domains: security, mobility, health, energy, water, waste, economic development and housing, and engagement and community. In particular, the presence of such amounts of big and complex data of different formats (text, symbols, numbers, video, images, etc.), recommends the use of advanced analysis techniques such as AI and ML to reach an optimal decision. Deep learning-based models, developed after accumulating data from multiple sources such as online weather websites, meteorological stations, taxi detectors, etc. are seen as the best method to address urban problems such as air quality prediction and calculation, crowd flow predictions, or water quality prediction (Atitallah, Driss, Boulila, & Ben Ghézala, 2020). Data analytics is the process of transforming raw data units into actions and optioneering insights through descriptive, predictive, or prescriptive processes. Descriptive analytics measure and contextualize past achievements and monitor current performance in order to improve decision-making by deriving conclusions, extract hidden patterns from collected data, and create meaningful reports. Predictive analytics are instead based on business intelligence techniques that allow for the extraction of patterns and the discovery of relationships from large amounts historical and current statistics, in order to forecast and predict behaviors and events. Lastly, prescriptive analytics, more advanced than either descriptive or predictive analytics, can quantify the effect of future decisions and then provide recommendations on possible results before making decisions.

The third layer is public usage. SC applications, in fact, can be successful only if they are widely adopted and manage to change behaviors. As people are required to adopt and use these technologies productively in the day-to-day life and business of the city, user experience becomes a critical success factor, and as the public becomes increasingly digitally savvy, expectations for a seamless experience continue to grow and the interfaces themselves need to be engaging and intuitive. In the SC paradigm, residents are not merely passive recipients of services, but active participants in shaping how their city operates and uses its resources. Mobility apps are already a successful case of changing the way people interact with the urban environment: people routinely use traffic apps to navigate around gridlocks, transponders in their cars automatically deduct the cost of tolls, smart parking apps guide them straight to available spots, riders simply wave their phones to pay transit fares, and taxis can be summoned from anywhere in the city seamlessly.

Digital cities are embracing a data-driven approach from planning to execution, leveraging DT for operating city infrastructure, urban planning, visualization, and simulation, to support infrastructure resilience and enhance stakeholder collaboration and resident engagement (Bibri, 2021).

Main SC applications include innovative services of security and safety, mobility, healthcare, buildings, energy, waste, and water (McKinsey, 2018).

Concerning security, the main initiatives include monitoring and, where necessary, directing crowds to ensure safety (crowd management), predicting and mitigating the effects of natural disasters such as hurricanes, earthquakes, floods, and wildfires (disaster early-warning systems), or intelligent monitoring to detect anomalies based on visual feeds from CCTV including facial recognition and license plate recognition (smart surveillance).

Regarding mobility, the main initiatives include car sharing, bike sharing, and E-hailing; algorithms-enabled ride-sharing services with fixed routes and stops to supplement existing public transit routes (demand-based microtransit); dynamic traffic lights and speed limits with priority to emergency vehicles and public buses; smart parking systems that guide drivers directly to available spaces; sensor-based monitoring of the condition of public transit and related infrastructure for predictive maintenance (IRENA, 2019c, 2019f; IRENA, 2020d; WEF, 2018; IRENA, 2021e).

Concerning health care, the main initiatives include real-time air quality information to detect and monitor the presence of indoor and outdoor air pollution; data collection, analysis, and response to prevent spread of infectious diseases, including awareness and vaccine campaigns (infectious disease surveillance); remote patient monitoring and virtual interaction through audiovisual technology.

Concerning buildings, the main initiatives involve deep energy renovation of private and public building stock by improving envelope and systems, integrating renewable energy sources (RES) and implementing building automation systems (BAS); structural and fire safety retrofit of the buildings to improve city resilience.

Concerning water, the main initiatives include remote monitoring of pipe conditions using sensors, and control of pump pressure to reduce or prevent water leakage; optimization of public irrigation using information such as local weather, soil conditions, plant type; real-time monitoring, and public alerting of water quality of rivers, lakes, and the sea.

Concerning waste, the main initiatives include digital tracking and payment for waste disposal with feedback to users to increase awareness and reduce waste; optimization of waste collection routes using sensors inside trash bins to measure trash volume and direct the routes of garbage trucks (Esmailian et al., 2018).

Finally, concerning energy, the main initiatives include smart grid technologies, including fault detection, isolation, and recovery (FDIR), Volt/Var Optimization, and substation automation to optimize energy efficiency and the stability of the power grid; dynamic adjustment of electricity prices to shave peak time demand and reduce electricity generation cost; connected energy-efficient streetlights that optimize brightness and reduce maintenance needs, equipped with speakers, environmental sensors, and other features to enhance functionality (IRENA, 2019a; 2019c; Shi et al., 2020). In particular, streetlights are uniquely positioned in the transformation of the urban environment and have been recognized as one of the most actionable and ready-to-implement SC technologies. In addition to favorable ROI for reduced energy consumption and maintenance spending, when networked they are also increasingly used as a platform for other SC applications including public safety, air quality and environmental monitoring, connectivity, EV charging, and parking (Casini, 2017).

An example is Schröder EXEDRA, a cloud-native smart lighting management tool that can remotely monitor and analyze streetlights by leveraging Azure IoT as a core platform, allowing city managers to dim the streetlight brightness according to specific needs, generate and manage maintenance tickets, easily create reports, and interact with other sensors and devices installed in public spaces. SMART.NODE is a comprehensive and self-contained smart pole solution that integrates smart LED lighting with communication, energy, environment, transport, safety, and media services. The data gathered are integrated through a central management system and analytics platform built on Azure allowing users to control, interact and analyze real-time data to enable responsive action and keep cities and public spaces efficient, and safe. Lastly, Dimonoff SCMS enables facility and site managers to automate the control, monitoring, and maintenance management of streetlights and other assets, increasing the sustainability of their infrastructure (Russom, 2020).

12.1.1 Big Data and machine learning

The huge expansion of Big Data and the evolution of AI and ML are playing an important role in the feasibility of many SC initiatives and can provide valuable insights from a considerable amount of data collected through various sources (Lima, Kimb, & Maglio, 2018). The unprecedented digitalization of human lives, where almost everything people do leaves a digital footprint, is allowing to spot patterns and relationships that were previously unknown, to predict future outcomes, allowing smarter decisions on what to do next and how to optimize city services. Urban Big Data consists in different formats, such as text, symbols, and numbers and includes photo, video, conversation, activity, text information as well as data from sensors and smart objects. All these data, appropriately collected and analyzed, can allow, through the support of AI, to produce information that can enhance different SC services and help decision makers plan for any improvement (Ahmed, 2019). Using advanced analytics and ML, various operational optimization problems can be solved and new insights for medium- and long-term strategy can be derived—such as forecasting when an asset will be available or how it should best be used to derive most benefits for citizens (Allam and Dhunny, 2019).

Main SC action areas that benefit from big data and ML include smart governance, smart mobility, health care, and smart environment. These initiatives can cover anything from power distribution, to transport systems, and even waste collection (Al Nuaimi, Al Neyadi, Mohamed, Al-Jaroodi, & Nuaimi, 2015; Allam and Dhunny, 2019).

Big Data analytics can help governments establish and implement satisfactory policies because they are already familiar with the needs of the people in terms of health, social care, education, and so on. In addition, the ratio of unemployment can also be reduced by analyzing the Big Data of different educational institutes.

Regarding mobility, the patterns obtained from the large amounts of traffic data can help improve transportation systems, for instance, minimizing traffic congestion by providing alternative routes and reducing the number of accidents by analyzing the history of mishaps, including factors such as their cause and the driver speed. Public transportation routes may be adjusted in real time according to demand, or traffic flows can be monitored and analyzed to improve congestion via intelligent traffic light systems (Zhu, Yu, Wang, Ning, & Tang, 2018). Artificial neural networks (ANNs) are the commonly used approach for the traffic flow prediction purposes (Khan, Nazir, García-Magariño, & Hussain, 2021; Ullah, Al-Turjman, Mostarda, & Gagliardi, 2020). Alibaba's City Brain system uses AI to optimize the city's infrastructure and has helped reduce traffic jams by 15% in the Chinese city of Hangzhou (Beall, 2018). Data generated by transport systems can also help optimize freight movements and consolidate shipments by reducing supply chain wastage. Smart transport data can also provide many benefits, such as reducing the environmental impact and increase safety as well as improving end-to-end user experience, among many others.

Concerning health care, proper analytics tools can allow healthcare specialists to collect and analyze patients' data, which can likewise be used by insurance agencies and administration organizations. Moreover, proper analytics of big healthcare data can help predict epidemics and diseases, as well as improve quality of life and avoid preventable deaths. Quantity and quality of information accumulated for specific patients' health issues can be increased via intelligent gadgets, which are associated with home or clinic patients to monitor behaviors and understand their records. In addition, the analytics of large amounts of healthcare data can enable doctors to detect the warning signs of serious illness during the early stage of treatment.

Regarding energy services, analytics on Big Data collected from the smart grid environment can help informed decision making in terms of the supply level of electricity while fulfilling the demands of the user, as well as to predict the need of the power supply in the future and determine pricing plans consistent with the supplies, demand, and production models. Big Data and AI also allow to improve renewable energy generation forecast, optimize energy storage operation, maintain grid stability and reliability, improve demand forecast, and optimize market design and operation (IRENA, 2019c).

Examples of Big Data and AI application in SC government are growing worldwide by the day (Kandt and Batty, 2021). The city of Vienna implemented the AI virtual assistant WienBot to help citizens with an array of operational tasks and to deliver more personalized, digital services. Available via Facebook Messenger, the chatbot provides answers to an array of user questions and continuously learns from the interactions, even preempting questions as it captures the most frequently used terms. It is expected that by 2022, 30% of customer experiences will be handled by conversational agents, up from just 3% in 2017 (Hippold, 2018). The city of Middelfart, Denmark, is collecting energy efficiency data from city properties, including information on the indoor climate, energy usage, and maintenance of the buildings. Through ML, data are analyzed to make adjustments for better energy efficiency. Mobile and broadband company Telefonica has invested in several SC initiatives in Spain: in one example, sensors-equipped waste containers can report how full they are, producing historical data which allows city officials to allocate waste collection resources more efficiently based on AI-powered predictions; in Valencia, sensors in parking spaces help monitor capacity and give officials real-time data on the density of parking across the city, which can then be modeled into AI traffic predictions. The Amsterdam SC initiative, which began in 2009, spans over 170 projects designed to improve the city's real-time decision-making, including smart streetlamps that can be dimmed according to pedestrian usage, traffic sensors, and domestic smart energy meters, producing a plethora of useful data to organize several city services. Milton Keynes (UK) is working with more than 40 partners on SC initiatives, including monitoring traffic and football through public spaces in order to plan public transport routes, footpaths, and cycle paths.

A particularly relevant application of AI and ML in SC is to predict flooding, which is the most common type of natural disaster worldwide, affecting tens of millions of people around the world each year and causing, on average, more than \$200 billion in damages. In 2020 the city of Cary (United States) introduced a flood prediction system based on water level sensors at various points along stream basins and rain gauges at several owned facilities. Leveraging AI services such as Azure IoT and SAS Analytics for IoT, the system allows to visualize flooding events in real-time, to issue notifications and generate work orders to stormwater personnel automatically and to share data with regional partners. AI analytics on collected and historical data are then used to model a predictive flood detection and management solution to better identify anomalies, such as rising water, through the integration of weather forecasting data, real-time sensor data measuring water and rain levels to deliver advanced warnings and forecast of flooding events both within the town of Cary and downstream to surrounding municipalities.

12.1.2 Smart city digital twin

As urbanization continues to take hold and cities face challenges to become more sustainable and livable, urban planning and operations strategies must adapt. Recent events such as the COVID-19 pandemic or increasing extreme weather phenomena have been progressively questioning the way we live, accelerating cities' future vision as a necessity of the present, and what it means to live in a connected and resilient urban environment. Both public and private organizations are coming together to push transformative solutions and change the way infrastructure and urban environments are planned and operated. To unlock their full economic, social, environmental, and business value, cities need to use digital technologies to transform and interconnect key areas of their ecosystem—from roads to cars, buildings to energy grids, citizens to government, and cities to cities (ECISO, 2021; JRC, 2019a; WEF, 2021). Technology innovations in IoT, AI, and DT are enabling connected solutions that can provide breakthrough insights in urban planning and management (Deng, Zhang, & Shen, 2021). By modeling the complex and high-value interactions between people, places, and things in the city, it is possible to unlock new opportunities, create new efficiencies and improve both public and private spaces.

With increasingly large and accurate building information models (BIM) combined with big data generated from IoT sensors in a SC, included data from geographic information systems (GIS), satellites, drones, and other sources, it is now possible to create city-wide DTs that can be used to model urban planning and policy decisions.

The DT is a pairing of the virtual and physical worlds that allows for analysis of data and monitoring of systems to predict events before they occur, and for simulations to plan future actions (see Section 11.4). Planners and engineers can study the city's DT and gain insights for improving services, planning developments, optimizing city's systems, and monitoring traffic flow. Designers can simulate ideas in the live, virtual city environment before they are constructed and understand in advance the impact of decisions such as where to position a bus stop, or the footprint of a new housing development.

SC DTs are still in their infancy, but their potential to transform our urban landscapes is remarkable. With the rise of augmented analytics powered by AI and ML, smart cities with autonomous decision-making capabilities are becoming a reality, and several municipalities are currently investing in virtual replicas of themselves. Worldwide, the market for digital-twin-supported solutions in smart cities is projected to reach US\$3.77 billion by 2026 (Digital Twins Market by Technology, 2021), with more than 500 SC DTs in operation expected by 2025 (Digital Twins, Smart cities, and Urban Modeling, 2019).

A DT model of the SC builds normally on five main layers of information (White, Zink, Codeca, & Clarke, 2021).

These contain, respectively, information about the terrain, the buildings, the infrastructure, the mobility, and IoT devices and sensors (SC DT).

The terrain layer contains the basic information about the city, such as what part of the city is offshore, where rivers or canals run through the city, where steep gradients or hills are, what part of the city is made of sand, which has fertile soil that can be used to grow crops, which has soil with poor draining that can cause landslides or flooding. The buildings layer adds current buildings in the city, made from BIM models, on top of the terrain layer. The infrastructure layer integrates the basic physical and organizational structures and facilities (e.g., roads, power supplies, telecommunication) needed for the operation of the city. The mobility layer contains information about the movement of people during their daily routines and the movement of the goods that help them in different aspects of their lives. The sensors layer contains data coming from real time monitoring of traffic and transportation systems, power plants, utilities, water supply networks, waste management, information systems, schools, libraries, hospitals, and other community services.

Together, these five layers represent the DT of the city, with its physical assets and real-time data on its operation. The integration of information on buildings, transport, parks, drainage, and more, enables city operators to monitor everything from traffic building operations to bridge maintenance, and even to simulate floods for disaster planning (White et al., 2021).

Within the DT, ML algorithms can be used to identify the best action policies to improve performance in a number of urban intelligence tasks, such as managing traffic and power systems. In addition to improving city management, the DT and its wealth of data can be transferred to a virtual layer where accurate simulations can be performed on a number of what-if scenarios starting from real time or predicted conditions, concerning mobility optimization, building placement or the design of renewable energy such as offshore wind turbines, landscaping and urban planning, flood, and crowd control. Simulated actions can then be fed back through the layers of the DT model where they are implemented in the physical world.

For instance, the DT virtual layer can be used to aid with the planning of buildings in the city. Using data collected in the DT, simulations can be created in the virtual layer to evaluate the city's response to the introduction of new

buildings in terms of skyline, traffic, utility grids, etc. Any proposed building plans can easily be added to the DT using their BIM model, allowing public officials and citizens to walk around the DT and see the impact that the new building would have on the skyline from different locations. Sunlight information from the SC could be combined with the BIM file of the new building to simulate the effect that a large structure would have on the sunlight access of nearby parks or public spaces, or how they would affect traffic and public transport.

The DT model can also allow for development of parks and recreational spaces in suitable areas of the city. Data from the sensors, such as air pollution, noise pollution, pedestrian traffic flow, and amount of direct sunlight, can be used to influence urban planning decisions of where to place these green spaces in the city.

DT can also help to address climate change issues and improve the resilience of cities. With DT is possible to simulate flood scenarios, highlighting the areas that would first be affected by a river flooding its banks or by heavy rain to decide where to deploy sandbags and what areas of the city to evacuate first. Data from the SC about rainfall amount and river levels can be fed to the DT, along with currents, materials in the riverbeds, sewage, and drainage systems, to determine a timeline of when flooding could occur and alert citizens accordingly. The historical data collected from the SC can then be used to create longer term flood prevention mechanisms to program large-scale projects, such as introducing water storage areas or diverting rivers. The simulation is able to identify roads and walkways that would become inaccessible to vehicles and pedestrians in a flood, which would alter the movement patterns in the city.

Several software platforms are available to develop SC DTs, often building on established DT tools from other industry sectors (see [Section 11.4.1](#)). Azure Digital Twins platform, for instance, starting from 2020 has enabled modeling and creating digital representations of connected environments like buildings, factories, farms, energy networks, railways, stadiums, and cities, then bringing these entities to life with a live execution environment that integrates IoT and other data sources. Furthermore, to enable urban experiences that are geospatially aware, Azure Maps provides several geospatial services including access to real-time traffic, public transit, and weather data. To drive openness and interoperability, Azure DTs are represented with an open modeling language, DT Definition Language (DTDL), which provides flexibility, ease of use, and integration into the rest of the Azure platform. Using DTDL, developers can describe DTs in terms of the telemetry they emit, the properties they report or synchronize and the commands they respond to, as well as the relationship between the digital and real twins. Although DTDL allows to model DT ontologies for places, infrastructure, and assets as desired, several premade ontologies are available, dedicated to the SC domain, to allow to jump-start and accelerate DT development without redeveloping the entire model. These open-source ontologies provide common ground for modeling connected environments, accelerate developers' time to results, and enable interoperability between DTDL-based solutions from different solution providers.

SC-specific ontologies include Saref4City, CityGML, ISO, and European Telecommunications Standards Institute (ETSI) NGSI-LD, among others. The latter was ported to DTDL in 2021 by a partnership between Microsoft, OASC and Sirus, providing an open framework for context information exchange, which comes with an information model that defines the meaning of the most needed terms, and a domain-specific extension to model any information. The core NGSI-LD meta-model provides a basis for representing property graphs using RDF/RDFS/OWL and is formed of entities, relationships, and properties with values. In addition to the core meta-model, NGSI-LD compliant open models for several aspects of smart cities have been defined by organizations and projects, including OASC, FIWARE, GSMA, and the Synchronicity project, and comprise models in the domains of mobility, environment, waste, parking, building, park, port, etc. Most models available focus on use cases that are increasingly relevant to cities given the availability of IoT devices and sensors, such as measuring air quality in a neighborhood, noise level in a district, crowd flows or traffic flows in a road segment, monitoring on-street parking and availability of EV-Charging, as well as enabling streetlight infrastructure for additional citizen-centric services. In addition to the ETSI NGSI-LD, the ETSI SAREF extension for smart cities ontology framework can be leveraged for topology, administrative area and city object modeling. Energy grid ontologies are also expected to be available in the next future.

Available SC DT programs differ in terms of potential and application areas. Siemens MindSphere City Graph is a solution to optimize city operations that uses Azure DT and the open DTDL language to build digital models of entire environments within an urban space and bring these DTs in a live execution environment with integration of real-time data. The first deployment has been successfully rolled out in Aspern, Wien, within the Aspern Smart City Research (ASCR) by Siemens Advanta, with focus on the improved forecasting of the charging demand of eCars and the understanding of their impact on the energy infrastructure.

Bentley's iTwin platform, along with the OpenCities Planner tool, can ingest geometry and metadata of a project and its environment, allow reality modeling at the urban scale and integrate real-time IoT data into a city-wide DT, enabling users to visualize operational data, time-series data, and analytics in contextual 3D and 4D models and to perform 3D spatial analysis during all the stages of infrastructure lifecycle at a city level. These programs have been

successfully deployed in the city of Gothenburg, Sweden, where a city-scale DT was created and made available to citizens and stakeholders as a simulation and dialog platform for urban planning, resulting in the city being listed in second place in the global ranking of smart cities in 2019 by the Future Today Institute.

One of the first main examples of a DT of a city is Virtual Singapore, which is a three-dimensional (3D) city model and data platform codeveloped with the French firm Dassault Systemes (see Fig. 12.2). This DT gathers information about demographics, climate, land use, traffic, public transport, and building infrastructure that is used by city planners to prototype and deploy their work, showing how government actions affect the city systems and the lives of people they depend upon. The Virtual Singapore platform is used by urban planners to test solutions in a virtual environment with remarkable benefits, including: (1) providing a bird's eye view of the city, (2) enabling virtual experiments to optimize related measures, (3) optimizing long-term planning and decision making, and (4) supporting large-scale simulations. The tool is used for improving accessibility, simulating emergencies in shopping areas or stadiums, deciding on the placement of facilities, such as foot bridges, and monitoring the value of green or sustainability initiatives, such as solar panels and cycle routes.

In 2020 51World created a complete virtual clone of the city of Shanghai in Unreal Engine, encompassing 3750 km². The company individually modeled over 20 landmark structures, and used data from satellites, drones, and sensors to generate digital versions of remaining buildings, roads, waterways, and green spaces. This model is planned to turn into a true DT that will be continuously updated in near real time.

Virtual Helsinki, a digital replica of the Finnish capital created by VR studio ZOAN, is being used for the promotion of tourism and virtual real estate tours (see Fig. 12.3). 3D studio Buildmedia has used Unreal Engine to develop an GIS-accurate model of Wellington, NZ, which is planned to integrate live SC data to create a DT useful for government action.

The city of Amaravati, India, new capital of Andhra Pradesh, is a US\$ 6.5-billion SC created using a DT that integrates more than 1000 datasets that manage the permitting process, monitor construction progress, and evaluate design plans for success in the city's extreme climate.

Cityzenith developed a "5D smart world platform" for city management which integrates digital images with available datasets and overlaid IoT networks with contextual data schema to create a virtual representation for an entire city. At present, the platform has been used in over 100 cities, including Chicago, London, Doha, and others.



FIGURE 12.2 Virtual Singapore Digital Twin. Credit: National Research Foundation (NRF), Prime Minister's Office, Singapore.

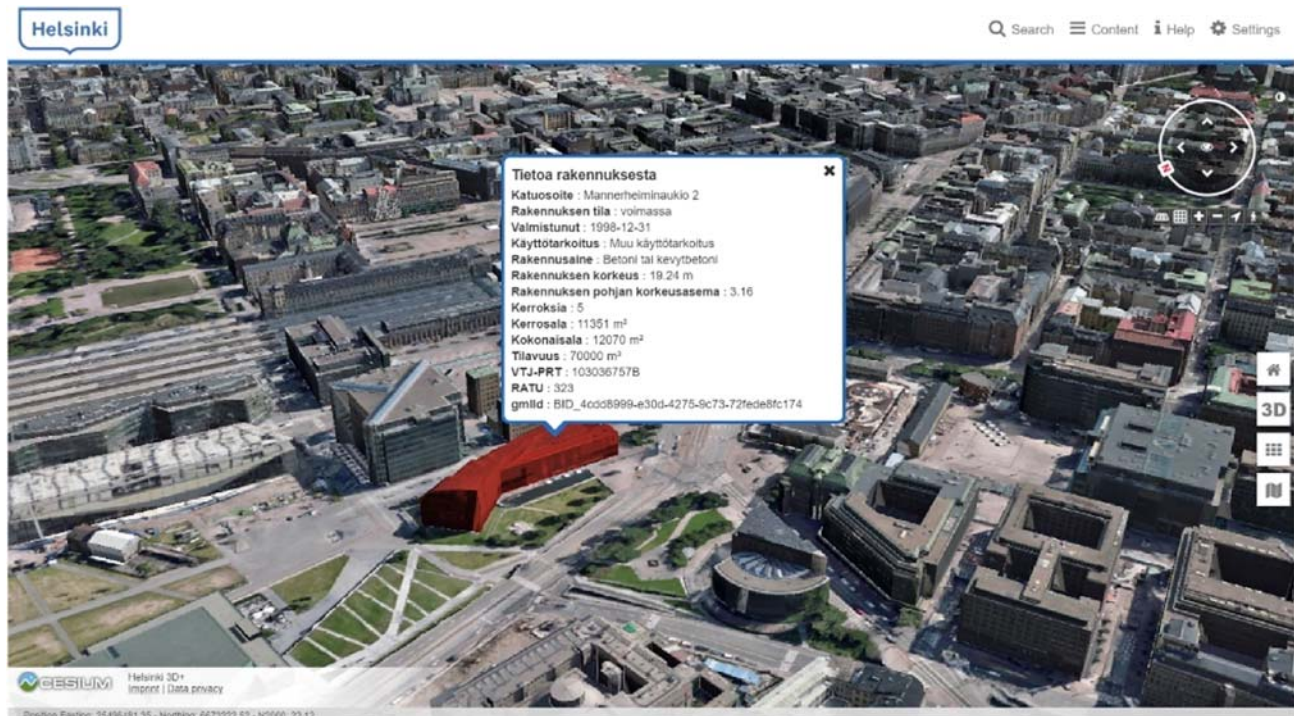


FIGURE 12.3 Virtual Helsinki Digital Twin (Helsinki city information model). <https://kartta.hel.fi/3d/#/>. (Accessed 10 June 2021).

The Cambridge Centre for Smart Infrastructure and Construction, supported by The Ove Arup Foundation, is currently developing a DT pilot project for the Cambridge subregion in collaboration with local authorities. This will test how isolated policies from transport, housing, environment, and energy can be bridged using the DT, and quantify some of the interdependencies among transport, air quality, housing, and energy infrastructure in relation to changes and uncertainties. Moreover, the work will test how the DT can be combined into the workflows of the local authorities and used with other models.

On an even larger scale, DT concepts can be used to model whole geographic ecosystems for the purposes of predicting and reacting to natural disasters: satellite imagery, weather stations, calls to emergency services, and social media data can be processed to react to incoming threats such as hurricanes, tsunamis, or forest fires. SkyAlert is a system used in Mexico that monitors custom-made sensors to give citizens up to two minutes' advance warnings that an earthquake is likely to strike.

12.2 Smart energy infrastructure

To shift toward a net zero carbon future, smart cities must develop an integrated energy system by focusing on three main areas (IEA, 2017, 2021; IRENA, 2019j; 2019l; IRENA, 2021c; 2021d; 2021e; JRC, 2019a; WEF, 2021):

- clean electrification of transport and building services (heating and cooling, lighting and home appliances) backed by zero carbon energy (WEF, 2018; IRENA, 2019j; IRENA, IEA, REN21, 2020);
- highly-efficient and connected building stock that combines passive strategies and high-performance and low-carbon buildings materials with distributed energy sharing and intelligent management systems (IRENA, 2021c);
- smart energy infrastructure, fully integrated with e-mobility charging stations, to seamlessly facilitate interactions between energy infrastructure, buildings and electric vehicles (EVs) and to ensure a cost-effective and secure electricity distribution grid (IRENA, 2019a; 2019j; 2019k; IRENA, 2021d).

A main characteristic of this smart energy infrastructure is flexibility, which in turn is based on five key technical options: supply-side flexibility (e.g., new flexible power plants), demand-side flexibility (e.g., sector coupling), flexibility from storage (e.g., batteries), grid infrastructure (e.g., transmission expansion), and improved operation (e.g., more efficient hydro-thermal co-optimization) (IRENA, 2019a; IRENA, 2021d). In particular, electricity storage has the

potential of greatly improving system wide operation of the energy infrastructure. As battery technology is becoming increasingly affordable, domestic users, especially households with solar PV systems, are installing batteries at scale, while distribution grid operators are turning to midscale batteries to avoid network upgrades, and power-to-X applications are emerging that support sector coupling (power-to-heat and power-to-hydrogen), with great potential to store energy in different forms (IRENA, 2019j).

Advanced metering infrastructure (smart meters) will be required throughout public and private services to implement demand optimization and efficiency improvements. Building automation and energy management systems will be able to react to signals from the grid, such as energy and water prices. Electricity, gas, and water readings will join data collected from street lighting, waste management, parking lots, and other IoT applications, to be integrated and cross-analyzed in shared data platforms. Various studies have confirmed the economic benefits of active network management: in particular, active RES integration is very competitive compared to an otherwise necessary grid expansion, with savings of 40% (IRENA, 2019j; JRC, 2019a).

Smart grids are the new generation of energy distribution and transmission infrastructure and are natively designed or retrofitted to best adapt to the specific needs of contemporary and future energy markets. These combine the traditional elements of energy grids, such as central power plants, with the new technologies that include renewable energy, utility-scale batteries, distributed energy generation, multiple sectors coupling, and smart meters. A smart grid is characterized by a high degree of flexibility in managing energy flows to and from consumers, which is largely allowed by extensive digitalization and also opens new market and business possibilities.

Micro-grids are a particular application of Smart Grids which consist in integrated energy infrastructures that combine energy production, mostly with distributed renewable resources, and energy consumption and are designed to be able to operate on a self-sustainable basis. They rely on RES generation, intelligent switching and protection, controllers and energy storage. When connected to the main Smart grid, micro-grids can improve its flexibility by providing frequency response, reduced grid congestion, and load management.

In this picture, interoperability between technologies and communication protocols will be essential, as one of the key challenges is the continuous transformation of collected data into knowledge useful for citizens and municipal officers to inform better decisions, such as where to invest in new energy infrastructure or when to schedule smart appliances. Interoperability is also particularly delicate in the energy sector since any operational, architectural, and functional failure will have high costs due to the scale of the power system and its economy. The ETSI defines four types of interoperability: technical interoperability, defined as a state that involves hardware and software components which enable communication between infrastructures; syntactic interoperability, which concerns data formats and the way the messages that need to be transferred are formed, semantic interoperability, that ensures that the information received is interpreted correctly by all the applications involved; and organizational interoperability, which deals with the ability of organizations to communicate and exchange useful data (JRC, 2019a).

In addition to promoting technologies such as distributed energy resources (DERs) and BAS, a smart EV charging infrastructure should be deployed and fully integrated with the electricity grid, to exploit the flexibility provided by EVs while ensuring the stability of the energy system. On the one hand, in fact, as the number of circulating EVs grows their charging patterns may disrupt the operation of distribution grids, creating rapid surges in power demand and leading to high grid congestion. On the other hand, connected EVs can provide additional storage capacity and services to the grid and buildings, enabling system cost savings and an easier integration of higher shares of variable renewable energy. Indeed, as with other cars, EVs typically spend around 95% of their lifetime parked, potentially making each of them a grid-connected energy storage unit that provides an attractive flexibility solution for the power system while at the same time reducing the peak load compared to what otherwise would be, as well as reducing the cost for charging. According to IRENA, smart charging can significantly reduce the peak load and therefore avoid grid reinforcements, at a cost of only 10% of the total cost of reinforcing the grid (IRENA, 2019j; 2019k).

Among these enabling technologies (see Table 12.1), digital technologies such as IoT, AI and Big Data, and blockchain are supporting to a significant extent the transformation of the power sector in several ways, including: better energy monitoring of assets and their performance; more granular, real-time management and control; implementation of new market opportunities as well as disrupting business models (see Table 12.2). Indeed, digitalization is a key amplifier of the evolution of the energy sector, as it enables the management of large amounts of data, the optimization of systems with many small generation units, enhanced communication and control and, in the future, automated smart contracts based on blockchain technology.

In addition to unlocking multiple new energy services, distributed generation and enabling technologies can be sources of valuable data. Detailed, real-time information on consumer patterns, load profiles, performance of components in electricity systems, failures and malfunctions become knowledge for better planning and system operation. The

TABLE 12.1 Enabling technology innovations in the power sector.

Innovation area	Technologies
Electricity storage	Utility-scale batteries Behind-the-meter (BTM) batteries
Electrification of end use sectors	EV smart charging Renewable power-to-heat Renewable power-to-hydrogen
Digital technologies	IoT AI and Big Data Blockchain
New grids	Smart grids Microgrids

BTM, Behind-the-meter; *EV*, Electric-vehicle; *IoT*, Internet of things; *AI*, Artificial intelligence.

TABLE 12.2 Emerging digital applications in the power system.

	Energy generation	Energy transmission	Energy distribution	Energy consumption
Current level of digitalization	Early stage	Advanced	Early stage	Early stage
Envisioned steps	Updating power plants, automatic grid control	Advanced algorithms for optimized operation	Full automation for grid stability, optimization	Fast-acting aggregated demand response, virtual power plants
Digital applications	Predictive maintenance Renewable energy forecasting and trading Enhanced flexibility through automation control	Predictive maintenance Maintain grid stability and reliability	Predictive maintenance Maintain grid stability and reliability Managing distributed energy resources assets for balancing the grid	Microgrids operation, peer-to-peer transactions Demand-side management

study of historical energy load patterns and behaviors also enhances the forecasting of electricity production and consumption by distributed sources. These features can reduce the uncertainty and risks associated with a higher share of variable renewable energy sources and promote their adoption without increasing the operation costs.

It is evident that the growing decentralization of generation through RES and the possibilities enabled by digital technologies are reshaping the dynamics between the physical energy system, typically operated by utilities, and the energy consumers, blurring the conventional boundary between energy production and consumption. Furthermore, innovative solutions that combine new business models built on such technologies, together with new regulations and innovative system operation practices for distribution grids, have offered cities a unique opportunity to revisit their relationship with the national energy system, both technically and institutionally. Whereas the conventional model had utilities supplying energy or fuel and customers sending back payments, with only a small amount of information exchange, today much more dynamic business models are possible. Energy, payments, and information can flow in all directions through buildings, transport, and the grid, enabling more robust demand response (DR) programs, time-of-use (TOU) and locational pricing, and energy storage services (IRENA, 2019j).

The increasing digitalization, decentralization, and electrification of the whole energy sector are contributing to the expanding notion and practice of the prosumer, that is, an user that is both a consumer and a producer of energy, typically using smaller PV systems to generate electricity. Self-production of energy by prosumers has the potential to

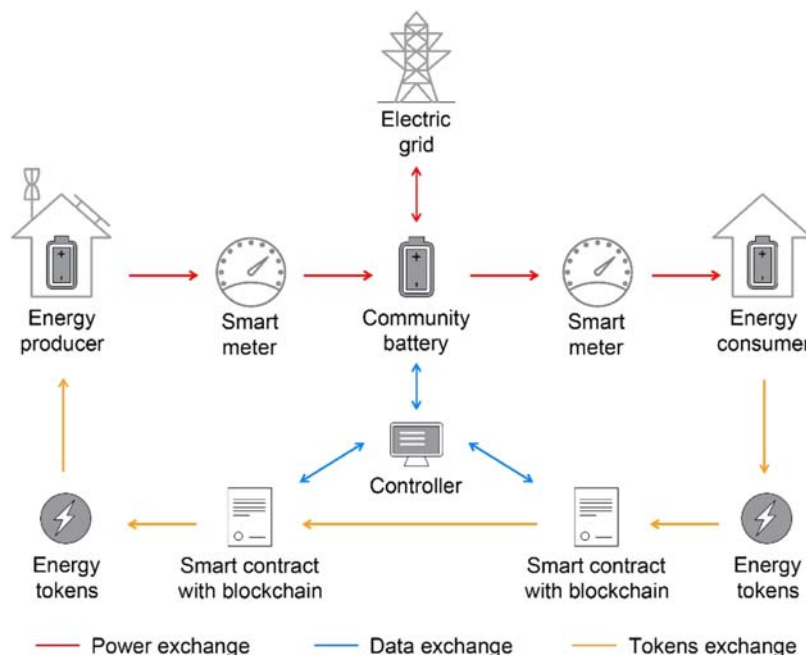
complement the traditional role of utilities, unlocking system flexibility for a high share of renewable energy penetration but at the same time requiring the regulatory regime to reconcile this broader range of participants in future regulatory and market designs. Other new emerging actors are the aggregators, which bundle several DERs, including prosumers, into a virtual power plant qualified to trade in wholesale power or service markets. Main new prosumer business models, enabled by smart meters and digitalization, include (IRENA, 2019a; 2019d; 2019h; IRENA, 2019j):

- peer-to-peer trading platforms, which operate similarly to resource-sharing platforms such as Uber or Airbnb by create an online marketplace for energy where consumers and distributed energy suppliers make peer-to-peer transactions;
- energy-as-a-service model, which refers to the shift from selling kWh to selling services to customers, such as demand management, support for customers with decentralized generation and energy storage, exchange of electricity via local networks, advice on energy savings, comfort and security-enhancing measures, and other different services;
- pay-as-you-go models, facilitated by mobile payment technologies that are easily accessible in remote areas, which make distributed electricity generators (e.g., rooftop PV) affordable for the end-user who pays directly for the service they use, often in the form of a package of appliances and the associated power supply, instead of regular, fixed payments, making renewable energy accessible even in off-grid areas;
- community-ownership models, in which energy-related assets are collectively owned and managed, allowing members of a community to share the benefits of a renewable power plant even if they cannot, or prefer not to, install the power plant on their own property.

Another innovative solution that may be highly relevant for cities is the creation of local flexibility markets: in these, utility operators can acquire flexibility from an online marketplace that brings together all resources available at the distribution level. Ongoing initiatives are being piloted in the UK and Germany by various stakeholders (IRENA, 2019j).

Particularly interesting, and exemplary of the potential disruption brought by distributed renewables and new digital instruments such as blockchain, is the microgeneration community model (see Fig. 12.4) (IRENA, 2019e). Traditionally, microgeneration, that is, the capacity of prosumers to produce electrical energy in-house or in a local community, has had little access to the energy market, which remains a privileged playing field for the incumbent energy suppliers. This has impacted heavily on the real large-scale diffusion of micro-generation due to the limited economic advantages this energy generation approach brings to prosumers. In the microgeneration community model, market mediation takes place in a central-to-the-neighborhood energy storage via blockchain-connected smart contracts (see Section 9.1.5). The energy is sent there from the producer and is stored until a consumer claims it. When energy is

FIGURE 12.4 Microgeneration community model.



sent to the central storage, a smart meter linked to each producer continuously measures how much energy has been injected, awarding virtual energy coins to the corresponding prosumer after a predefined amount of energy has been sent to the storage. Conversely, the grid's smart contract takes energy coins as input and then releases the energy that corresponds to the payment made by the sender. Such system allows federated prosumers to produce energy, store it for local energy consumption, release excess energy to the grid and receive virtual coins in return, transfer these virtual coins or redeem them in exchange for energy with the grid or within the community itself. The use of the blockchain ensures that smart meters and the electrical grid are considered trusted parties and that the agreements for the generation and redemption of energy coins are transparent and can be verified by any interested party (JRC, 2019a).

Lastly, the integration of AI and ML into smart grid management systems offers a promising opportunity to maximize the efficiency of increasingly digitalized energy systems and the market, characterized by high shares of variable energy sources dynamically linked with energy storage systems and other sector-coupling technologies. However, to implement concrete innovative solutions, the deployment of smart energy infrastructures must be complemented with the update of current market design and regulation, as well as smart grid protocols for interoperability between assets and systems (IRENA, 2019c; 2019j; JRC, 2019a).

12.2.1 Smart grids

Over the last twenty years, the current centralized model of energy production and distribution has proven unable to efficiently and effectively meet the new needs for growth and flexibility in energy demand, service reliability, and integration of RES and of EV charging systems. Electricity uses are in fact undergoing profound and rapid changes. Some, already existing, have taken a considerable growth. Others, such as EVs and heat pumps, are rising sharply (Ourahou, Ayirir, Hassouni, & Haddi, 2020) (see Section 1.2). At the same time, the power sector is facing a major transformation with the increased deployment of variable renewable energy (VRE) technologies (solar PV and wind in particular) that provide intermittent energy supply, DERs, bidirectional flow of electricity, increased use of energy storage, and an evolving role of utilities and consumers (IRENA, 2019a). The major demand of consumers in all the residential, commercial and industrial sectors, has led over the years to an over dimensioned and unoptimized energy system in which 20% of the power generation capacity is latently available to meet a peak demand that occurs only for around 5% of the time (Haider et al., 2016). Moreover, this grid redundancy did not translate into a greater reliability and quality of power supply able of maintaining always a constant voltage and avoiding blackouts at local and large scale. Furthermore, the massive integration of RES on power grids, necessary for a fast transition to a low-carbon and climate-resilient economy, poses technical problems, particularly for grid operators. A first issue concerns that the insertion of decentralized production leads to the bidirectional operation of networks traditionally designed to carry energy only in one direction. Indeed, current network infrastructure is not built to allow for many distributed feed-in points, and typically even if some feed-in is allowed at the local (distribution) level, the transmission-level infrastructure cannot accommodate it. A second aspect concerns the imbalances in the network caused by the progressive increase in the penetration rate of RES. Rapid fluctuations in distributed generation, such as due to cloudy or gusty weather, present significant challenges to power engineers who need to ensure stable power levels through varying the output of the more dispatchable generators such as gas turbines and hydroelectric generators. To cope with these emerging challenges and to guarantee the efficient functioning of the network, it is necessary to implement new “smart electricity grids”, that can intelligently integrate the actions of all users connected to it: generators, consumers and prosumers that do both (see Table 12.3).

TABLE 12.3 Expected structural changes in the energy system made possible by digitalization (IRENA, 2019j).

Energy system	Yesterday	Tomorrow
Production	Few large power plants	Many small power producers from renewables
Market	Centralized, mostly national	Decentralized, ignoring boundaries
Transmission	Based on large power lines and pipelines	Including small scale transmission and regional supply compensation
Distribution	Top to bottom	Both directions
Consumer	Passive, only paying	Active, participating in the system

A smart grid can be defined as the integration of an electrical distribution network and an information network, with the goal to guarantee an intelligent electricity transmission able to ensure an economically efficient, sustainable and reliable power system with low losses and high levels of quality and security of supply. In particular, a smart grid employs innovative products and services together with intelligent monitoring, control, communication, and self-healing technologies in order to: better facilitate the connection and operation of generators of all sizes and technologies; allow consumers to play a part in optimizing the operation of the system; provide consumers with greater information and options for how they use their supply; deploy and integrate DERs, including RES, significantly reducing the environmental impact of the whole electricity supply system; meet the future demand growth and improve the existing levels of system reliability, quality and security of supply.

A smart grid consists in several components that allow for a two-way flow of information and electricity and for advanced operation and management, which include smart technologies for metering, communications (concerning grid operations and status), and distribution automation, smart appliances and consumer devices, renewable energy resources, electricity storage facilities and peak-shaving technologies, including plug-in electric and hybrid vehicles, and thermal storage air conditioning (Dileep, 2020) (see Table 12.4).

Designing a smart grid envisages the application of digital processing and communications to the power grid (the digital layer), making data flow and information management central to its operation, and entails a transformation of the distribution model (from centralized to decentralized) and of the business process. The ICT infrastructure can be an ad hoc network (fiber optics, GPRS, etc.) or use the electrical grid itself to collect data from sensors installed therein and convey information (e.g. powerline technology). Smart grid set-up requires pervasive devices to monitor, examine and control the overall grid, where differing types of sensors and meters are deployed at power plants, transmission junctions, distribution areas and finally at the users side. As such, the utmost concern for smart grids is connecting the devices, controlling them at high speeds and finally monitoring their data feed in a continuous fashion. Technologies like IoT and 5G have enabled the rapid development of smart grids as most of the information is usually stored and processed on cloud servers. ML techniques can be used to obtain and predict information related to price fluctuation, load forecasting, failure detection and cyber-attacks (IRENA, 2019c; Reka & Dragicevic, 2018; Shi et al., 2020). In particular, AI tools can be employed to assess the security of the smart grid, that is, the degree of risk in a power system's ability to survive imminent disturbance (contingencies) without interruption to customer service, and to assess and predict its stability, that is, its ability to maintain synchronisms with connected machines, steady voltages at all buses, and constant frequency even after being subjected to a system upset. Once the future outcome is successfully predicted, the smart grid itself can react preemptively to minimize repercussions of any disturbance on connected services, or, if the preventive actions have not been successful, deploy emergency measures such as load shedding, generator tripping, or controlled system splitting to restore the system to a secure state. Concerning fault detection, classification and location, conventional methods based on traveling wave and impedance models are ill suited for smart grids strongly characterized by DERs and VREs, whereas AI-based algorithms can obtain satisfactory performance if trained with data of sufficient quality and quantity.

Concerning the business model, the smart grid opens the possibility for prosumers who produce their own energy and for citizen energy communities to respond to energy prices when buying and selling back to the grid, and enables new market actors, such as aggregators and energy service companies, to offer new types of services to consumers to adjust their consumption and exploit this new flexibility. Overall, the development and adoption of smart grids is expected to progressively shift the energy supply industry from being infrastructure-driven to being more and more service-driven (Niesten & Alkemade, 2016). On the consumer side, in order to take full advantage of the opportunities provided by the smart grid, building energy systems shall be integrated with advanced management infrastructures to obtain Smart Grid Optimized Buildings (SGOBs). A SGOB is different from zero energy or low carbon buildings, as its design and features prioritize the techno-economical optimization of bidirectional power exchange with the smart grid,

TABLE 12.4 Digitalization of the energy value chain (IRENA, 2019j).

Generation	Transmission and distribution	Consumption
RE generation forecast Automated control of power plants Optimized market design and operation	Maintain grid stability and reliability Optimized energy storage operation Optimized market design and operation	Aggregation and control of DERs Automation of demand-side management Operation of connected mini-grids Optimized market design and operation

rather than the sole energy efficiency and energy savings, with a heavy focus on energy storage systems (Andreas, 2018). In this picture, two key elements for accomplishing a fully realized integration between SGOBs and the smart grid are the adoption of smart meters and the deployment of micro-grid technologies.

12.2.2 Smart meters

A smart meter is an electronic system capable of measuring electricity either consumed from the grid or fed into the grid, and of providing more information than conventional meters. Using a form of electronic communication, such system is capable of transmitting and receiving data for information, monitoring, and control purpose and enables a range of benefits for both the energy system and its end-users, who to-date have been passive actors in the electricity system. Smart meters allow introduction of new services permitting greater involvement of consumers, who have begun to take on an important role in the use and management of energy (Avancini et al., 2019).

First and foremost, better informed users are likely to modify their behavior to reduce their consumption, thus contributing to the promotion of a more responsible use of energy (Batalla-Bejerano, Trujillo-Baute, & Villa-Arrieta, 2020).

Secondly, for consumers who wish to be more actively involved in the electricity market, on their own or with the help of a service company, smart meters allow to adapt their energy usage to different energy prices throughout the day, shifting consumption toward lower price periods, and saving money on their energy bills. However, historically passive users are often beholden to rigid daily routines and may struggle to shift demand considerably, rendering any increase in energy plan options welfare-neutral, at least in the short run (Gosnell & McCoy, 2019).

Thirdly, smart meters are also relevant for users who generate their own electricity, typically from on-site RES or combined heat and power (CHP) facilities, allowing them to measure the electricity their building supplies to the grid and communicate this supply to the grid manager automatically.

Finally, smart metering gives network operators informed insight on the state of that part of the grid, allowing them to better plan their investments and manage their infrastructure to respond to the requirements of their customers and therefore reduce the costs for the network operation and maintenance.

Smart meters adoption has been promoted by several national and local administrations worldwide, with substantial penetration achieved in key markets such as the United States and the EU. In 2019 United States electric utilities had about 94.8 million smart metering installations, of which 88% were residential customer installations (US Energy Information Administration, 2020). In the EU, 123 million smart meters are expected to be installed by 2020, corresponding to a 43% penetration rate, with 2030 projections reaching 266 million units and a 92% penetration rate. To date, smart meters have proven a convenient and effective solution, with an average cost of €180-€200 and savings of €270 on average for electricity per metering point (distributed amongst consumers, suppliers, distribution system operators, etc.), as well as an average energy saving of at least 2% and as high as 10% based on data coming from pilot projects (Tounquet and Alaton, 2020).

Smart meters are also known as two-way or AMI (advanced metering infrastructure) meters and represent a substantial evolution from conventional one-way or AMR (automated meter reading) meters, which only allow utilities to automatically read customers' consumption for billing.

Smart meters must be equipped with the right functionalities, as given for instance in the Electricity Directive (EU) 2019/944, which shall include accurate measurement of actual electricity consumption and of electricity fed into the grid from the active customers' premises, provision to final customers of information on actual time of use, availability of validated historical consumption data through a standardized interface or through remote access, in order to support automated energy efficiency programmes, DR, and other services. Connectivity is therefore a critical technology to communicate the information collected by the smart meter to the operator's location (head-end network): applied technologies mainly employ power line communication (PLC), ethernet or wireless networks. Several smart meters may be part of the same local area network, connected through a single hub to an interface display in addition to the head-end. Additionally, the local area network can also allow HVAC systems and appliances to communicate to the smart meter, and from there to the utility operator itself, although the several standards currently in place still hinder interoperability.

12.2.3 Microgrids

The microgrid is a further development of the decentralized smart grid and consists in a smaller, more localized infrastructure which brings energy sources closer to where the energy is being used, improving the overall efficiency of the power system by reducing distribution energy losses (IRENA, 2019h). A microgrid can be summarized as a low-voltage energy distribution system which acts as a single controllable entity with respect to the main grid and is

characterized by the presence of DERs, flexible loads, and energy storage devices (Saleh, Esa, & Mohamed, 2019). Typically, microgrids are employed in remote, off-grid locations where connection to the main grid is unfeasible, in which they always operate independently (island mode), although recent examples of microgrid application include hospitals, universities, data centers, military bases and airports to aggregate on-site generation, often using CHP, and localized loads. Housing communities are also deploying microgrids to share distributed renewable energy sources and energy storage facilities among users, involving up to thousands of households (Alilou, Tousi, & Shayeghi, 2020).

Grid-connected microgrids have been indicated as an economically convenient solution with several cost advantages, mainly related to the following factors:

- possibility of enabling demand-response strategies, wherein the microgrid adapts its exchanges with the main grid based on instructions or incentives from the utility;
- possibility of selling the electricity generated within the microgrid to the main grid;
- establishment of local energy markets between different connected microgrids to leverage and compensate each other's DER and energy storage facilities;
- increased energy resiliency, as power generation and storage within the microgrid allow redundancy and backup power in case of electricity outages (Stadler et al., 2016).

Concerning the latter, in fact, one of the main advantages of microgrids is the capability to operate not only while connected to the main grid, but also when disconnected in case of blackout or scheduled power interruption, in an islanded mode (Saleh, Althaibani, Esa, Mhandi, & Mohamed, 2015). This is allowed by an independent microgrid controller which monitors the status of the point of common coupling (PCC), where the main grid and microgrid connect, and isolates the microgrid when a power disturbance occurs in the main grid ensuring smooth transition between the two modes with minimal load disruption under intentional and unintentional conditions.

Power generation in these microgrids is often dominated by renewable DER, which is volatile and non-dispatchable by nature; therefore, proper control, relaying, and protection are required to ensure sufficient power quality. While grid-connected, in fact, the microgrid frequency and PCC voltage are dominantly determined by the stable main grid, with DERs not actively participating in voltage or frequency regulation but only optimized to support local objectives. Conversely, in island mode, the microgrid controller must carry out voltage and frequency regulation itself by controlling DER and load set-points (Stadler et al., 2016).

Global microgrid capacity accounted to 3,5 MW in 2019 and is expected to reach almost 20 MW by 2028 (Guidehouse Insights, 2019), with the pace of installation picking up as DER prices drop and with an increased recognition of electric reliability issues, due to increased climatic incidents, cyberattacks, and other threats.

One of the most recognized examples of connected microgrids is the Stone Edge Farm in Sonoma Valley, California, a 16-acre winery which facilities include a micro-turbine, PV power plants, and battery stacks, as well as a hydrogen electrolyzer to convert excessive electricity into hydrogen to power on-site vehicles and fuel cell hives. Advanced microgrid control and power self-sufficiency allowed to evacuate the farm and disconnect it from the main grid during the 2017 California wildfires for over a week, maintaining fundamental functions such as powering the irrigation pumps and cellar processes.

Another notable microgrid implementation is Lidl's Järvenpää warehouse in Finland, which includes 1600 solar panels, a battery storage system and a cogeneration plant supplying heating and cooling, allowing 100% operation with renewable energy and a negative operational carbon footprint. The microgrid features a predictive energy management system (EMS) that combines real-time data collected from multiple IoT sensors (occupancy, thermal, and electricity demand) with external information (energy pricing, weather forecasts, etc.) to anticipate energy needs, for instance, by storing heat before colder days. The microgrid is integrated within the local community to supply the excess energy to surrounding homes, including the condensed heat generated by cooling processes which is distributed via the district's heating system to up to 500 single-family homes. Electricity grid services are provided to the Finnish system operator, securing grid stability. The project used the integrated Schneider Electric EcoStruxure Microgrid and EcoStruxure Building Operation solution, delivering energy cost savings of up to 70%.

12.2.4 The role of hydrogen in decarbonization

Hydrogen is a clean energy carrier that can play an important role in the global energy transition toward zero carbon since important synergies exist between accelerated deployment of renewable energy and hydrogen production and use (IRENA, 2019b).

Research on hydrogen has evolved over the past two decades, with a shift in attention from applications for the automotive industry to hard-to-decarbonize sectors such as energy-intensive industries, trucks, aviation, shipping and heating applications. In more recent years, the growth of hydrogen has been spurred by the decrease in the cost of hydrogen supply from renewables and the increased urgency of GHG emission mitigation, with many countries starting to take action to decarbonize their economies, notably energy supply and demand. In fact, hydrogen entirely produced from renewable sources (so-called Green Hydrogen) is a near-zero carbon production route that today is enjoying unprecedented political and business momentum, with the number of policies and projects around the world expanding rapidly. In this picture, current policy discussion suggests that technologies should be scaled up and costs further reduced to allow hydrogen to become widely used (IRENA, 2020b).

Hydrogen can positively contribute to decarbonization in several ways:

- it can help tackle various critical energy challenges by offering ways to decarbonize a range of sectors—including intensive and long-haul transport, chemicals, and iron and steel—where it is proving difficult to meaningfully reduce emissions. It can also help improve air quality, strengthen energy security, and increase flexibility in power systems;
- it is a free energy carrier that can be produced by many energy sources, therefore versatile in terms of supply and use;
- it can be used to produce synthetic fuels—methanol, jet fuels, methane, and other hydrocarbons—through chemical processes with a carbon source (CO and CO₂) captured from emission streams, plants, and animals or directly from the atmosphere, which in turn can be used to directly replace their fossil-based counterparts. Synthetic fuels produce carbon emissions when combusted, but if their production process consumes the same amount of CO₂, in principle this allows them to have net-zero carbon emissions;
- it can enable renewables to provide a greater share of the energy supply by mitigating their variable output, such as PVs and wind power. Hydrogen is poised to become a low-cost option for storing large quantities of electricity over days, weeks or months and even transport it over long distances.

Large-scale adoption of clean hydrogen and hydrogen-derived fuels may in turn trigger a significant increase in demand for renewable power generation. In total, IRENA sees a global economic potential for 19 EJ of hydrogen from renewable electricity in total final energy consumption by 2050, whereas others (e.g., the Hydrogen Council) see this number increasing to around 80 EJ, although not necessarily all from renewables (IRENA, 2019b). This translates into around 4–16 terawatts (TW) of solar and wind generation capacity to be deployed to produce renewable hydrogen and hydrogen-based products in 2050, considering losses along the supply chain. In comparison, current overall global power generation capacity is 7 TW, with only 1 TW from solar and wind power (IRENA, 2019b).

At the beginning of 2021, the widespread use of clean hydrogen in global energy transitions is facing several challenges:

- hydrogen is still almost entirely supplied from natural gas and coal and its production for industrial use is responsible for annual CO₂ emissions equivalent to those of Indonesia and the United Kingdom (UK) combined;
- cost of producing hydrogen from low-carbon energy such as renewable electricity is very high, although falling rapidly;
- hydrogen is still used mostly in oil refining and for the production of ammonia and is almost completely absent in sectors where it can make a significant contribution to the clean energy transition, such as transport, buildings, and power generation;
- the deployment of hydrogen infrastructure is difficult and costly and is holding back widespread adoption, requiring further development and deployment of new and upgraded pipelines and efficient and economic shipping solutions;
- development of a clean hydrogen industry is also limited by current regulations, thereby governments and industries must work together to ensure that existing regulations are not an unnecessary barrier to investment.

Today, around 120 million tons of hydrogen are produced each year, of which two-thirds is pure hydrogen and one-third is mixed with other gases. This equals 14.4 EJ of energy, about 4% of global final energy and nonenergy use, according to International Energy Agency (IEA) statistics. Around 95% of all hydrogen is generated from natural gas and coal and around 5% is generated as a by-product from chlorine production through electrolysis. In the iron and steel industry, coke oven gas also contains a high hydrogen share, some of which is recovered. Currently there is no significant hydrogen production from renewable sources.

The vast majority of hydrogen is produced and used on-site in industry, with the production of ammonia and oil refining accounting for two-thirds of hydrogen use. Ammonia is used as nitrogen fertilizer and for the production of other chemicals. At petroleum refineries, hydrogen is added to heavier oil for transport fuel production. Concerning non-industrial use of hydrogen, the residential sector has increasingly adopted fuel-cells to convert hydrogen and

oxygen into electricity, with a total of 225,000 units installed globally as of the end of 2018, 98% of which installed in Japan (IRENA, 2019b). Regarding vehicular mobility, only 380 hydrogen refueling stations are currently open to the public or fleets, and the global fuel cell electric vehicle (FCEV) stock reached 11,200 units at the end of 2018 (IEA, 2019c). Sales of hydrogen-powered vehicles amounted to around 4000 that year, a small fraction of the 2.5 million EVs sold globally. The Hydrogen Council envisions 3000 refilling stations by 2025, which would be sufficient to fuel around 2 million FCEVs (see Table 12.5).

As reported, almost all hydrogen is still produced from fossil fuels, from methane using steam methane reforming (SMR) or coal gasification, without CO₂ capture (so-called gray hydrogen). Although the cheapest solution for hydrogen production today, it is not sustainable for a route toward net-zero emissions: hydrogen from SMR has an emission factor of around 285 grams of CO₂ per kWh (9.5 kilograms of CO₂ per kilogram of hydrogen), and coal gasification has an emission factor of around 675 grams of CO₂ per kWh, accounting only for energy use and process emissions (IEA, 2019c).

Ensuring a low-carbon, clean hydrogen supply is therefore essential for energy transition applications. Along with gray hydrogen, current and future sourcing options include fossil fuel-based hydrogen production combined with carbon capture, utilization and storage (CCUS), known as blue hydrogen; hydrogen from the pyrolysis of methane (turquoise hydrogen) and hydrogen from renewables (green hydrogen) (see Table 12.6) (IEA, 2019c).

The production of blue hydrogen from fossil fuels with CCUS has some attractive features and has been proposed as a bridging solution to hydrogen adoption as the cost of producing hydrogen from renewable power decreases. Notably, industrial processes like steel production may require a continuous flow of hydrogen; blue hydrogen could be an initial solution while green hydrogen ramps up production and storage capacity to meet the continuous flow

TABLE 12.5 Main hydrogen end-uses (IRENA, 2018; IRENA, 2021b).

Sectors	Applications
Industry	• Oil refining • Ammonia production • Methanol production • Steel production
Power production	• Ammonia co-fired in coal power plants • Hydrogen and ammonia in gas turbines and fuel cells • Long-term and large-scale energy storage
Transport	• Direct use of hydrogen in FCEVs, mainly cars and trucks • Indirect use via hydrogen-based fuels in internal combustion engines, for trucks, aviation, and shipping • FC trains to operate in nonelectrified rails
Buildings	• Blending or replacing methane with hydrogen • Direct use of hydrogen in fuel cells (paired with heat pumps) • Hydrogen boilers

FCEVs, Fuel-cell electric vehicles.

TABLE 12.6 Selected shades of hydrogen (IRENA, 2020b).

Production	Hydrogen types and shades			
	Gray hydrogen	Blue hydrogen	Turquoise hydrogen	Green hydrogen
Process	SMR or gasification	SMR or gasification with carbon capture (85%–95%)	Pyrolysis	Electrolysis
Source	Methane or coal	Methane or coal	Methane	Renewable electricity and water

SMR, Steam methane reforming.

requirement. Moreover, it offers a prospect of continuity to fossil fuel producers, and it can contribute to meet climate objectives at an acceptable cost.

However, blue hydrogen has inherent limitations that have so far restricted its deployment: being still based on fossil fuels, it uses finite resources, is exposed to market price fluctuations, and does not support the goals of energy security. In addition, deployment of blue hydrogen is not necessarily CO₂-free: CCUS capture efficiencies are expected to reach 85%–95% at best, thereby 5%–15% of CO₂ will be emitted nonetheless even in best cases. Moreover, these processes use leakage-prone methane, which is a much more potent GHG. Finally, blue hydrogen faces some social acceptance issues, as its production is associated with additional costs for CO₂ transport and storage and requires transparent CO₂ monitoring, verification and certification to account for noncaptured emissions and retention of stored CO₂ (such information is needed for global hydrogen commodity trade).

For these reasons, blue hydrogen should be seen only as a short-term transition to facilitate the uptake of green hydrogen on the path to net-zero emissions. Currently, it sees limited niche applications, for instance, in California, it is a mandatory component of FCEV fuel.

Turquoise hydrogen production uses natural gas as feedstock with no CO₂ production: through the process of pyrolysis, the carbon in the methane becomes solid carbon black, a byproduct with its own industrial market which provides an additional revenue stream. Moreover, carbon black is much easier to store and transport than gaseous CO₂. At the moment; however, turquoise hydrogen is still at the pilot stage (IRENA, 2020b).

Finally, green hydrogen, that is, hydrogen entirely produced from renewable energy, is the most suitable for a fully sustainable energy transition. The most consolidated technology for producing green hydrogen is water electrolysis, that is, the electrochemical process that splits water into hydrogen and oxygen, with other solutions including biomass gasification and pyrolysis, thermochemical water splitting, photocatalysis, supercritical water gasification of biomass, combined dark fermentation, anaerobic digestion and SMR with biogases. However, with the exception of the last one, these technologies are not mature at commercial scale yet. Green hydrogen from water electrolysis has been gaining increased interest, as its production is consistent with the net-zero route, is seeing decreasing costs due to low VRE costs and technological improvement, and allows the exploitation of synergies from sector coupling, thus decreasing technology costs and providing flexibility to the power system. For these reasons, electrolysis technology is evolving and scaling up quickly, from the megawatt to the gigawatt scale, meanwhile costs are projected to halve by 2040 to 2050, from 840 USD/kW today. Renewable hydrogen is expected to become the cheapest clean hydrogen supply option for many greenfield (i.e., newly established) applications (IRENA, 2019b).

The three main electrolysis technologies currently in use are alkaline electrolysis, proton exchange membrane electrolysis, and solid oxide electrolysis cells, with efficiency of current electrolyzers ranging between 60% and 81% depending on the technology type and load factor. In addition to electricity, electrolysis requires water as well to produce hydrogen: 1 kgH₂ requires around 9 L of water and in turn produces 8 kg of oxygen as a by-product, which at smaller scale can be used in the health care sector or at a larger scale for industrial purposes. If the current hydrogen production of around 70 MtH₂ were entirely produced by electrolysis, this would result in a water demand of 617 million/m, roughly twice the current water consumption for hydrogen from SMR (345 million/m of water for 52 MtH from SMR) corresponding to 1.3% of the water consumption of the global energy sector today (IEA, 2019c). Therefore, access to freshwater may impede scaling up of green hydrogen production in water-stressed areas, which crucially are often those with the highest potential in terms of PV production to turn toward hydrogen. In coastal areas, using desalinated seawater could be a suitable alternative, as reverse osmosis for desalination requires an electricity demand of 3–4 kilowatt hours (kWh) per m³ of water and costs around USD 0.7–2.5 per m³ of water (IEA, 2019c), meaning the increase in total hydrogen production costs would be limited to USD 0.01–0.02/kgH₂. Instead, use of nondesalinated seawater in electrolysis currently leads to corrosive damage and to the production of toxic chlorine.

Nonetheless, such hydrogen-based energy transition will take an extended time to take place. Hydrogen will likely trail other decarbonization strategies, such as electrification of end-use sectors, and its use will target specific applications. The need for a dedicated new supply infrastructure may also limit hydrogen use to certain countries that decide to follow this strategy. Thereby, hydrogen represents a complementary solution that is especially relevant for governments with ambitious climate objectives (IRENA, 2020a).

Hydrogen supply costs are 1.5 to 5 times those of natural gas per unit of energy, a price difference that is partly offset by low-cost and highly efficient hydrogen applications. Currently, significant energy losses occur in hydrogen production, transport, and conversion; therefore, their reduction is critical for decreasing the hydrogen supply cost. Concerning transport infrastructure, although dedicated hydrogen pipelines have been in operation for decades, transport of hydrogen via existing and refurbished gas pipelines is being explored to reduce new infrastructure investment needs and help to accelerate a transition. However, equipment standards need to be adjusted, which may take time.

While international hydrogen commodity shipping is being developed, another opportunity that deserves more attention is trade of energy-intensive commodities produced with hydrogen (IRENA, 2018). Prime markets would include ammonia production, iron and steel making, and liquids for aviation, marine bunker fuel or feedstock for synthetic organic materials production (so-called electrofuels or e-fuels, that are part of a power-to-X strategy), but cost and efficiency barriers still need to be overcome. This may offer an opportunity to accelerate global renewables deployment with economic benefits.

Regarding the building sector, hydrogen has several potential applications with different advantages and infrastructure requirements. A low-investment method to support the energy transition is the addition of hydrogen to gas already used for building heating (blending ratios between 5% and 20%), or its replacement with methane entirely produced from clean hydrogen. Both allow to maintain the current gas networks and equipment, but full decarbonization can be achieved only by using gas from low-carbon hydrogen and low-carbon CO₂ inputs.

More interesting is the switch to 100% use of hydrogen in buildings, for example, via fuel cell or hydrogen boilers. From the perspective of costs, this appears most attractive for relatively large commercial buildings or building complexes, and for district energy networks because of the substantial investment related to infrastructure upgrade. Fuel cells, cogeneration units, or other hybrid systems could be used in such cases with energy storage capacity (provided by thermal storage or via a district energy network) to meet heating, cooling and electricity demand, taking advantage of on-site renewables or low electricity prices, improving power system balancing across the year, avoiding large seasonal peaks and enabling greater flexibility in the grid. Paired with large-scale heat pumps, those district energy solutions could also dramatically increase the overall efficiency of heat production for buildings (IEA, 2019c).

12.2.5 Modeling tools for urban energy system planning

The radical transformation that energy infrastructure is undergoing, as described in the previous paragraphs, requires utilities and planners to not only update their technologies and program portfolio, but also to shift to a more informed and data driven approach to urban energy system planning. In fact, many institutions have developed effective frameworks and practical tools to guide local authorities throughout the planning process, with a particular focus on meeting targets for sustainability and renewable energy integration (IRENA, 2020d). Other factors previously unaccounted for include the proliferation of prosumers and of DERs, as well as the recent attention to enhancing long-term urban resilience in response to climate change, as urban energy infrastructure typically has a life span of up to 50 years or more.

Nowadays, a wide range of modeling tools are available to support urban energy system planning, varying in their spatial and temporal scales, underlying methodologies, and analytical scopes, in particular concerning their suitability to model the growing shares of local renewables in urban energy systems. Indeed, modeling tools help determining the feasibility of renewable energy solutions in early programming stages as well as the design of renewable energy systems (e.g., sizing and operation) at later planning phases.

The growing digitalization of all the energy sectors and actors, from supply to demand to the infrastructure in between, is producing an unprecedented amount of data—for instance, one million smart meters in an urban distribution network with a sampling rate of every 15 minutes will generate 35.04 billion records per year (JRC, 2019a)—which can be effectively leveraged with the right tools to extract important knowledge for strategic planning at different scales. In urban energy systems, in particular, more granular data are required compared to large-scale models, which are often more challenging to collect or obtain in a structured and complete dataset.

Concerning the demand side of the urban energy system, modeling requires hourly demand profiles covering at least a one-year period, divided by energy use (power electricity, space heating and cooling, domestic hot water, and process heat) and by sector (residential, commercial, industrial and transport) at varying spatial scales (e.g., for different residential building types, commercial business types, industries, and transport modes). Demand elasticity and flexibility should also be factored in. Demand elasticity in the context of energy systems refers to how sensitive energy demand is to changes in economic variables, such as the energy price. Demand flexibility instead refers to users' ability to forgo, shift or substitute certain loads, for instance following energy retrofit of the building which may shift and reduce heating/cooling demand.

Regarding the supply side of urban energy systems, instead, modeling needs hourly profiles on potential energy generation and fuel supply (e.g., grid electricity, natural gas, biofuels, transport fuels, and other fuels) as well as on the existing electricity supply mix (i.e., shares from different non-renewable and renewable energy power plants), in order to define at best the future mix, with different temporal, and spatial scale requirements depending on the energy resource type. VREs such as PVs and wind turbines, in particular for decentralized installations in urban scenarios,

require at least hourly generation profiles, whereas hydropower may be estimated seasonally and wood- and waste-to-power potentials annually.

Concerning urban infrastructure, data should include the power distribution network (grid capacities, transformers, substations, etc.), district heating, cooling, and gas networks as well as vehicular transport network. Buildings are a decisive part of urban energy infrastructure; therefore, data are needed on buildings' function and structure gross floor area, occupants, age, energy performance, etc.), existing energy converters (heating/cooling technologies, on-site power generation), and access to infrastructure networks (natural gas, district heating, transport network access). It is important to contextualize urban infrastructure data with spatial information, for instance by using GIS (see [Section 6.1.2](#)).

Once sufficient datasets have been gathered, urban energy systems can be effectively modeled and simulated using a range of software tools. The most commonly used include OSeMOSYS, Balmorel, EnergyPLAN, HOMER, TIMES, MESSAGE, and LEAP. These differ according to their commercial model (some are open source or free to use, others require to buy a license), their user friendliness for practitioners and experts, their level of granularity in terms of time steps and sectoral disaggregation, as well as their short-term or long-term focus. An effective strategy is to employ high level tools such as LEAP, Balmorel, or EnergyPLAN for broader strategic programming, then interfacing with more detailed programs such as OSeMOSYS, HOMER, or TIMES to add more technical planning. Ideally, the analysis will model a city's complete energy system, with all sectors, any energy demand commodity, and all supply resources, with the objective to identify the cost-optimal integration pathways and policies for renewable energy capacity and dispatch planning in the long term by considering a range of climate, technology, and policy scenarios.

Care should be taken in assessing these models' compatibility with the actual energy conditions in the context of developing countries, given that 90% of urban population growth in the next three decades is expected to come from there, mostly from Asia and Africa ([The world's cities, 2018](#)). Indeed, many urban energy planning and modeling frameworks assume perfect conditions, markets, and foresight, whereas developing countries usually struggle with poor power sector management and performance, voltage and frequency fluctuations, power outages, load shedding, grid security issues, poorly designed pricing mechanisms, lack of effective revenue collection, as well as electricity theft through unpaid bills and tapped grid lines. In addition, the informal and transitional economies in developing countries do not provide as much data as needed, as they often include illegal activities, tax evasion or avoidance, and monetary and nonmonetary transactions. To produce more realistic results, especially concerning financial and economic viability of planned interventions and policies, these energy issues should be considered either explicitly in technical representations (e.g., through low availability factors or other performance specifications) or implicitly in energy modeling scenarios.

12.3 Smart energy buildings

The transition to the Construction 4.0 model and low carbon cities requires fully electric, highly efficient, grid-interactive (Building to Grid, B2G) or smart grid optimized buildings (SGOB) with on- and/or off-site renewable energy systems and smart e-mobility infrastructure ([IRENA, 2021c](#); [WEF, 2021](#)). Key technological innovations include building integrated renewable energy systems with battery storage, net metering, smart energy management, highly efficient appliances, IoT, AI fueled by Big Data, and blockchain technology ([PEEB, 2019](#)).

The ultimate goal is to achieve smart energy buildings perfectly integrated into their environment, connected to the global network and able to receive, process and take advantage of data and information to communicate with their users and share their infrastructure with that of the city and the transport systems, acting as funding elements for a wider, highly efficient urban system, delivering better quality services for citizens and accompanying benefits such as local job creation, health, and well-being.

Central to smart energy buildings is the EMS, possibly integrated within the BAS, designed to allow an optimal and flexible integration between loads, production, storage and grid exchange and minimum power losses (see [Fig. 12.5](#)). In normal operation mode, all building electric loads are powered primarily from on-site renewable energy production, secondly from the battery storage and finally, if production and storage are not enough, from the grid. The goal is not only to provide a positive net energy balance, but also to use the electricity in the same place and at the same time where it is generated, reducing the need for transmission lines and minimizing the electricity transport losses. Electric distribution within the building is organized starting from main smart switchboards with several functions: protect, measure, connect, act. Circuit breakers are not only protection devices, but they are also connected with the building EMS and can send measures and receive commands from it. The panel is also equipped with dedicated meters and actuators that allow real-time monitoring and loads control. Ideally, such EMS allows:

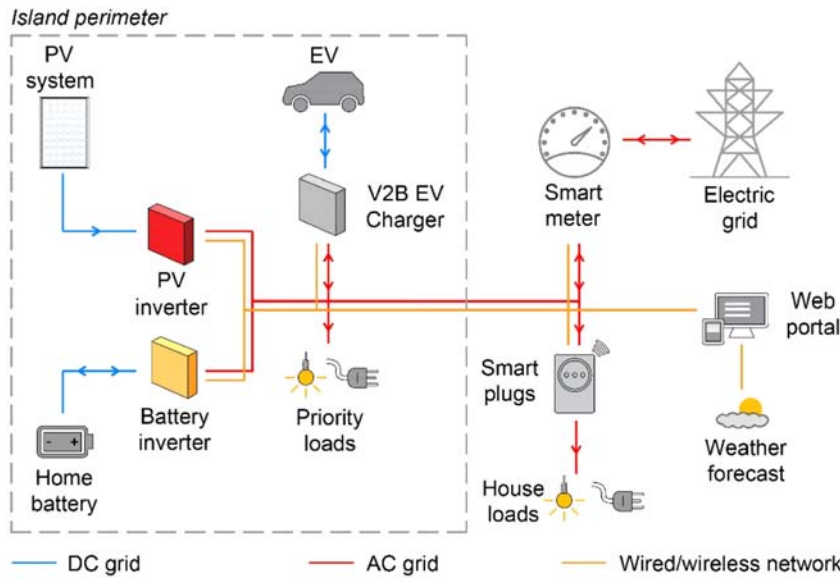


FIGURE 12.5 Smart energy building system.

- remote monitoring and control smart scheduling, on/off switching, and modulation of electrical loads;
- smart management of PV and grid energy use and charging/discharging of house energy storage according to the house net electrical balance, temporary generation-consumption, and DR function;
- optimization of EV charging/discharging according to current and predicted house energy production, consumption, and cost of energy.
- real-time and historical information on expected and actual system performance, on energy consumption and production and suggestions on their optimization.

Smart energy buildings also allow power backup: when the grid is down due to blackouts or intentional disconnections, the system can turn to stand-alone in island/emergency operation mode. Nonvital loads shut off, while island loads are still powered in an off-grid electrical subsystem. Island loads are powered primarily from on-site energy production and secondly from the battery storage or from the connected EV. In this operating mode, the island subsystem has a virtually unlimited autonomy as long as the daily energy absorbed by island loads is lower than the daily on-site production. Normally, island loads include fire protection systems, alarm systems, BAS, lighting, water pumps, electric outlets.

Smart energy buildings can provide services to, or benefit from, other sectors, such as mobility and energy, leading to faster decarbonization and a reduction of upstream costs, such as congestion relief and investment deferrals. EV charging can allow for the optimization of renewable energy produced on-site, storing power not only for the car, but, while the car is not in use, also for the house (V2B) or for the surrounding community thanks to smart-charging infrastructures (V2G). Electricity produced from renewables can also be shared with local renewable energy communities, enabling emerging, efficient and resilient sharing models to evolve.

12.3.1 Building integrated renewable energy

The integration of renewable resources in buildings is a fundamental instrument of the 21st century architecture to reduce the consumption of fossil energy and cut carbon emissions in urban areas (GlobalABC/IEA/UNEP, 2020; Global Alliance for Buildings and Construction & OID, 2021; IEA, 2019a; IEA, 2020a; IEA, 2021; IRENA, 2019j; 2020d; IRENA, 2021a; 2021c; REN21, 2020; REN21, 2021; UNEP, 2020; WEF, 2021).

The goal is to promote positive energy buildings able to self-produce on-site, through renewables, more energy than is needed to meet their different needs, as well as share their production with the grid to optimize energy use at the district and SC level.

Among the different possible sources of nonfossil energy (wind, solar, aerothermal, geothermal, hydrothermal, tidal, hydropower, biomass, landfill gases, residual gases from purification processes and biogas), those that can more easily be applied in today architecture are undoubtedly solar technologies, vertical axis wind technologies, biomass energy

exploitation as well as energy harvesting systems such as in-pipe mini-hydro systems and energy-producing pavements (see Fig. 12.6).

Renewable energy can be used in various forms in thermal systems, such as through the capture of solar heat gains for space or water heating, the use of biomass for heating, or heat pumps (thermal, geothermal or hydrothermal) for space and water heating as well as for space cooling. Solar thermal collectors absorb and convert the solar radiation to heat, with efficiencies of up to 80%, depending on the operating temperature, and have long been adopted to provide water and space heating for buildings, but they can also generate industrial process heat. In cities, these systems can be placed on roofs, façades, balconies, and any outside building area. Collectors on the market for stand-alone systems include flat plate and evacuated tube collectors (to produce temperatures of 120°C and below) and low concentrating collectors (120°C and above, up to 200°C). For countries at lower latitudes, an individual solar hot water system can cover up to 100% of a single-family demand, whereas at higher latitudes that have large seasonal variation in irradiation, the systems can provide between 20% and 60% of the heat demand for domestic water and space heating, and even more if a seasonal storage system is present. In California, the average share of water heating that solar thermal can provide is 70%–80%, with a seasonal range of 25%–90%. In commercial and service buildings such as hotels, hospitals and shopping malls, where thermal demand tends to be constantly high, such systems are often used to achieve cost savings and/or to demonstrate corporate social responsibility. A growing number of cities and countries have adopted mandatory use of solar water heaters for all new buildings as part of the building code. Concerning installed solar thermal power capacity, China alone accounts for 337.6 GW, or 70% of the world total, while Europe is the second largest market, with one-sixth the installed capacity of China (IRENA, 2020d).

Renewable electricity can be produced through the use of PV, wind, mini-hydro and piezoelectric systems. The use of cogeneration (CHP) or trigeneration (cogeneration of heat, cooling and power, CHCP) systems using gas, biomass or hydrogen with fuel cells, allows to combine the production of electrical and thermal energy ensuring greater conversion efficiencies compared to separate production. District heating and cooling systems driven by energy from renewable sources are also viable.

These technologies shall be accurately mixed, integrated and operated according to the specific climate and local conditions, including costs and incentives. EVs and plug-in hybrid EVs (PHEVs) can also be integrated into the shared energy concept, serving as both electrical storage and load management devices, but also providing backup power to buildings during power cuts (Vehicle to Building—V2B and Vehicle to grid—V2G).

Within cities, solar PV systems are usually installed on, or integrated with, the roofs and façades of buildings. These systems are generally smaller in scale than centralized ground-mounted solar power plants located on the outskirts of cities. The median size of installed residential PV systems in 2018 was around 6.4 kW, which was 8% larger than in 2014 due primarily to falling costs (IRENA, 2020d). The key technical advantage of residential systems is their proximity to the load, which avoids the energy losses and wheeling charges often associated with long-distance transmission. However, cities are also increasingly recognizing the many social and environmental cobenefits that these systems provide, including greater resilience to extreme weather events and the impacts of climate change.

In recent years, solar energy has assumed a greater role also in district heating and cooling (IEA, 2019b; IRENA, IEA, REN21, 2020).

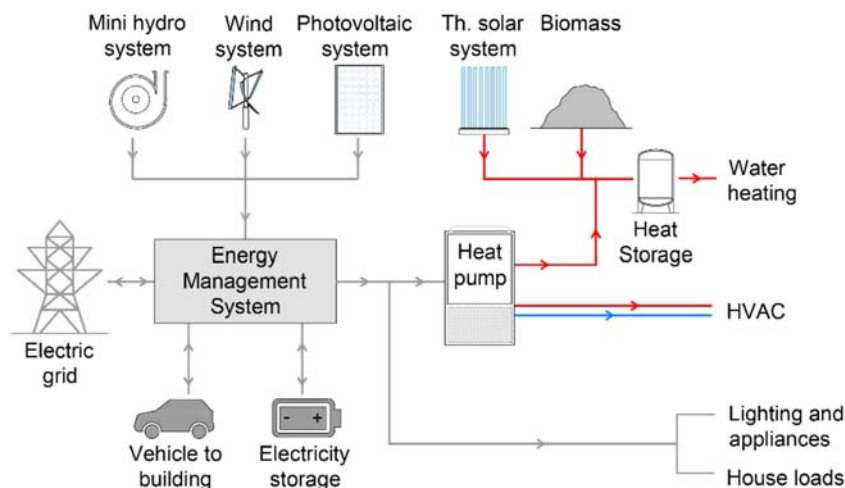


FIGURE 12.6 Building renewable energy equipment system scheme.

In solar district heating, large solar collectors installed on the ground or on a building roof distribute the produced heat via district thermal networks. Solar district heating was enabled by the transition of heating networks towards low-temperature (below 60°C–70°C) district heating systems, known as the fourth generation. The main benefits of solar district heating are that the system can be installed with low solar resources, provides a stable cost for at least 25 years and uses already mature and available technology with zero emissions. Due to scale economies, solar district heating systems normally have lower specific investment costs than smaller applications. In Europe, there are hundreds of solar district heating plants and a total capacity exceeding 1.1 GW by 2019, mainly in Denmark, Austria, Germany, and Sweden.

More recently, the applications of solar thermal energy have extended gradually into the cooling sector through deployment of absorption chillers. Because of the higher temperature these require, evacuated tube or concentrating solar collectors are usually adopted. To further improve system efficiency and utilization rates, hybrid systems are a promising solution: in summer, solar thermal energy can be used for cooling, whereas in winter it can be used for space heating or hot water supply. A main advantage of solar cooling, apart from being a more environmentally friendly option, is the potential to lower peak demand on the grid during increasingly hot summers, reducing grid overloads and the need for grid enhancement. In the most ideal conditions, in fact, such systems can reduce by 50% the primary energy required to produce cooling energy. Free cooling sources such as rivers, lakes and ambient air can also be exploited as a renewable source of cooling energy.

Cold water distribution networks are designed to maintain a small temperature difference between the cold supply temperature and the warmer return temperature. Hence, district cooling pipes tend to be much wider than district heating pipes at the same capacity demand. Cold losses are limited in temperate climates such as in Europe, where the annual average ground temperatures are often almost equal to the distribution temperatures. Climates characterized by higher ground temperatures, such as the Middle East, call for greater insulation of pipes. Cold deliveries are managed by substations in each connected building, with or without heat exchangers. Since the temperature difference between the supply and return pipes is very small, heat exchangers have long thermal lengths to not reduce the transfer capacity in the cold distribution networks.

Both district heating and cooling systems can be configured in combination with a thermal energy storage (TES) facility (such as seasonal thermal storage), with great benefits in terms of efficiency of scale. Storage capacity linked to district networks serves to decouple heat and cold generation from consumption, giving the possibility to store energy across a range of timescales, from hourly to a seasonal basis. In particular, underground seasonal hot water storage systems are already applied for small solar district heating and cooling systems, like the one in Munich (Germany), where a 6000 m³ thermal storage facility enables solar energy to meet about half of the heat demand for 320 apartments (IRENA, IEA, REN21, 2020). Ice is also currently used as latent heat storage in several district cooling schemes. PCM technologies (see Section 7.5.3.2) and thermochemical systems are being developed and expected to help further decarbonize the sector. In the medium term, other innovative PCM and solid-state solutions could integrate high shares of renewables via power-to-heat or via seasonal solar thermal schemes. By 2030 efficiency levels of over 92% are expected for TES technologies used in industrial applications, and by 2050 inexpensive thermochemical systems with prices as low as USD 10/kWh will enhance opportunities for renewables deployment in district heating and cooling, especially in combined cooling and power applications. Moreover, sector integration and smart control technologies should intensify opportunities, particularly for wider harvesting and storage of waste heat/cold from industrial applications (IRENA, 2020c).

Conventionally, heating and cooling services are provided through two separate thermal pipeline networks. More innovative designs, such as Ectogrid, use a single thermal network connecting with different end-users to move around the wasted thermal energy (for instance, the waste heat from cooling systems in office buildings, hospitals, and data centers), while heat pumps can tap into this low-temperature thermal energy as a way to increase the temperatures required, and cooling machines or reverse-cycle heat pumps can be used to reduce the temperatures to a desired level. The primary advantage of such an approach is the greater overall energy efficiency that results from reusing the wasted thermal energy discharged from different end users in the system before adding additional energy when needed. In addition, the low-temperature thermal energy in the pipeline allow to reduce if not eliminate distribution losses and enables renewable-based thermal energy as a supplementary source.

12.3.1.1 Building integrated photovoltaics

PV technologies represent today the main resource for on-site generation of electricity in net-zero energy buildings (SolarPower Europe, 2019). In fact, they have a huge potential in terms of the ability to integrate with the building envelope to reach the definition of a new architectural language in which solar energy capturing surfaces can become

an expressive and compositional element. For this reason, PV systems should be considered as just another element in the building that is being designed, and therefore their proper location should be chosen from both the technical and esthetic points of view to ensure that the module and its supports have the maximum visual and efficiency quality. PV technologies should be interpreted as one more element in architecture that contributes to the formal quality of the whole.

At the base level, integration may be limited to the application of panels on the outer surface of the building envelope, parallel with the supporting surface, without replacing any of the supporting materials below (Building Adapted PV systems—BAPV). BAPV modules are used solely for generating energy, even as part of the architectural composition of the building, and do not replace any or perform as a construction component. Such is the case for example in retrofit applications, with PV modules over sloped roofs, arranged with a given angle on flat roofs or assembled on facades or shading devices.

PV integration can indeed go further, by replacing the actual architectural elements of the building with PV ones (Building Integrated PV systems—BIPV). In BIPV, PV construction elements are part of the building envelope, acting not only as an energy generator, but also performing as an envelope function, on roofs, facades, atria, or shading elements (Ghosh, 2020; Jelle, 2016; Kuhn et al., 2021).

The design approach can aim to an “invisible application” in which the solar modules are located out of sight or are intentionally designed not to be distinguished from the rest of the building envelope (see Section 7.4.6) or push at enhancing or even determining to a significant extent the image of the building. There are more and more examples of residential or commercial buildings that present an advanced architectural integration of PV systems on the facade, on the roof, or in solar shading or windows, both for new construction and in the case of energy retrofits. In fact, every element of the building surface, from the roof to the perimeter walls, to the transparent closures and shading screens, is suitable for the installation of PV systems. Their integration into the building organism allows, in addition to energy production, the provision of other major functions such as sound insulation, thermal insulation and solar radiation protection, resulting in reduced air conditioning load during summer. BIPV can also allow economic benefits: by replacing the building material with a solar module the value of the first is deducted from the total cost of the system; furthermore, if the system is an integral part of the building, the cost of its support structure and the lot on which it is placed are already accounted.

Among most interesting projects of the last years, particularly noteworthy is the Bullitt Centre in Seattle by The Miller Hull Partnership (see Fig. 12.7), voted “Sustainable Building of the Year 2013” and certified according to both Net Zero Energy standards and Living Building Challenge systems. The building features an intelligent, highly efficient



FIGURE 12.7 Bullitt Center, Seattle. *Courtesy of Miller Hull Partnership.*

PV solar envelope able to produce on-site 100% of the net energy demand through the PV roof and solar facades which together deliver an output of about 230,000 kWh/year.

Another significant example is the Kathleen Grimm School for Leadership and Sustainability at Sandy Ground by Skidmore, Owings & Merrill LLP (SOM). Completed in 2015, the building is the first net zero energy school in New York City and one of the first of its kind worldwide (see Fig. 12.8). The 6300 m², two-story school, designed to comply with the SCA Green Schools Guide, harvests as much energy from renewable on-site sources as it uses on an annual basis. Orientation and massing of the courtyard-shaped building was optimized to take advantage of sunlight for both daylighting and to power the PV arrays on the roof and south facade. The shape of the building's roof has been optimized for energy production and also creates an iconic feature that represents a core mission of the project. The PV panels produce 662,500 kWh/year of energy, enough to offset the energy consumption of the building and its users.

Another interesting example of BIPV façade is the Neue Building + e Kita (plus-energy-/solar building) by Opus Architekten in Marburg, Germany (see Fig. 12.9). It is one of the first children's day-care centers in Germany to achieve the plus energy standard Effizienzhaus Plus (Efficiency House Plus). With a capacity of 52 kWp, the 390 m² PV installation (305 m² on the roof and 85 m² on the façade) provides about 41,000 kWh/yr, enough to cover the entire energy demand of the building.

A remarkable application of PV in shading devices is that of the Museu do Amanhã by Santiago Calatrava, located on the Pier Mauá, in Rio de Janeiro (see Fig. 12.10). The building envelope of the museum (aligned in the north-south direction) was conceived as a flexible organism, a sort of "solar machine" able to expand its own surface and to capture

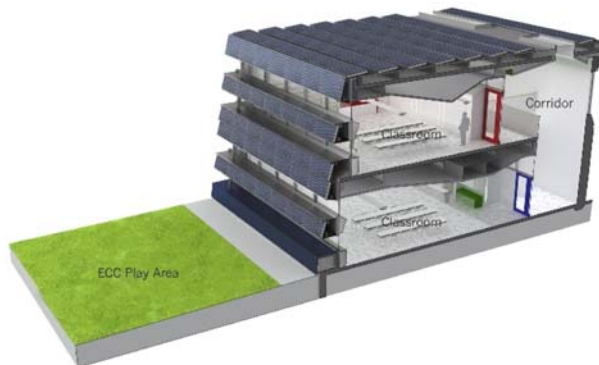


FIGURE 12.8 Kathleen Grimm School for Leadership and Sustainability at Sandy Ground. *Courtesy of SOM.*



FIGURE 12.9 Nursery + e In Marburg. *Courtesy of Opus Architekten.*



FIGURE 12.10 Museu do Amanhã, Rio de Janeiro. *Courtesy of Santiago Calatrava llc.*

energy in all directions, optimizing daylighting and energy production over the course of the day. This is achieved by gradually tilting the dynamic, PV integrated elements of the building roof according to the daily and seasonal sun path.

Concerning energy retrofit, Hanwha HQ office tower in Seoul by UNStudio, completed in 2019, is characterized by a PV array on its facade perfectly integrated with the building's architecture (see Figs. 12.11 and 12.12). The renovation envisaged a profound remodeling of the envelope, transformed in an integrated facade which improves the indoor climate and fully complements both the program distribution and the location. The existing facade of horizontal bands of opaque paneling and single layers of dark glass was replaced by clear insulated glass and aluminum framing to accentuate views and daylight and allow the integration of PV solar panels. The geometry (pattern, size and reveal) of the framing is further defined by the sun and orientation factors to ensure user comfort inside and reduced energy consumption. Parts of the facade that hold the solar panels are also angled to make the most of the sunlight while shading the windows below.

Currently, several products for the integration of PV technologies in the building are available on the market, characterized by advanced design, flexibility, attention to detail, variety in color, shape, and transparency degree, in order to meet any requirement (IEA PVPS Task 15, 2019; SUPSI, 2017; Taylor and Jäger-Waldau, 2019).

Thanks to thin-film technology, PV systems can now be integrated on any surface and in any building element, from roof tiles to flat or curved windows, ETFE cushions, shading elements, pavements, up to street furniture elements.

Today, the main BIPV products available on the market are:

- PV modules specifically designed for architectural applications such as flexible PV modules, thin film strips on a rigid support and PV roofing tiles; transparent PV modules for facades, windows, and roofs conveniently built and installed to allow the passage of light inside the building envelope (Husain, Hasan, Shafie, Hamidon, & Pandey, 2018);
- special components for roofing, opaque vertical surfaces, or ventilated facades, constituted by the assembly and the integration of unframed laminated PV modules in place of conventional building materials, and provided with certified fixing system (see Fig. 12.13).



FIGURE 12.11 Hanwha HQ Building. *Courtesy of UNStudio, ©Rohspace.*

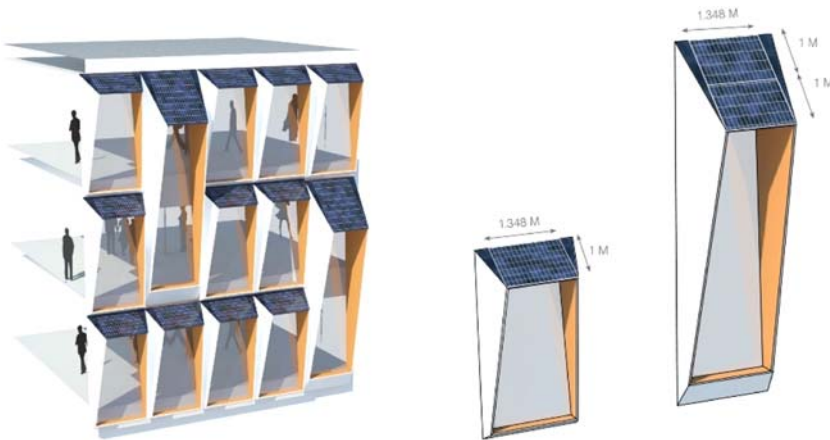


FIGURE 12.12 Hanwha HQ façade PV details. *Courtesy of UNStudio.*



FIGURE 12.13 PV Façade modules installation. *Courtesy of Heliartec.*

In particular, semitransparent BIPV products can use several PV cell technologies, from spaced opaque crystalline silicon cells (see [Fig. 12.14](#)) to thin-film transparent PV cells (see [Figs. 12.15 and 12.16](#)), and can replace conventional windows and skylights in both commercial and residential buildings.

In most commercial buildings, where reduction of cooling energy costs is important, semitransparent PV glazing may be used to reduce solar heat gains and generate solar electricity while providing adequate daylighting and vision



FIGURE 12.14 Spaced crystalline PV cells. *Photo by the author.*



FIGURE 12.15 Skylight with semitransparent a-Si PV cells. *Courtesy of Onyx Solar llc©.*



FIGURE 12.16 Semitransparent a-Si BIPV facade, GenYo Centre, Granada. *Courtesy of Onyx Solar llc©.*

through, in place of more conventional tinted or ceramic fritted outer glass panes of insulating windows. In residential buildings, semitransparent modules can be used in skylights or clearstory windows.

Concerning solar cells technologies, there are several options that power modules currently available on the market of under development, each characterized by different efficiency, cost, sustainability, and potential applications (see [Table 12.7](#)).

In terms of overall PV market, monocrystalline and polycrystalline silicon (c-Si) wafer-based PVs (see [Fig. 12.17](#)) are by far the dominant technology, with a 2019 share of over 95%. C-Si architectures include:

- aluminum diffused back surface field cells (AL-BSF), used on both multi- or mono-crystalline wafers, which was the dominant standard up to 2015 and still accounts for more than 40% of the market;
- passivated emitter rear contact cells (PERC), an evolution of AL-BSF architecture which currently accounts to about 50% of the market;

TABLE 12.7 Main PV technologies.

PV technology	Solar cells
Crystalline silicon	p-type n-type
Thin film (TF)	Chalcogenides: CdTe, CIGS, CZTZ, etc. III-Vs: Ge, GaAs, GaInP, etc. Organic, Dye sensitized Perovskite Silicon TF and others thin films
Hybrid	TF silicon on wafer silicon Other TF on wafer silicon Others including III-V substrate

**FIGURE 12.17** Crystalline silicon PV cells. *Courtesy of Kaleo Solar.*

- bifacial cells, in which rear contacts allows light through making both front and back surfaces productive, with a market share of about 12%;
- metal wrap through (MWT) and interdigitated back contact (IBC), which move contacts to the back of the panel to eliminate shading on the front area and increase efficiency. Although more expensive to produce, their gap-free and connection-free appearance makes them suitable for BIPV application. Market share for these amount to about 5%;
- heterojunction (HJT or HIT) cells, in which an ultra-thin layer of amorphous silicon is deposited on the front and back surfaces of a monocrystalline wafer. Combined with IBC contacting, this yields high efficiency and has recently entered the market.

Although more flexible in BIPV applications, thin-film silicon PV (amorphous and microcrystalline silicon) have lost market shares due to their lack of efficiency improvements, whereas thin-film modules using cadmium telluride (CdTe) and copper indium gallium diselenide (CIGS) had marginally better market results but are still shy of 5% of total annual PV module production. CdTe and CIGS modules are in fact competitive with crystalline silicon in terms of yield, but their larger scale deployment is limited by their material needs: tellurium is scarce, and indium and gallium are on the critical materials lists of many countries, including the EU. Concentrating PVs (multijunction technology using III-V semiconductors) have yet to reach mainstream market due to problems with overall system cost reductions. Concerning the so-called third generation PV, some organic photovoltaic (OPV) and dye-sensitized solar cells (DSSC) devices have been commercialized; however, these technologies mostly remain in the novel and emerging categories. For instance, France-based Ductal manufactures UHPC façade rainscreen panels integrated with Heliatek's OPV, claiming optimal performance in autumn and spring seasons. Hybrid organic-inorganic perovskite materials have emerged in the last five as a promising option, in particular combined with wafer-based silicon to offer high efficiency and attractive manufacturing costs (Taylor and Jaeger-Waldau, 2020).

Current yield of PV modules available on the market allow to install an electrical power between 80 and 220 Wp per square meter of surface area exposed to the sun, depending on the type of solar cells used (see Table 12.8). Common module dimensions are 1x1.5–1.7 m, with thickness of 4 cm, and peak power ratings range from 260 W to 400 W.

PV bifacial modules allow a greater production of electricity by exploiting the indirect radiation reflected from the surfaces underlying or adjacent the modules (see Fig. 12.18), up to over 220 Wp/m² (see Table 12.9).

An ongoing development of PV technology is represented by organic photovoltaics, also known as third-generation PVs, consisting of proper OPV, DSSCs, and perovskite solar cells (PSCs). These, thanks to the ability to also exploit diffused light effectively, can be applied on any part of the building envelope with any exposure, and even in interiors (see Section 7.5.6).

PSCs are arguably the most promising technology among third generation PV. They are based on semiconductor compounds structured as the actual perovskite mineral, or calcium titanium oxide, and usually consist in hybrid tin or more commonly lead halide materials such as methylammonium lead halide. PSCs can operate as a conventional thin film cell or as a DSSC, and even be combined with conventional crystalline silicon cells to obtain a hybrid tandem device. Thanks to their promising efficiency due to a convenient band gap range and cheap manufacturing costs, they have rapidly advanced in the last years, with lab efficiency increasing from 3.8% in 2009 to 25.5% in 2020 in single-junction architectures, and, in silicon-based tandem cells, to 29.15% (Green et al., 2021). Perovskite is very easy to process from base solutions and also lends itself well to spray application, with the potential to make a number of substrates energy active at a reduced cost, and print processing as well. At this moment, however, perovskite-based cells still suffer from high instability in ambient conditions as the organic molecules part of their hybrid structure quickly degrade when exposed to elements. Long-term stability, along with enhanced power conversion efficiency, is the main scope of current research and development of next generation perovskite solar-cells (Suresh Kumar and Chandra Babu Naidu, 2012). A promising research area on this topic is the use of ML algorithms to identify and describe factors that

TABLE 12.8 Comparison between main PV technologies available on the market: efficiency and energy yield.

Technology	Crystalline Silicon		Thin film		
	Mono-IBC	Poly	CdTe	CIGS	a-Si/ μ c-Si
Product	Sunpower Maxeon 3	TrinaSolar-TSM-PE06H	First solar Series 6	Solar frontiersf170-s	Kaneka U-SA 110
Module efficiency (%)	22.6	17.6	18.3	13.8	9.0
Area (m ² /kW _p)	4.4	5.9	5.5	7.2	11.1
Maximum energy yield at Lat. 55°N (1025 kWh/m ² yr)					
Production for installed power (kWh _{el} /kW _p yr)	871				
Production for installed surface (kWh _{el} /m ² yr)	197	153	159	120	78
Maximum energy yield at Lat. 41°N (1737 kWh/m ² yr)					
Production for installed power (kWh _{el} /kW _p yr)	1476				
Production for installed surface (kWh _{el} /m ² yr)	333	260	270	203	132
Maximum energy yield at Lat. 38°N (1963 kWh/m ² yr)					
Production for installed power (kWh _{el} /kW _p yr)	1669				
Production for installed surface (kWh _{el} /m ² yr)	377	294	305	230	150



FIGURE 12.18 Bifacial crystalline PV cells. Faculty of Architecture—Sapienza University of Rome. *Photo by the author.*

TABLE 12.9 Bifacial photovoltaic cells yield.

Contribution of solar radiation on the back of the panel	0%	5%	10%	15%	20%	25%	30%
Power (Wp/m ²)	160	168	183	190	198	213	220
Module efficiency	16.1%	16.8%	17.6%	18.3%	19.0%	19.8%	20.5%

produce a decay of efficiency, and therefore design more stable cells ([Rangel-Martinez, Nigam, & Ricardez-Sandoval, 2021](#)).

Regardless of the technology employed, produced electricity depends on available sunlight, and therefore latitude, the state of the sky, the temperature, the orientation and inclination of the module, as well as its ability to capture direct as well as diffused solar radiation.

The efficiency of solar cells and modules has steadily increased over time, compared to an equally important cost reduction of installed Wp. Only in the last 10 years, the efficiency of average commercial wafer-based silicon modules increased from about 12% to 17% (super mono 21%). At the same time, CdTe module efficiency increased from 9 to 19%. Between 1990 and 2019, in Germany prices for a typical 10 to 100 kW_p PV rooftop-system dropped from 14,000 €/kW_p to 1050 €/kW_p, a net-price regression of about 92% over 29 years. The experience curve—also called learning curve—started in 1980 shows that the module price decreased by about 24% with each doubling of the cumulated module production due to economies of scale and technological improvements ([Fraunhofer, 2020](#)). Cost information on BIPV products is more difficult to evaluate both because of the wide range of different products and applications and the fact that it is less commonly reported. In Europe, 2017 surveys found prices from 100 to 400 €/m², whereas a standard polycrystalline silicon module has a cost level of approximately 36 €/m² ([Taylor and Jaeger-Waldau, 2020](#)).

Solar models aging and performance degradation has also improved over time, and currently available products come with guaranteed performance of 90% of original power output after 10 years of weather exposure and 80% after 20–25 years, although some high-end manufacturers such as Sunpower and LG guarantee 88%–92% power output on most modules after 25 years of use. Typically, the first year degrade is 2%–3% due to the effects of light induced degradation (particularly present in PERC modules), while in the remaining 24 years will be much less at 0.5 to 0.7% per year. Furthermore, testing on PV products manufactured in the 1980s with lower standards than today already showed >80% performance in a vast majority of samples. Regarding the carbon footprint, a typical silicon crystalline solar panel will generate enough energy to repay the embodied energy within 2–3 years from its installation, down to less than 2 years for high performance panels in many areas with high average solar radiation.

Although standard test conditions measured the power output of a solar panel at a cell temperature of 25°C, in real world use cell temperature generally depends on the ambient air temperature, wind speed, time of day and amount of solar irradiance, ending up 20°C–30°C higher than ambient air temperature, which equates to approximately 8%–12% reduction in total power output, depending on the type of solar cell and its temperature coefficient.

Rising cell temperature reduces power output by a specific amount for every degree above 25°C. This is known as the power temperature coefficient which is measured in $\%/^{\circ}\text{C}$. Polycrystalline silicon cells have an average temperature coefficient of $(-)\ 0.41\%/^{\circ}\text{C}$, whereas monocrystalline cells have slightly better values $(-)\ 0.38\%/^{\circ}\text{C}$. The best performance is that of monocrystalline IBC, equal to around $-0.30\%/^{\circ}\text{C}$, and of monocrystalline HJT cells, which are as low as $-0.26\%/^{\circ}\text{C}$.

PV systems can also be integrated with heat production systems (BIPVs with heat recovery or BIPV/thermal—BIPV/T) with the advantage of requiring less surface area to produce the same amount of thermal and electrical energy compared to side-by-side BIPV and solar thermal technologies. By co-generating solar electricity and heat in a single component, PV/T collectors increase the combined efficiency and yield an optimized utilization of available space, especially in densely populated urban areas. Depending on the climate, operating conditions and design, BIPV/T systems can produce 2 to 4 times more heat than electricity.

In these systems, the absorbed solar energy that is normally wasted as heat is instead recovered either actively, using a fan or pump, or passively by a heat removal fluid flowing on the rear side of the PV layer (see Fig. 12.19). As the fluid, either air or water, circulates behind the PV module, it extracts heat from the cells through convection, reducing the PV cell temperature and therefore increasing their electrical efficiency (Lämmle et al., 2020). Removing heat from the PV cells can also improve PV cell lifetimes.

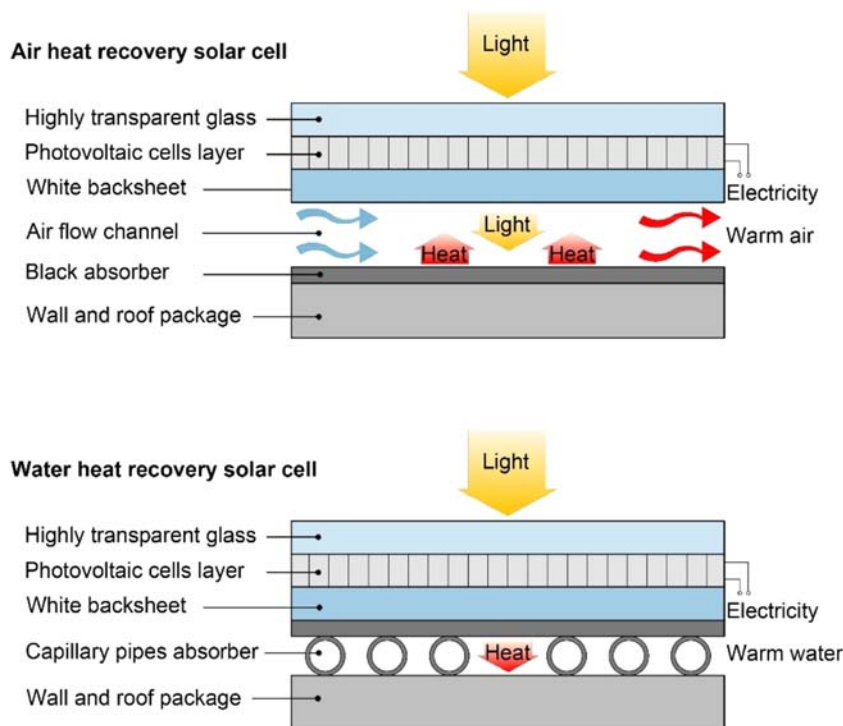


FIGURE 12.19 BIPV/T systems.

Recovered hot air generated in PV/T air collectors can be used for space heating, while the hot water generated in PV/T water collectors can be used for swimming pool heating, space heating (directly for low temperature underfloor panels or indirectly in combination with heat pumps for improved COP), or domestic water heating.

BIPV/T systems have been demonstrated as part of various composition of the structure, such as wall, roof, window, and shading devices (Maghrabie et al., 2021). PV/T technology has also been the focus of IEA SHC Task 60, application of PVT collectors.

Several commercial hybrid PV/T systems for building adapted installation are already available or about to enter the market. Naked Energy's Virtu PVT hybrid panel, for example, combines high efficiency vacuum tube technology to harvest solar heat with electricity production by a monocrystalline silicon solar cells array covering the coaxial water tube. VirtuPVT claims conversion of 20% of the sun's energy to electricity and 60% as heat, with a peak efficiency of 80%. Other hybrid models such as DualSun's Spring and Fototherm AS are instead optimized for BIPV/T applications and come as a preassembled package with a monocrystalline silicon panel on the front, indistinguishable from an ordinary PV panel, and a heat exchanger on the back to produce hot water. Electricity generation is claimed 15% higher than comparable nonhybrid PV modules, with a thermal power of more than 600 W/m².

12.3.1.2 Building augmented wind turbines

In the last decade, the development of small wind turbines, quiet and specified for urban use, has allowed to harness wind power also for building on-site energy generation. These turbines, reaching a maximum of 20 kW of power, can find space on rooftops or in gardens, have relatively little visual impact and are able to produce energy even from modest wind flows. Moreover, in contrast to large wind turbines, such systems do not require major infrastructures for electricity transmission to utilities and lend themselves to distributed generation. Small wind systems can be used as stand-alone systems or as grid connected systems as well, and both can be paired with other energy conversion systems, such as PVs, and with energy storage solutions. At the end of 2015, at least 990,000 small wind turbines were installed worldwide, with a 5% increase compared to the previous years. The associated power generation capacity was mentioned more than 945 MW, up 14% compared to 2014 (Small Wind World Report Update, 2017).

Small wind turbines can have either horizontal or vertical axis, the latter being of particular interest for the application on buildings (see Fig. 12.20). Unlike classic horizontal axis wind turbines (HAWT), which need to be always aligned to the wind direction, generators with vertical axis rotors (vertical axis wind turbines, VAWT), thanks to the helical blade profile or the presence of arms, are able to capture incoming wind from any direction, and therefore do not need to be oriented; they can also take advantage of turbulences. The wind speed necessary for starting is 2–3 m/s, and noise production is almost zero for low to normal winds. For small powers up to 1.5 kW, they can be installed directly onto the building. With a vertical axis, the generator and other primary components can be placed near the ground, with no need for the shaft to support them and easier accessibility for maintenance.

Although vertical axis wind turbines can have different shapes, they can be divided in two main groups (see Fig. 12.21): the Savonius turbines (developed in 1929) working primarily on the aerodynamic drag principle, and the Darrieus turbines (1931) which operating on the principle of lift.

Savonius turbines are commonly used when high reliability is required, such as in ventilation and anemometer applications. Being drag-based, they are less efficient than the common HAWT, but are excellent in areas of turbulent wind and can self-start at low wind speeds.

Darrieus wind turbines have good efficiency but produce large torque ripple and cyclic stress on the shaft, which decreases their reliability. They also generally require some external power source, or an additional Savonius rotor, to

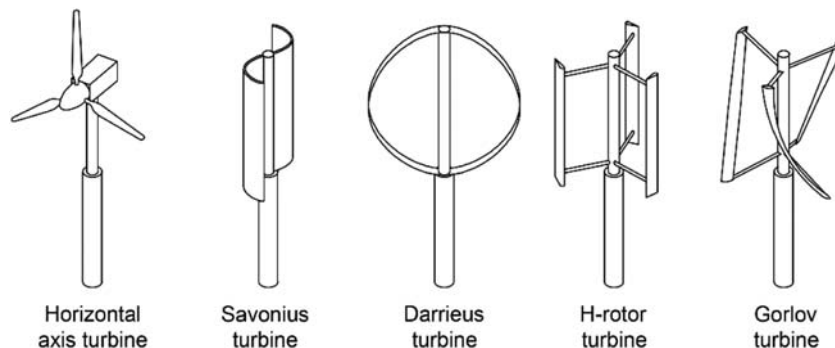


FIGURE 12.20 Types of wind turbines.



FIGURE 12.21 Darrieus (left) and Savonius (right) wind turbines. Photos by the author.

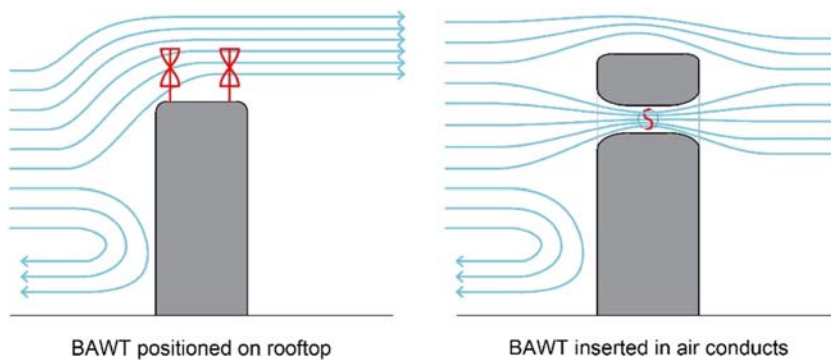


FIGURE 12.22 Building augmented wind turbines configurations.

start turning because of the very low starting torque. Torque ripple is reduced by using three or more blades, resulting in a higher solidity of the rotor. Solidity is measured by blade area over the rotor area. Darrieus turbines can either have circular or straight wings (the latter called H-blade Darrieus); a further development has a helicoidal winged design called Gorlov, after its inventor, and it is more efficient.

Rooftops can be an excellent location for wind turbines, both because the electric power generation is close to the user and because they allow to take advantages of faster winds while reducing the cost of support towers. However, the turbine can guarantee its best outcome only if the wind, its characteristics of flow, and wind direction are measured accurately before installation, because turbulences or areas of calm, generated by surrounding buildings or different obstacles located on the roofs (air conditioning systems, antennas), could lead to an energy production significantly lower than expected. The process of estimating the amount of wind energy in any plant is defined as wind energy assessment (WEA) and has the main objective to select the location and wind turbine for the proposed wind farm regarding the characteristics and availability of wind. Wind resources in urban can be estimated by using anemometry on-site and CFD simulation (Tasneem et al., 2020).

At the same time, it is possible to benefit from the interaction between the wind and the built environment in order to channel air currents to very specific areas where wind turbines can be installed. Turbines able to exploit the concentration of wind power due to the shape of the building are known as building augmented wind turbines (BAWT) and their configurations can be divided in two main groups (see Fig. 12.22):

- BAWT located on the building, on the rooftop or along the sides, exploiting the acceleration of the air flow at the upper corners and the sides of the facade of the building;
- BAWT inserted in air conducts through buildings in order to use the difference in air pressure generated by the winds that affect the opposing facades (passing wind ventilation).

One of the most interesting examples of BWAT is the 309-meter-tall Pearl River Tower by SOM in Guangzhou (China). Completed in 2010, the tower's sculpted body directs wind to dedicated openings at its mechanical floors, where accelerated winds push Savonius VAWTs that generate energy for the building. Other integrated sustainable elements include solar panels, a double-skin curtain wall, a chilled ceiling system, under-floor ventilation, and daylight harvesting, all of which contribute to the building's energy efficiency (see Figs. 12.23 and 12.24).



FIGURE 12.23 Pearl River Tower. *Courtesy of SOM.*



FIGURE 12.24 Savonius VAWT inside Pearl River Tower. *Courtesy of SOM.*

In all three cases, the areas of effective availability of air currents are limited compared to the whole building surface, requiring the use of compact and properly located rotors to take advantages of them. Moreover, power augmentation concepts can also be implemented by using diffuser and shrouded brims around wind turbines with significant

power coefficient increase: such mechanisms can re-direct and accelerate the airflow over the building rooftop towards the wind turbine, which can be installed inside of the diffuser casing to minimize visual and noise disturbance (Dilimulati, Stathopoulos, & Paraschivoiu, 2018).

Today there are many models of VAWT turbines on the market, with different dimensions and characteristics according to the use and power ranges from 200 W to 10 kW. The most widely used material for their manufacture is aluminum, with Darrieus turbines often employing glass fiber and carbon fibers for their blades.

Darrieus turbines, and their development, Gorlov turbines, constitute the best solution to obtain maximum energy production. With the same generator power, yields are generally higher than traditional Savonius solutions (a UGE Vision Air 5 with 3.2 kW of power promises 4000 kWh/year of electricity production at an average speed of 5.5 m/s, while a comparable Savonius model, Helix Wind S594, does not reach 3,000 kWh/year even with a higher average speed—7 m/s—and a more powerful generator—4.5 kW). Their structure is, however, more fragile than Savonius', and they need braking systems in case of excessively fast winds (models like the Kessler Spinwind do not work with wind speeds over 16 m/s).

The Savonius turbines, basing their operation on wind drag rather than wind lift, are limited by the tangential speed of the blades, which in any case cannot exceed the speed of the wind pushing them. They are quicker to start than the Darrieus or Gorlov (products like Turbine Energy already begin to produce electricity with winds of 1.5 m/s), but need higher air speed to perform at their best, managing to maintain productivity even with winds exceeding 30 m/s.

Some more innovative models on the market take advantages of the features of both: such hybrid designs of Darrieus and Savonius are driven by both drag and lift forces and have better efficiency and self-starting capability. An example of hybrid VAWTs is DS-700 by Hi-VAWT Technology Corp, which consists of an S-type Savonius rotor with three Darrieus airfoil blades to maximize the performance: it can generate electricity from the wind at relatively low cut-in wind speed (2 m/s) and achieves rated capacity (700 W) at 10 m/s (Kumar, Raahemifar, & Fung, 2018).

Darrieus model always present a higher production of electricity per power unit for any wind speed compared to the Savonius model, even in case of high deviations of the average annual wind speed compared to the minimum and maximum average. However, in terms of produced energy cost for average annual wind speeds exceeding 12 m/s the Savonius is more convenient. The production of electrical energy of Darrieus turbines remains in fact constant over 9 m/s, while the production of the Savonius increases with the increase of the wind speed without operating limits (Casini, 2016).

Compared to PV systems, it is apparent that for values of solar irradiance between 1000 and 1500 kWh/m² (typical European values), wind systems are competitive in terms of produced energy cost for average annual wind speeds between 6 and 8 m/s for Darrieus turbines and 9 and 11 m/s for Savonius. A 4 kW Darrieus turbine 4.5 m high (cost about 20,000 €) produces at 8 m/s approximately 13,000 kWh per year, corresponding to the production of more than 90 m² of polycrystalline PV panels exposed to a solar irradiance of 1250 kWh/m² (cost over € 27,000). Regardless of wind speed, wind systems also provide a viable alternative to PV systems in the case of small available surfaces or lack of sunlight access (Casini, 2016). Obviously, in view of the need for wind power plants to maintain a minimum distance between the generators (at least 4 times the diameter), the possibility of installing more turbines depends on the geometry of the roof and the available power may be less than the one reached by the use of a PV system installed on the same surface. In such situations the Savonius turbines, which require a lower minimum distance (5 m) in comparison with the Darrieus, may allow a higher installed power.

12.3.1.3 Energy harvesting systems

Energy harvesting refers to the collection of energy dispersed by users and by ancillary building services for their operation, which is usually wasted. Examples of energy harvesting systems, which are becoming particularly interesting for the integration of renewable resources at urban and building scale, include pavements able to generate energy from pedestrian or vehicular traffic (see Fig. 12.25), and in-pipe hydro systems that convert excessive pressure in the distribution grid into electricity.

Energy generating pavements are either based on the piezoelectric effect, in the case of Veranu tiles, or on electro-mechanical power conversion, such as for Pavegen and Energy Floors Dancer. The piezoelectric effect consists in the property of some crystalline materials to polarize when subjected to a mechanical deformation (direct piezoelectric effect), generating a potential difference, and at the same time to deform in an elastic manner when traversed by electrical current (inverse piezoelectric effect). The piezoelectric effect occurs only along one direction and deformations associated with it are the order of nanometers. Many common devices, including doorbells, speakers, and microphones or quartz watches are based on piezoelectric technologies. Veranu tiles exploit piezoelectric elements to harvest energy



FIGURE 12.25 Energy-generating pavement. Courtesy of Pavegen.

from kinetic stress induced by walking pedestrians. Each Veranu tile, a square 30 cm wide and 4 cm thick, can be positioned over the existing pavement and produces up to 2 W of electricity for each step, which can be used to power urban lighting systems or to detect pedestrian movements for crowd control or consumer tracking.

Pavegen V3 tiles are instead triangular, with 50 cm side and 10 cm thick, and generate 5 W continuous power from footsteps via electromechanical power conversion. As people step on the tiles, their weight causes the top surface to vertically displace by between 5 mm and 10 mm. This creates a downward pressure on the three generators beneath each corner of the tile, initiating a rotation in their electro-magnetic mechanisms, to produce current and data. The tiles also have wireless sensors to collect real-time footfall data about movement behavior in areas where Pavegen is installed. This can help to create an idea of peak times for foot traffic in an area, predict consumer trends, and create heat maps of popular urban spaces. Energy Floor Dancer tiles work similarly: modules flex when stepped on, and the electromechanical system transforms this small vertical movement into a rotating movement that drives a generator. Each module by the size of 75x75x20 cm can produce up to 35 watts of sustained output and between 5 and 20 Watt per person.

As energy harvesting devices, in-pipe water to wire power systems are becoming particularly interesting for the integration of renewable resources at city and building scale because of the potential to harness clean energy from excess head pressure in urban and domestic water pipelines (Casini, 2015).

Able to operate across a wide range of head and flow conditions, these particular micro-hydro power systems can be deployed in municipalities, energy-intensive industries and agricultural irrigation districts providing a consistent amount of clean and continuous energy without the typical intermittency of wind and solar, while at the same time helping in pipelines management and maintenance. All cities are served by pressured piping grids systems to supply water where it is needed for drinking, domestic or industrial use, while drain and sewage systems are usually gravity fed. Untapped energy potential derives from excessive grid pressure, which makes drinking water processors and industrial manufacturers typically install pressure reduction valves (PRV)—hydraulic devices that maintain preset pressure ranges—to relieve the excess pressure and release it as waste heat. Theoretically, all systems that employ pressure reducing devices could replace them with in pipe generators, maintaining the same control on water flow and pressure while producing usable electricity. Small turbines can be used to power water metering and control stations that are isolated from the electrical grid in exchange for a negligible loss of water head allowing to reduce water lost due to spilling and leaks, in particular in countries where the water resource is scarce and the infrastructure aging. For instance, in Israel, several microturbines have been deployed to power pressure regulators, flow and water quality measurers that supply control centers with 24/7 data and allow for quick responses in case of leakage or pressure loss.

The harvested energy can be returned to the electric grid as well and used alongside other renewable and traditional energy sources: examples include the Lucidpipe Power System installed in 2015 in Portland (United States), constituted by four 42" vertical axis turbines for a total 200 kW power, or the twin Rentricity turbines installed in the Keen (US) water treatment facility, with a combined output of 55 kW.

In-pipe hydro power systems can be divided in two main designs (Casini, 2015) (see Fig. 12.26):

- internal systems, where the runner is entirely contained within the pipe section and only the generator protrudes from the conduit;
- external systems, where the runner is contained in a secondary conduit that bypasses the main one.

Internal systems have the advantage of a more compact size that makes them more suitable, but not restricted, for smaller applications. Power output ranges from 5–10 watts, sufficient to supply self-powered water metering or monitoring systems, to 100 kW for more energy intensive applications. External systems do not depend so strictly on pipe

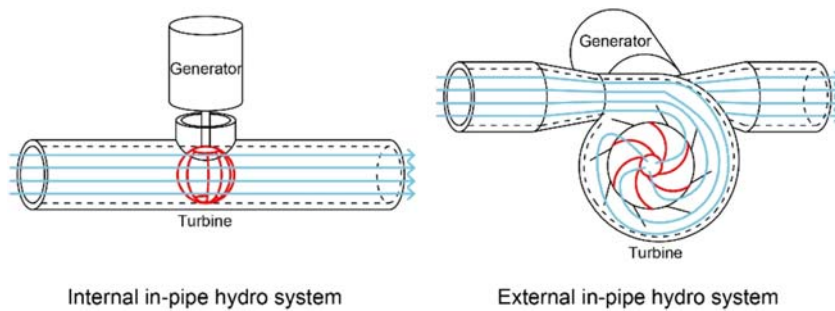


FIGURE 12.26 In-pipe hydro power systems.

size since the runner is enclosed in a dedicated conduit and allow for even greater flexibility. Their main drawback is the need for larger vaults to accommodate the turbine and generator assembly, making them less ideal for retrofit intervention on existing water infrastructures.

In addition, potential energy lies in the piping systems of single buildings, for tap water supply, drainage and cooling and heating circuits, with particular regard to larger structures such as commercial and residential high-rises or shopping malls. In particular, skyscrapers require large amounts of pressure to supply water to the higher floors, and the excess pressure in the lower section is usually wasted via PRVs. These systems, usually below 5 kW (pico-hydro), can exploit the overpressure normally available on the lower floors or be integrated in the pipes of single habitation units along with measuring sensors, constituting self-powered IoT water monitoring tools able to transmit via Wi-Fi information such as water consumption, operating temperature and water quality and contributing to the intelligent management of all energy services of the building.

12.3.2 Building electricity storage

Electricity storage is becoming an increasingly important feature of any power system, from large macrogrids to the scale of the single building, as it is well complementary to the diffusion of RES and of smart grids and smart meters that allow a more informed exchange of energy with the utilities (Miao Tan et al., 2021).

In fact, electricity storage copes with the fact that, unlike other fuels, all the power we use is generated just moments beforehand and must be consumed instantly, which makes temporary balancing of energy supply and demand a key challenge, particularly considering the rising importance of electric mobility on the demand side, and of VRE sources (i.e., dependent on weather conditions) on the supply side. Therefore, electricity storage has become an important element of the global transition toward carbon neutral energies, and, according to the IEA, close to 10,000 GWh of energy storage capacity across the energy system will be required annually by 2040, compared with around 200 GWh in 2020 (IEA, 2020d).

An electrical energy storage system typically consists in a storage unit and in a power-converting unit. Direct current voltages are utilized for operating the energy storage unit with the aid of an inverter for transforming the DC current to alternating current (AC), which can in turn be consumed on the spot or added to the grid. Conversely, a rectifier transforms AC to DC to recharge the storage systems (Olabi et al., 2021).

Depending on the size and application of the electrical energy storage, several solutions are currently employed or under development mainly based on chemical, mechanical or electrochemical operation.

Chemical storage systems use excess electricity to generate chemical fuels via power-to-gas (P2G) processes, mostly using electrolysis to produce hydrogen which can be stored then used when needed to fulfill directly the additional demand using fuel cells, or converted into other energy carriers (synthetic gas, methane, or LPG). These systems have still little diffusion due to technological and infrastructure limitations, but are seen as a great potential in view of their high energy density, long storage stability and variety of applications (electricity distribution itself, but also heating and mobility) (Stadler and Sterner, 2018).

Mechanical storage systems transform electricity into mechanical energy, and operate based on either kinetic energy (e.g., accelerating and decelerating a flywheel), gravitational potential (e.g., pumping water uphill in hydroelectric plants to store it for later use in turbines), or pressurized gas (e.g., compressing air into vast reservoirs such as underground caves then letting it out to turn turbines). They are mainly applied at the macrogrid level by pumping water in hydroelectric dams, and today account for 91% of global installed electricity capacity. However, their scale makes them inherently unsuitable for distributed or urban applications.

Lastly, electrochemical storage systems use electricity to perform chemical reactions which can be reversed at will to obtain power back. These include common batteries and more specific applications such as supercapacitors. This storage technique benefits from the fact that both electrical and chemical energy share the same carrier, the electron, allowing to limit the losses due to the conversion from one form to another. Electrochemical batteries are seeing increasing applications at both grid and building levels and are perceived as a key element for meeting current environmental and energy security objectives, although large-scale applications are constrained by their cost, and they accounted for only 5% of global installed capacity in 2020. In particular, building applications of battery storage, indicated as BTM, have proven extremely beneficial in enabling a more productive exploit of on-site generated energy and more advanced strategies of energy exchange with the grid (DR, peak clipping, load shifting, etc.). Today, battery storage is arguably the most common electricity storage solution employed worldwide in terms of number of installations, and has seen remarkable R&D efforts spurred by the advancements in mobile device technologies and, in the last ten years, electric mobility. This progress has greatly reverberated into building energy storage systems, which have seen substantial improvements in cost to capacity ratio, size, longevity and safety of use, and are therefore seeing increasing market penetration. For reference, 40% of recent rooftop solar PV systems in Germany have been installed with BTM batteries, and 21,000 BTM battery systems have been installed in Australia by 2017, aiming at 1 million BTM batteries by 2025 (IRENA, 2019i).

BTM batteries can provide tangible benefits to both single consumers and the energy infrastructure at large (see Table 12.10). They can store the excess electricity from distributed generation technologies, such as rooftop solar PV systems, to be used for local consumption when needed. In countries where electricity injected into the grid is not remunerated, BTM battery storage can lead to increased self-consumption of the electricity produced by solar PV systems and improve return of the investments for distributed, on-site renewables, promoting their deployment. From the grid side, in places with high penetration of rooftop solar PV systems, distribution system operators could struggle to absorb highly variable generation from distributed sources. BTM batteries maximize the local usage of such variable generation and minimize exports to the grid, supporting the system and avoiding issues related to the backflow of variable power. Fig. 12.27 shows a typical solar PV generation curve, as well as the battery charging and discharging cycle increasing the hours of self-consumption.

Moreover, BTM battery storage greatly increases the energy resiliency of consumers: in case of grid outage, it can provide back-up power at various scales, ranging from sub-second-level power supply for important industrial operations, to whole days of island operation if paired with an on-site solar PV system.

Technically, a battery is constituted by multiple cells linked in series or parallel to provide the desired voltage and capacity. Each cell consists of two conductor electrodes and an electrolyte, coupled inside a sealed container and linked to the external circuit (either a power source or load). The reversible chemical reaction involves the transfer of electrons from one electrode to the other. Battery assemblies are completed by a dedicated control and power conditioning system, the battery management system (BMS), to ensure the safest operation of the entire system.

In particular, the BMS manages the operational behavior of a battery and integrates it into the equipment that charges it or uses its output; it plays an essential role in maximizing the battery's lifetime, for example, by regulating its temperature to stop overheating and by distributing the charge evenly across the cells to avoid damage caused by undercharging or overcharging individual cells. It also ensures that the battery does not operate outside its safe current, voltage and temperature boundaries.

TABLE 12.10 Service provided by BTM battery storage systems.

Electricity consumers	Increased self-consumption Backup power Savings on electricity bills Demand charge reduction
System operation	Frequency regulation Network investment deferral Peak capacity Investment deferral
Mini-grids	Replacing diesel generators Backup power Smoothing of VRE

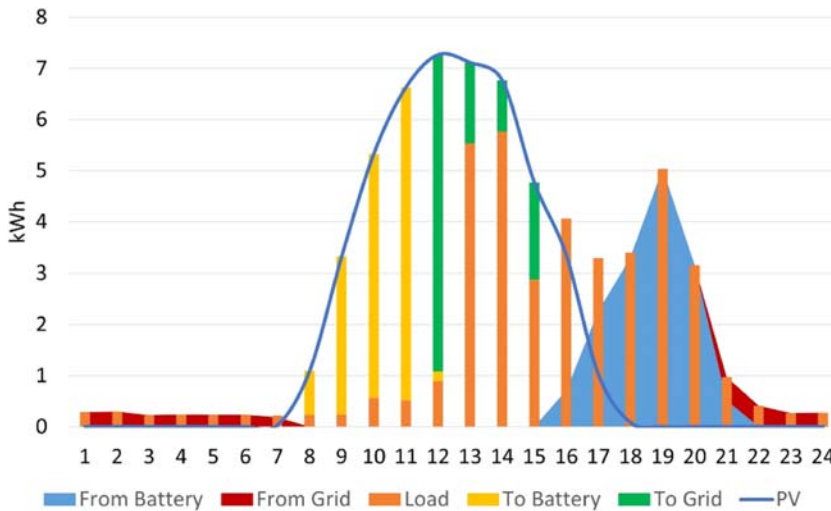


FIGURE 12.27 Daily energy flows of a home PV system with battery energy storage.

Performance of batteries for energy storage use is indicated by the following main specifications:

- capacity, which refers to the total amount of electricity that can be stored (measured in kWh or Ah). Most batteries are designed to be stackable to get the desired capacity (multistorage systems).
- power rating, which is the amount of electricity that a battery can deliver at a given moment (measured in kW). Considering building applications, a battery with a high capacity and a low power rating would deliver a low amount of electricity (enough to run a few crucial appliances) for a long time, whereas a battery with low capacity and a high-power rating could run multiple systems, but only for a few hours.
- efficiency, which refers to the amount of energy that can be used as a percentage of the amount of energy that it took to store it (also called “round trip efficiency”). Higher efficiency translates to better economic value for a given capacity.
- depth of discharge (DoD), which indicates the maximum amount of a battery’s capacity that can be used for optimal performance. For instance, a 10 kWh battery with 90% DoD should not be used for more than 9 kWh before recharging it, otherwise its useful life may be shortened.
- guaranteed cycles, which refers to how long the battery will maintain its ability to hold a charge after a number of charge and discharge cycles, which in building applications often occur daily. For instance, a battery warrantied for 5000 cycles or 10 years at 70% of its original capacity, will have lost no more than 30% of its original ability to store energy at the end of this period.

Main battery storage methods for building applications are lead-acid and lithium-ion technologies. Lead-acid batteries are a well-established and relatively inexpensive technology, and are the only ones virtually 100% recyclable, however they are heavy and bulky (energy densities up to 30 Wh/kg and 120 Wh/l), slow to charge and sensible to environmental conditions which may shorten their lifespan and decrease their efficiency. DoD of lead-acid batteries is also inferior compared to other technologies. Lead-acid batteries are mostly used in larger scale applications such as backup power in technological facilities but are less suited for smaller applications like residential buildings. Lead-acid technology is still advancing with the release of higher performing tubular gel or lead-carbon products by manufacturers that include BAE, Sonnenschein, Deka, GS Yuasa, and YHI Power. These batteries usually come in single units, similar to those used in the automotive sector and with capacity between 50 and 100 Ah, and are assembled to the desired capacity.

Lithium-ion batteries are by far the most popular battery storage option today—they constitute more than 90% of the global grid battery storage market—and share the same technology of batteries found in most mobile devices, laptops, and EVs (Ajanovic, Hiesl, & Haas, 2020). Compared to lead-acid batteries, they have higher power density, meaning lighter and more compact installations (energy densities of 150–300 Wh/kg and 250–650 Wh/l), and better efficiency over time, which offsets their higher upfront investment into lower life-time costs. There are several types of lithium-ion chemistry used in home batteries, such as lithium nickel-manganese-cobalt (NMC), used by Tesla and LG Chem, or lithium iron phosphate (LiFePO₄, or LFP) which is said to be safer than NMC due to lower risk of thermal runaway (battery damage and potential fire caused by overheating or overcharging) but has lower energy density and is used in home batteries made by muRata, BYD, and Sonnen.

Concerning ongoing development, a large effort worldwide is directed toward research and development for various advanced Li-ion as well as post-Li and non-Li-ion battery technologies, such as:

- all solid-state Li-ion batteries with Li metal anodes (ASSB LiM);
- lithium-sulfur batteries (Li-S);
- sodium-ion batteries (Na-ion);
- RedOx flow batteries, including these with organic shuttles (organic RedOx).

These developments have the potential to deliver higher energy density (ASSB LiM, Li-S), improved safety and higher power density enabling fast charging (ASSB LiM, organic RedOx), reduced cost (Na-ion, Li-S), potential to avoid scarce or critical raw materials (CRMs) (Na-ion, Li-S, organic RedOx), extended lifetime and exceptional scalability and flexibility (organic RedOx), allowing a greater uptake of electricity storage in a variety of applications.

In particular, ASSB LiM, expected to enter the market by 2030, present a number of advantages compared to conventional Li-ion batteries with liquid electrolytes, including higher energy densities up to 700 Wh/kg and 1400 Wh/l, improved safety as no flammable, toxic or corrosive electrolyte is present, higher power output enabling faster charging, broader operational temperature range up to $>100^{\circ}\text{C}$, as well as longer shelf life (low self-discharge rate) (Lebedeva, Ruiz Ruiz, Bielewski, Blagoeva, & Pilenga, 2020).

The wider adoption of home-sized PV systems, governments incentives, as well as variable energy price programs from utilities, have greatly expanded the market for plug-in domestic-sized building energy storage solutions (see Fig. 12.28), and today several solutions are available (see Table 12.11).

These products come as self-enclosed boxes or cabinets to allow free floor or wall-mounted installation, normally have capacity ranges between 3 and 20 kWh, often stackable, with a price of 800–2000 \$/kWh depending on features such as built-in AC-DC inverter or powercut backup (i.e., the ability to continue supplying the home during a blackout). Manufacturers include established actors such as LG Chem, Samsung or Varta, and also some automotive companies (Tesla, BMW, Nissan) that aim to leverage their EV expertise or create a market for second life EV batteries. In fact, batteries in EVs are commonly replaced once storage drops to about 70%–80% of its initial capacity and makes the driving range excessively short. Such residual capacity, however, is still suitable for stationary energy storage for



FIGURE 12.28 Examples of main home batteries on the market: Tesla Powerwall (top left), BYD B-Box (top center), Triple Power T45 (top right), Sonnen ECO (bottom left), LG Chem RESU (bottom center), Varta Pulse (bottom right).

TABLE 12.11 Main domestic electricity storage solutions on the market.

Manufacturer	Model	Type	Use	Capacity (kWh)	Power (kW)	Chemistry	Cost \$/kWh
LG Chem	RESU	DC, 48 V	Storage Backup Off grid	3.3–13	3.5–5.0	Lithium NMC	738
Tesla	Powerwall 2	AC coupled	Storage Backup	13.5	7.0	Lithium NMC	890
Sonnen	ECO	AC coupled	Storage Backup	4–16	3	Lithium LFP	1188
BYD	B-Box Pro	DC, 48 V	Storage Backup Off grid	2.5–10.2	2.5–10.2	Lithium LFP	710
Varta	Pulse 6	AC coupled	Storage	6.5	2.5	Lithium NMC	1100
Triple Power	T45/T63	DC, 100 V	Storage Backup	4.5–6.3	2.5	Lithium LFP	742

buildings and grid applications, and their reuse would improve the overall economic efficiency of EV as well as decreasing the environmental impacts due to longer battery operative life (Aziz, Oda, & Kashiwagi, 2015).

Home batteries are particularly beneficial when coupled with on-site energy generation systems such as PV panels, as they allow to store unused energy generated during the day and exploit it at night or during peak demand, minimizing the energy taken from the grid over the whole 24 h. In battery-less PV systems, in fact, the electric grid itself acts as a virtual storage system, which buys generated energy not consumed on the spot, then sells it back when needed. As PV electricity subsidies are decreasing; however, the feed-in price has become lower than the buying price, diminishing their economic viability. By adding a battery to the system, the self-consumption ratio, therefore, the profitability, can be greatly increased (Kharseh and Wallbaum, 2017). Appropriate control of the flows of energy from the PV system and between the battery and the grid can also allow to implement energy management strategies, such as storing cheap energy from the grid in off-peak times and selling PV production when the feed-in price is highest, or filling the batteries before impending grid disturbances (cloudy days, scheduled maintenances, severe weather phenomena) to ensure operation of home services.

Identifying the correct capacity of the home battery system to install mainly depends on the expected purpose, whether to ensure off-grid operation during emergencies or to maximize self-consumption and profitability of the system. In the former case, the system should be dimensioned to ensure at least a day's worth of backup power, whereas in the latter case the optimal size largely depends on local electricity prices and helps to reduce the payback time of the PV system even though the up-front costs of such a system is increased (Kharseh and Wallbaum, 2017).

12.3.3 Vehicle to building

Building-based energy storage systems are showing promising growth, however their contribution to the smart grid in terms of capacity is still shy of the capacity needed at the system level to store excess power from discontinuous renewable energy sources (wind and PV) as well as to shift electricity demand from peak to off-peak pricing. A viable solution to overcome this issue is the exploitation of batteries inside EVs when connected to the grid, a technology known as Vehicle-To-Grid (V2G), Vehicle-To-Building (V2B), Vehicle-to-Home (V2H), or even Vehicle-to-Everything (V2X) depending on battery technology status (Buonomano, 2020). Potential benefits of this technology are substantial, as it is estimated that the cumulative battery capacity of the EV fleet will amount to 16,000 GWh in 2030 and about 5% of this could be available for V2G, unlocking several hundreds of gigawatt-hours to help grid management (IEA, 2020c).

Grid integration of EVs, PHEVs or FCEVs is based on the communication with energy providers to manage either unidirectional or bidirectional energy flows: in the first case, EVs are able to schedule or throttle their charging rate to

modulate demand on utility loads (so-called V1G), whereas in the second case they can also return stored energy to the grid or to the building (see Table 12.12).

Bidirectional energy exchange requires the correct infrastructure on both vehicles and chargers. Currently, it is only accessible through DC chargers using the CHAdeMO protocol, which are typically associated with public fast-charging stations (see Fig. 12.29), although reduction in size and price may ultimately allow for widespread domestic use as well (Zecchino, Thingvad, Andersen, & Marinelli, 2019). Energy exchange can in turn occur with the main grid or with local microgrids. These are commonly limited to single households, although pilot projects of tertiary buildings with V2B fleet have been demonstrated. EVs have in fact on-board batteries with capacity and power rating at least equal, or more often superior, to building installations—around 10 kWh for PHEVs, 40 to 60 kWh for entry-level EVs such as the Nissan Leaf or Chevrolet Bolt, up to 100 kWh for upscale models such as the Tesla Model S, with charge/discharge speed of 3 or 10 kW on current technology. A V2B enabled EV can therefore be used when parked at home to increase self-consumption of energy produced on-site, akin to a building-integrated battery, and as a back-up power supply during power outages, providing up to several days' worth of electricity.

V2B applications are still mostly at the prototype stage, with market solutions already established only in Japan where bidirectional flow EVs and PHEVs have been available from 2012, marketed as backup power solutions after the 2011 Tōhoku earthquake and tsunami, and gaining interest in places such as California (United States) where about 40% of EV and PHEV owners also own solar PV systems (Delmas, Kahn, & Locke, 2017).

Relevant large-scale applications of V2B include the Edison Project in Denmark, in which plugged-in EVs are used to store excess power produced by wind turbines and to release it during peak demand times, or the proposed integration of United States electric school bus fleets, which are usually plugged-in for most of the day, in V2G programs to supplement the grid in peak-demand times, and act as storage when demand is low.

TABLE 12.12 Different integration of EV infrastructure with building and grid management.

Type of EV charging/ discharging	Smart control over charging power	Possible uses
Uncontrolled EV charging with time-of-use tariffs	None	Peak shaving by the user following demand response; long-term grid capacity management
Unidirectional control (V1G)	Real time adjustment of the charging rate	Grid congestion management
Bidirectional vehicle-to-grid (V2G) and grid-to-vehicle (G2V)	Instant charging/discharging reaction to grid conditions	Grid frequency and voltage control; control of VRE loads in the grid, distributed energy storage, distributed power backup
Bidirectional vehicle- to-X (e.g., V2H/V2B)	Integration between V2G and building EMS	Smart energy building and micro-grid optimization, building energy storage, building power backup

VRE, Variable renewable energy; EMS, Energy management systems.



FIGURE 12.29 EV charging stations. Photos by the author.

However, the large-scale implementation of these techniques currently faces a number of challenges, including the lack of standardized communication protocols which affects interoperability, the need to invert the DC power of the EV back to AC which inevitably incurs some losses, as well as unclear models to manage the energy stored in the EVs according to the preferences of the owners as well as the needs of the electric grid. In particular, round-trip efficiency of EV Li-ion batteries is usually over 90%, but is reduced in V2B applications limiting the benefits of the operation. V2B energy losses were extensively investigated in the Smart Grid Interoperability Laboratory of the EU Joint Research Centre JRC site in Petten, the Netherlands, which is equipped with a Nissan Leaf ZE1 EV and a bidirectional 3-phase CHAdeMO charger with a (-) 10 kW (discharge)/ + 6.6 kW (charge) range. The round-trip efficiency of such setup was determined to be about 80% for the studied charging/discharging power levels, observing an important role of the charger itself. In this case, 80% efficiency translates in ca. 8kWh loss, enough to power an average house for a day (Videgain Barranco and Covrig, 2021). In other experiments, power losses in the whole V2G were as low as 70% (Apostolaki-Iosifidou, Kempton, & Codani, 2018). Furthermore, the added strain and charge/discharge cycles of EV batteries may reduce their lifespan, and thus discourage EV owners to lend their vehicles to V2G programs as batteries themselves make-up for a substantial part of the total cost of the vehicle and are expensive, if not impossible to replace.

12.3.4 Demand response

The term Demand Response (DR) encompasses many different strategies by which commercial, residential, municipal, and industrial electricity customers are incentivized to adjust, in the short-term, when they use electricity (United States DoE, 2016). Therefore, DR is fundamentally different from energy efficiency and energy conservation policies, that instead seek to reduce total electric load. In particular, DR refers to any program and strategy established to incentivize end-consumers of electricity to adapt their consumption patterns in response to changes in electricity prices in the grid. For its operation, DR takes advantage of the two-way communications and information networks between the smart grid and users' smart meters. From the user side, DR asks commercial, industrial, and household consumers to respond to electricity market variations by modulating their energy withdrawal from and feed-in to the Smart Grid in exchange to economic benefits, whereas from the utility operator side, it allows to achieve energy saving measures, peak load shaving, improve the efficiency, stability and flexibility of the grid system, and reduce the need for power investments (Hussain and Gao, 2018).

DR as a strategy aims to address the issues related to the daily variations of the demand, which usually peaks in determined times and is lower in others, such as nighttime. Supply-side, conventional power sources (nuclear, coal, fossil fuel power plants) have little modulation capacity and operate more efficiently at their optimal regime, hence are ill suited to face these demand peaks. On the other hand, renewable energy sources such as PV or wind power are being more and more integrated in the grid, but are inherently discontinuous in their supply and add uncertainty to the baseline supply. This has led to oversizing both generation capacity and grid distribution, decreasing the efficiency of the whole energy supply chain.

In this picture, DR is an evolution of established incentives to spread consumer demand as evenly as possible over the 24 h and reduce peaks. These include cheaper prices of electricity at nighttime and in weekends to promote the use of energy hungry services in those moments, or the separate billing of overall consumption and instant demand by enforcing "peak demand charges" that is, charging more when the user needs power at higher intensities for shorter time periods. In this case, for instance, a manufacturing plant may decide to switch its machines on not all at once, but rather one by one over a longer period.

Generally, the current DR schemes can be classified into two types: "incentive-based" and "price-based," although other names include "system-led" and "market-led," "emergency-based" and "economic-based", or "direct" and "indirect" DR (Haider et al., 2016).

In incentive-based schemes, customers (mainly industrial or commercial ones, although residential communities and single households are both entering this market) are encouraged to modulate their energy consumption upon request offers or according to a contractual agreement between the customer, the aggregator, and the grid operator. Normally, incentive-based DR is carried out as follows: the grid operator, which is responsible for managing the electricity system and ensuring it remains stable, notifies the aggregator of the necessity for a balancing order when a grid stability problem occurs; the aggregator, also referred to as the BSP (balance service provider), must establish the load and/or generation capacity in its portfolio of customers that will be required to increase or decrease energy use; clients implement (either manually or automatically) the modulation plans, reducing stress on the grid, and receive remuneration in exchange for the amount of capacity delivered for the dispatch. A common type of incentive-based DR is direct load control (DLC), in which customers agree to provide program administrators with direct access to their premises for on/

off operation, schedule or disconnection during peak time intervals, although this approach poses potential privacy issues (Hussain and Gao, 2018).

In price-based schemes, instead, customers are offered time-varying rates that reflect the value and cost of electricity for different time periods, and are encouraged to react to the fluctuations in the electricity prices by individually managing their loads and reducing or shifting their energy consumption from peak hours to less congested hours. The price of electricity may vary at preset times or dynamically according to the hour, day, week, or year. Price-based DR schemes include TOU, critical peak pricing (CPP), and real-time pricing (RTP) programs (Yan, Ozturk, Hu, & Song, 2018). The TOU pricing program uses a static pricing scheme based on predefined price values, normally charging a premium rate during peak hours and a discounted rate off-peak, which are usually maintained during each season. TOU programs are the easiest to understand and to follow for consumers and have the highest participating ratio. Their main drawback resides in how they condition the usage patterns, which tend to shift energy-hungry services (i.e., stoves and kitchen appliances, EVs or PHEVs charging) right when peak prices drop, creating a new, bigger demand peak in the evening instead of spreading it evenly on the off-peak hours. CPP programs are instead event driven, normally during abnormal situations such as scheduled maintenance or expected extreme weather conditions, and use high electricity prices (normally higher than TOU rates) as control signals to affect electricity consumption during peak hours. Day-ahead CPP values are delivered to consumers through social media such as newspaper, text messages, and websites, making these programs very easy to understand and follow by average consumers. Users can visualize their incentives and are more willingly to participate in such event rather than re-scheduling all their energy behavior. Therefore, CPP are more effective in ensuring system reliability than in improving overall energy consumption efficiency. Finally, in RTP programs energy price varies continuously in response to the wholesale market prices, with dynamic tariffs made available to the public an hour or sometime one day ahead. In RTP programs, utility companies can distribute the electricity price reflecting the actual demand-supply elastics, signaling consumers with prices to adjust their electricity consumption accordingly in order to achieve financial benefits. Compared to TOU or CPP programs, RTP programs have the potential to deliver even more benefits to operators and consumers; however, their exploit requires a degree of hardware infrastructure in end-use systems, especially residential households. In fact, smart meters, EMS and BAS are prerequisites in order to overcome customer's difficulty in manually responding to time-differentiated prices.

Global DR programs accounted for 40 GW as late as 2018, with demand-side flexibility largely centralized and restricted to large industrial or commercial consumers (IEA, 2020b). Main market for DR is the United States, with around 28 GW of program participation equal to 6% of peak demand. However, DR currently utilizes less than 2% of its potential, which amounts to over 3.000 TWh for buildings and over 800 TWh for industrial and agricultural applications, and global capacity of all forms of demand-side flexibility expanded only 5% year-on-year in 2019. In this picture, applying DR to new services could provide new revenue streams and decrease transaction costs, allowing DERs to participate in a wider range of markets.

By 2040, under existing and planned policies, global DR capacity is expected to increase to around 200 GW, 85% of which could exist in buildings and transport, with the majority linked to flexible cooling demand (IEA, 2018). Digitalization and IoT diffusion promises to further increase the size of available DR capacity up to 450 GW globally, following the adoption of digital strategies, smart energy infrastructure, and the deployment of smart appliances—11 billion smart appliances in 1 billion smart households could be deployed by 2050.

It is understood that increasing the scale and scope of DR schemes to promote their adoption requires an innovative framework, which allows automation and can be able to adjust in a dynamic environment and learn from its operation (e.g., consumers' preferences). It is increasingly apparent that AI can contribute greatly to the future success of DR schemes by automating the energy management process, while learning the preferences of end-use consumers. Taking advantage of data generated by bidirectional smart meters, AI algorithms can be applied across the spectrum of DR, both supply side by providing the tools for prediction, real-time control and scheduling of distributed loads, or by supporting program design and decision making, and on the consumer side by optimizing building loads to meet DR signals (Antonopoulos et al., 2020).

Concerning prediction, AI can be employed effectively to forecast both electricity prices and various load types, with the objective of informing real-time electricity scheduling as well as system and operators planning. Most used AI method for prediction is ANN, with both single and multiple hidden layers (deep neural networks) to discover patterns between controlled factors. Short-term prediction of loads, weather-related production, or price can improve actual DR scheduling, enabling the aggregators to provide better services, and the consumers to respond optimally to DR signals. Long-term prediction, on the other hand, can help service providers and operators to understand the available flexibility, which consumers to target for DR, and which DR signals to transmit (compensation/prices).

Regarding DLC programs, the growing number of participants to DR initiatives, and the large range of devices which can be used for this purpose, make it unfeasible for BSPs to manage their portfolio of clients without automating the process of scheduling and control of the demand-side appliances. This can only be achieved by leveraging various technologies like Big Data management (primarily cloud based), ML techniques to interpret these data, optimization algorithms, and IoT devices to allow a bidirectional communication between the aggregator and the controllable end-users appliances. ML allows to model the interaction between clients and operators and act accordingly to their preferences. Most used ML methods in this sector are reinforced learning (Q-learning in particular) for smaller, residential or office applications, and deep reinforced learning when the space of actions and environment states becomes larger, especially at the service provider level (Medved, Artač, & Gubina, 2018) (see Section 10.4.4).

Concerning DR design and decision making support, AI techniques can be employed to assist the definition of both incentive and price-based DR schemes, supporting the optimization of rewards given to participants and of the BSP's own profit to ensure appeal of new clients and retain of enrolled ones. In incentive-based DR programs, AI can learn the optimal incentive rate for different electricity consumers based on profitability for both clients and providers, or learn the probabilities of consumers to accept the various offers. In price-based DR programs, AI can be used to identify the optimal day-ahead pricing scheme that maximizes the BSP's profits while complying with market constraints and minimizing consumer's discomfort or disturbances, or to model the relationship between RTP rates and electricity consumption. For both types of DR, AI supports operators in categorizing and segmenting enrolled clients for selecting the optimal subjects for different modulation or curtailment in DR scenarios, and in discovering potential customers based on their load profiles, employing classification, and clustering algorithms.

On the consumer side, DR requirements can be addressed either manually or, much more effectively, by integrating them into the building BAS and EMS to optimize energy storage management, thermal and visual comfort for occupants, and building services operation (see Chapter 10). Most relevant building services to provide DR capabilities include HVAC and domestic hot water (DHW) production, which together account for most energy consumption in residential or tertiary buildings. These systems can contribute to DR by modifying the temperature set points, shifting the loads by preheating or precooling the buildings (passive energy storage) or by directly storing thermal energy or hot water in an energy storage system (active energy storage). Home appliances in turn can be equipped with smart plugs or replaced with connected devices (e.g., dishwashers, washing machines, dryers) that allow scheduling their tasks during a specific time window or on/off switching in response to changes in the electricity prices. Regardless of the DR program subscribed, building features such as on-site energy generation and energy storage in particular are proving key elements in achieving the best results in terms of both cost reduction client-wise and improved grid stability and efficiency utility-wise. In fact, DR programs typically follow strict schedules, and curtailing energy use often requires equipment shutdowns or adjustments in the building that can impact occupants' comfort, prevent energy customers from reaping the benefits of DR or limit utilities' ability to leverage it as a resource. Renewables paired with energy storage give customers additional flexibility to reduce their site's grid demand at critical times without increasing the overall electricity consumption, making DR participation a lot easier. Another important factor that affects building energy management are EVs, which electrical storage capacity and inherent connectivity hold a great potential for integrating them in the future.

In this picture, AI can greatly contribute to the implementation of DR programs on the demand side by automating building energy systems and appliances (active demand side management—ADSM) in response to DR signals, while learning from occupant's behavior how to minimize user discomfort and the level of required human-controller interaction (Vázquez-Canteli and Nagy, 2019). Using weather forecasts, occupancy, usage, dynamic energy prices, and patterns identified in consumer behavior, AI can optimize the energy management of a consumer's house, reducing their electricity bill.

In particular, ML and AI applications in ADSM may pertain single subsystems, such as the prediction of on-site renewable energy generation, or, more commonly, the development of a centralized algorithm that coordinates distributed energy generation, energy storage, smart appliances, EV charging, HVAC and DHW, and other building services.

Concerning prediction of distributed energy generation, common approaches employ SVR methods to forecast the productivity of PV panels or wind turbines to pair historical production data with meteorological data from weather stations or database repositories (Rocha et al., 2021). User comfort levels can instead be predicted using K-means clustering methods on historical appliances and HVAC data consumption.

Smart appliance control and scheduling can be modeled using reinforced learning to correlate user defined tasks to be completed with target times that ensure the maximum satisfaction, also taking into account interdependent home services (e.g., clothes washer and clothes dryer), and using this information to minimize the cost of scheduled tasks under different DR signals (Vázquez-Canteli and Nagy, 2019). Another approach instead employs several ANNs, one for each

task to schedule, to program the different tasks, which are then coordinated by an additional ANN that ensures no overlap to minimize power demand (Matallanas et al., 2012). Regardless of the AI method, the on-demand nature of appliance use, as well as EV use and charging, requires users to input the tasks they want to carry out with a reasonable anticipation, to allow the controller to optimize the related schedule based on the effective needs.

Energy storage management can be greatly improved by AI, to predict and decide when to store excess renewable electricity in batteries and discharge them to meet demand at a later point in time, while considering forecasted demand, renewable energy generation, DR energy price and network congestion, as well as the impacts these services have on the state of health of the batteries. By using AI, versatile battery storage systems can optimize opportunities to purchase electricity from the grid when prices are low and then to sell back to the market when prices are high. Tesla's Hornsdale battery in Australia has operated via an algorithmic autobidder to capture the best revenue streams to a degree that could not have been achieved by human bidders alone, achieving an estimated US \$24 million in revenue in its first year of operation (IRENA, 2019c).

Finally, ADSM can be modeled as an optimization problem between maximizing both DR profitability and user's thermal and visual comfort, which in turn can be solved using nature-inspired algorithms such as genetic algorithms or ANN depending on the objectives set and the variables controlled. Nature-inspired algorithms, and NSGA-II in particular, are most utilized for scheduling tasks, a problem that can be highly complex, nonlinear, and nonconvex and is therefore suited for their exploration and exploitation ability (Antonopoulos et al., 2020).

12.4 Conclusions and future trends

World cities are increasingly relevant to climate change mitigation and adaptation, not only due to their high contribution to global carbon emissions, but also because of their huge potential to mitigate emissions of all kinds and of the rising need to build climate-resilient urban infrastructure able to adapt to the future conditions. In fact, cities will need to accommodate two-thirds of the world's population in a livable, low-carbon environment by 2050.

To shift toward a net zero carbon future, smart cities must develop an integrated energy system by focusing on four main goals:

- decarbonization of the electric power grid;
- electrification of building services, including space and water heating;
- widespread efficiency improvements to reduce overall energy demand;
- digitalization to improve flexibility of the energy grid in meeting the needs of building occupants.

These four good “deeds” combine in providing a comprehensive pathway for buildings and communities to contribute to a low carbon future. Decarbonization and climate action objectives require a gradual transformation of the energy system of cities, phasing-out fossil energy sources, and in turn integrating RES in the energy mix. In addition to environmental benefits, local development of renewables will also reduce countries dependency on energy imports, promote research and innovation to boost growth and competitiveness, and overall provide positive impacts on gross domestic product and employment. In this picture, green hydrogen produced with renewable energy can play an important role in the global energy transition toward zero carbon.

Such transformation of the energy system will deeply affect how energy is produced, transmitted, distributed, and consumed. The energy infrastructure must become more “intelligent” and flexible to integrate energy sources that have different behaviors and technical characteristics compared to traditional ones. Therefore, functions such as energy storage, demand side management, efficiency in use and distribution, DERs, and more flexible markets become necessary to foster the energy transition. In turn, these require the widespread deployment of new technologies and infrastructures, including smart meters, power electronics, and smart grids. The new infrastructure must cater to the communication needs of a new set of energy actors, that is, prosumers, distribution and transmission system operators, aggregators, and of the new devices that participate in the system.

All these new technologies, paradigms, services, and devices require the energy distribution infrastructure and data exchange channels and platforms to be interoperable and interconnected not only in terms of energy, but also in terms of data flows between all players and devices in the new energy system. New consistent frameworks are needed to allow the management of interactions with all energy commodities and non-energy sectors like water, finance, and transport, considering the technological aspects as well as matters of social acceptance and business models. They need to integrate new technologies such as advanced metering infrastructure, blockchain, IoT, and AI.

In this picture, the crucial enabler of the energy transition is the digitalization of the system in terms of technologies, infrastructures, and services. Smart energy infrastructure is in fact needed to seamlessly facilitate interactions between

energy grid, buildings, and EVs in the city and to ensure a cost-effective, secure electricity distribution. Fully electrified, highly efficient, grid-interactive buildings with on- and/or offsite renewable energy systems and smart e-mobility infrastructure are a decisive component of this infrastructure. Key technological innovations include building integrated renewable energy systems with battery storage, smart metering, smart energy management, highly efficient appliances, IoT, AI, and ML functions enabled by Big Data, and blockchain technology.

Such new city model will leverage data collection and processing using different technologies of communication, networking, and computing, which in turn allows to implement smart services to citizens across different sectors including health, transportation, security, and governance. The huge expansion of Big Data and the evolution of AI and ML will play an ever-important role, as the considerable amount of data collected through various sources, including data from GIS, satellites, and drones, can be analyzed to discover evident or inferred patterns and provide valuable insights to city officers. By combining these data with increasingly large and accurate BIM models of the building stock and GIS systems, it is possible to create city-wide DTs that can be used to model urban planning and policy decisions. The digital transition toward smart cities will create a market for a qualified workforce, as well as new services and activities with a new industrial value chain that can at least partially replace the jobs lost due to phasing out fossil-based energy sources. Nonetheless, the impact will be enormous and disruptive: the physical, social, market, and business configurations of the energy system in the future may be very different from today.

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Construction 4.0 Advanced Technology, Tools and Materials for the Digital Transformation of the Construction Industry

Provides a comprehensive overview of the Construction 4.0 approach, embracing the entire building process from design to construction, operation, and maintenance.

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