CONSTRUCTION 4.0

Modelled on the concept of Industry 4.0, the idea of Construction 4.0 is based on a confluence of trends and technologies that promise to reshape the way built environment assets are designed, constructed, and operated.

With the pervasive use of Building Information Modelling (BIM), lean principles, digital technologies, and offsite construction, the industry is at the cusp of this transformation. The critical challenge is the fragmented state of teaching, research, and professional practice in the built environment sector. This handbook aims to overcome this fragmentation by describing Construction 4.0 in the context of its current state, emerging trends and technologies, and the people and process issues that surround the coming transformation.

Construction 4.0 is a framework that is a confluence and convergence of the following broad themes discussed in this book:

- Industrial production (prefabrication, 3D printing and assembly, offsite manufacture)
- Cyber-physical systems (actuators, sensors, IoT, robots, cobots, drones)
- Digital and computing technologies (BIM, video and laser scanning, AI and cloud computing, big data and data analytics, reality capture, Blockchain, simulation, augmented reality, data standards and interoperability, and vertical and horizontal integration)

The aim of this handbook is to describe the Construction 4.0 framework and consequently highlight the resultant processes and practices that allow us to plan, design, deliver, and operate built environment assets more effectively and efficiently by focusing on the physical-to-digital transformation and then digital-to-physical transformation. This book is essential reading for all built environment and AEC stakeholders who need to get to grips with the technological transformations currently shaping their industry, research, and teaching.

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CONSTRUCTION 4.0

An Innovation Platform for the Built Environment

Edited by Anil Sawhney, Mike Riley and Javier Irizarry

Routledge
Taylor & Francis Group
LONDON AND NEW YORK

First published 2020

by Routledge

2 Park Square, Milton Park, Abingdon, Oxon OX14 4RN

and by Routledge

52 Vanderbilt Avenue, New York, NY 10017

Routledge is an imprint of the Taylor & Francis Group, an informa business

British Library Cataloguing-in-Publication Data
A catalogue record for this book is available from the British Library

Library of Congress Cataloging-in-Publication Data
A catalog record has been requested for this book

Typeset in Times New Roman

ISBN: 978-0-367-02730-8 (hbk)
ISBN: 978-0-429-39810-0 (ebk)

by Swales & Willis, Exeter, Devon, UK

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ACKNOWLEDGEMENTS

The editors would like to thank everyone who helped with the inception, development writing, editing, and support for this handbook. This manuscript has resulted from the combined efforts of nearly 60 individual contributors from across the globe, including academics, practitioners, and industry stakeholders. This is a triumph of collaboration and teamwork!

The editors wish to express their sincere thanks to all of the individual chapter authors for their commitment, energy, and enthusiasm in co-creating this work.

Many individuals, companies, and organizations have assisted in developing the various chapters and providing illustrations and information that has allowed the various authors to produce this work. Many of these are cited in the context of specific illustrations or figures within the main text.

In addition, however, we would like to express specific acknowledgement for various chapters as follows:

In relation to Chapter 3, we would like to thank Takefumi Watanuki, a graduate student of the Construction Engineering and Management graduate programme at Columbia University. We also would like to thank Autodesk and Procore for their permission to use the illustrations. Autodesk products referenced in the chapter are registered trademarks or trademarks of Autodesk, Inc, and/or its subsidiaries and/or affiliates in the USA and/or other countries. Procore products referenced in the chapter are registered trademarks or trademarks of Procore Inc. and/or its subsidiaries and/or affiliates in the USA and/or other countries. iModelHub and iModel are registered trademarks or trademarks of Bentley Systems Inc. and/or its subsidiaries and/or affiliates in the USA and/or other countries.

In relation to Chapter 4, we would like to thank everyone who helped with the inspiration, ideas, structure, writing, editing, and support for this chapter. An incomplete list includes: Tristan Randall, Eddy Krygiel, Frank Moore, Steve Duffett, Manu Venugopal, Scott Borduin, Dustin Hartsuiker, Richard Holbrook, James McKenzie, Anil Sawhney, Alan Mossman, Zoubeir Lafhaj, Rafael Sacks, and Lauri Koskela.

The material within Chapter 13 is, in part, based upon work supported by the National Science Foundation Grant #1446765. The support and help of Reconstruct and the construction team in collecting data are greatly appreciated. The opinions, findings, and conclusions or recommendations expressed within this chapter are those of the authors and do not reflect the views of the NSF, or the company mentioned above.

The author of Chapter 20 would like to thank Professor Alan Penn for supporting his construction blockchain research at the Bartlett Faculty of the Built Environment, University College London. He would also like to thank the Construction Blockchain Consortium (CBC) team for their ongoing support and encouragement.

The authors would also like to acknowledge the kind support of WikiHouse (now Opensystemslab) and Oracle in allowing reproduction of the materials required to produce the case studies in Chapter 21.

Finally, the editors would like to express their sincere gratitude for the invaluable contribution of Cristina Toca Pérez, who has committed time, effort, and energy without hesitation. Cristina's input has been crucial to the successful completion of this work.

Co-Editors: Anil Sawhney, Mike Riley, and Javier Irizarry

FOREWORD

With increasing pressures on the built environment sector to provide the infrastructures and homes that are the key economic enablers to city growth, and as people globally are entering our cities at the rate of 3 million people a week, the heat is on construction to design, build, modify, and operate these assets to our changing needs and that of the communities whose evolving demands occupy the space provided.

Construction has continued to innovate, but not at the rate or expectations demanded of it. Therefore, we need to consider the opportunity to radically transform our methods and approaches to construction that enable it to be more efficient and effective in adopting the technologies from other sectors and services to enable it to reshape the way our built environment assets emerge now and for the future. The time is now, because the demand is there for rapid supply, balanced against the costs of the intensification for the supply of skills and resources, coupled with the desire for improved and innovative design.

You will see from reading this book that the key to unlocking the potential and pace of a more rapid "right first time" mentality is putting the physical-to-digital and digital-to-physical transformation at the heart of the delivery process.

The book is timely, as we are at the tipping point of transformative change for construction with already establishing digital practices of Building Information Modelling (BIM), Modern Methods of Construction (MMC) as well as VR/AR, AI, 3D, and IoT as rapidly evolving technologies to expedite design, deliver, and operate are all coming to the fore, backed by the essential data to feed and inform.

There is no doubt that this is an exciting time for the built environment sector and for the transformation of the construction processes that deliver it. But there is a level of pace of change that is needed now to deliver, transform, and metamorphosize the sector and this book captures well the elements necessary to deliver that change.

With this in mind, this book provides the key to unlocking the potential of the built environment sector at a time where the sector needs unlocking to gear it to transform the delivery of our infrastructure, homes, and cities. The key to unlocking the change needed sits within these pages, with digital innovation at the heart, and the power of you to drive the transformation that will re-establish construction as a key economic enabler for growth.

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The 2017 McKinsey Global Institute's publication "Reinventing Construction: A Route to Higher Productivity" showed that the greatest impact on productivity improvement in the construction industry is through the advancement and application of digital and technology solutions. Over the last few years there has been a significant investment by private equity funds in construction industry related digital and technology start-ups and tech companies which has fuelled tremendous growth and innovation in this part of the industry. In "Construction 4.0" the authors pull together all of the relevant elements of these essential solutions and practices and show how they will enable more effective and efficient planning, design, delivery, and operation of physical assets (i.e., capital projects) through a digital transformation. The industry has already made significant advancements over the past 2–3 years but much more is required among all members of the supply chain involved with capital projects. This publication presents a comprehensive review of these emerging solutions and systems and makes the connection of technology with people and processes. Companies and organizations that do not have a "digital strategy" will be able to understand better through "Construction 4.0" how each element complements one other and how each is able to improve performance across all phases of a capital project. While many companies in the industry have utilized BIM or VR/AR in one form or another, other advancements such as data analytics, Internet of Things (IoT) and use of artificial intelligence are shown to be significant disruptors to the traditional model of project development, design, and delivery with significant benefits to be realized by project owners, designers, and contractors. Construction performance and productivity has stalled tremendously since World War II compared to every other major industry and in order to be ready for the Fourth Industrial Revolution, industry players will need to change and "Construction 4.0" is an excellent guidebook to such transformation.

In addition to helping professionals working in the industry already, this handbook will be a useful resource for several folks in academia … undergraduate and graduate students, researchers and scholars with a keen interest in the ongoing transformation of the construction industry using the Industry 4.0 framework.

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Ron Wakefield is Professor of Construction, Deputy Pro Vice-Chancellor; International and Dean of the School of Property, Construction and Project Management at RMIT, Australia. Ron researches and teaches process simulation and modelling, residential and commercial construction and use of information technology in construction management. Prior to joining RMIT, he was the William E. Jamerson Professor of Building Construction in the Department of Building Construction and Associate Director for Building Technology Research at the Center for Housing Research, Virginia Tech. Ron has over 25 years' experience as an international researcher, consultant, and engineer in building construction. He is Director of Launch Housing and JJR Consulting and co-opted member of the Victorian Building Practitioners Board.

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FIGURES

TABLES

PART I

Introduction and overview of Construction 4.0, CPS, Digital Ecosystem, and innovation

1
CONSTRUCTION 4.0
Introduction and overview

Anil Sawhney, Mike Riley, and Javier Irizarry

1.1 Aims

- Provide an overview of Industry 4.0 and the Fourth Industrial Revolution.
- Provide a comprehensive review of the current state of the construction sector.
- Describe the overall Construction 4.0 framework.
- Articulate the purpose of Construction 4.0.
- Describe the handbook, its three parts, and its various chapters.

1.2 Introduction to Construction 4.0

With the advent of the Fourth Industrial Revolution (4IR) and the resulting framework of *Industry 4.0 (I4.0)* (MacDougall, 2014), the built environment sector also has the opportunity to leapfrog to more efficient production, business models, and value chains. Such a transformation is possible through the convergence of existing and emerging technologies that form part of the Industry 4.0 paradigm (Oesterreich and Teuteberg, 2016). This transformative framework is called the *Construction 4.0* framework in this handbook. Modelled after the concept of Industry 4.0, the idea of Construction 4.0 is based on a confluence of trends and technologies (both digital and physical) that promise to reshape the way built environment assets are designed and constructed.

In 4IR, the fundamental driver is the use of cyber-physical systems. *Cyber-physical systems* (CPS) are enabling 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 (Griffor et al., 2017). A conceptual model of the CPS is provided in Figure 1.1.

The Construction 4.0 framework uses CPS as a core driver and links it with the concept of Digital Ecosystem where 'A digital ecosystem is an interdependent group of enterprises, people and/or things that share standardized digital platforms for a mutually beneficial purpose, such as commercial gain, innovation or common interest' (Gartner, 2017). The idea of a Digital Ecosystem is shown in Figure 1.2.

Construction 4.0 combines CPS and Digital Ecosystem to create a new paradigm for the design and construction of our built environment assets as shown in Figure 1.3.

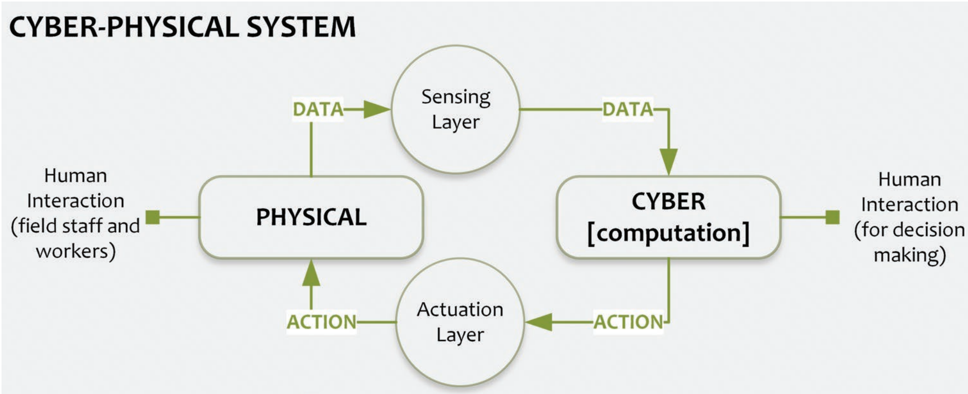

Figure 1.1 Conceptual model of CPS

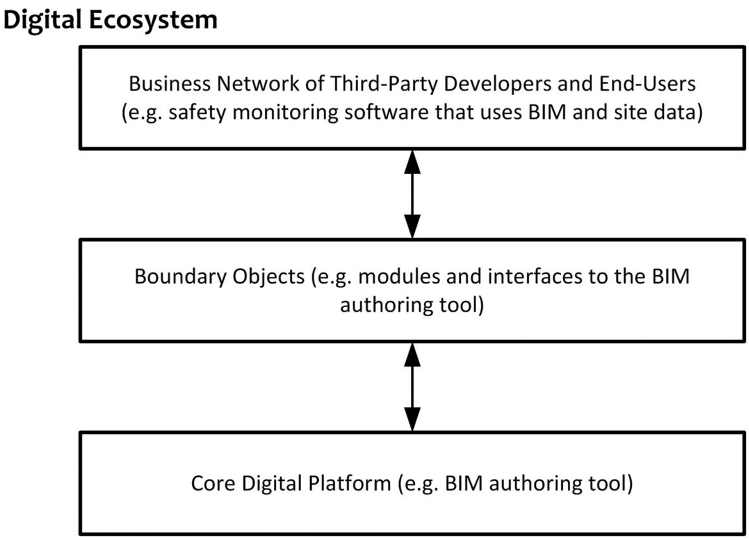

Figure 1.2 Conceptual model of a Digital Ecosystem

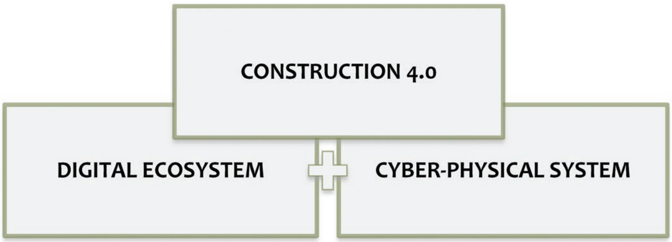

Figure 1.3 Construction 4.0 as a combination of CPS and Digital Ecosystem

Using the CPS, the cyber-physical gap that exists in the built environment can be bridged, and by concomitantly using the Digital Ecosystem the work processes to collaborate efficiently across the project delivery network to design and construct the asset can be enhanced. The Construction 4.0 framework, therefore, provides a mechanism via which we can:

a. Digitally model the built assets that already exist in our physical world.
b. Design new assets in the backdrop of what already exists or plan for the retrofit and rehabilitation of existing assets using these digital models.
c. Once these assets are digitally captured and designed, use digital and physical technologies to deliver these physical assets.

The same framework can be adopted during the operation phase of the constructed asset by using similar digital and physical technologies to support Facilities Management (FM) functions. However, the focus of this handbook is limited to the design and construction phases.

The aim of this handbook is to describe the Construction 4.0 framework and consequently highlight the resultant processes and practices that allow us to plan, design, and deliver built environment assets more effectively and efficiently by focusing on the physical-to-digital transformation and then digital-to-physical transformation. This concept is illustrated graphically in Figure 1.4.

With the pervasive use of Building Information Modeling (BIM), lean principles, digital technologies, and offsite construction the industry is at the cusp of this transformation. The critical challenge is the fragmented state of our teaching, research, and professional practice in the built environment domain. The authors and editors of this handbook aim to overcome this fragmentation by describing Construction 4.0 in the context of current state, emerging trends and technologies, and people and process issues that surround the proposed transformation.

Construction 4.0 is a framework that is a confluence and convergence of the following broad themes:

- Industrial production (prefabrication, 3D printing, and assembly, offsite manufacture).
- Cyber-physical systems (robots and cobots for repetitive and dangerous processes, and drones for surveying and lifting, moving and positioning, and actuators).

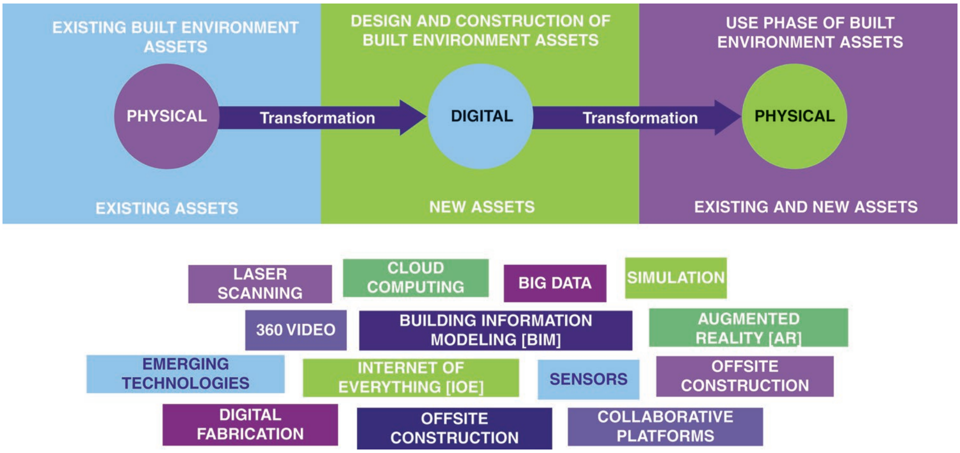

Figure 1.4 Physical to digital and digital to physical transformation

Figure 1.5 Themes of Construction 4.0

- Digital technologies (BIM, video and laser scanning, IoT, sensors, AI and cloud computing, big data and data analytics, reality capture, Blockchain, simulation, augmented reality, data standards and interoperability, and vertical and horizontal integration).

With this background and motivating factors, the handbook will address issues surrounding the key themes of people, processes and practice, and new technologies (as shown in Figure 1.5).

Modern digital and physical technologies are required to achieve the overarching vision of the 4IR (Jacobides, Sundararajan, and Van Alstyne, 2019) that underpins the Construction 4.0 framework, therefore, the framework relies on two broad paradigms: (1) cyber-physical systems and (2) Digital Ecosystems. Innovations in both cyber-physical and digital paradigms are necessary to advance the vision of Construction 4.0 in our industry.

1.3 Current state of the construction sector

Given the importance of the construction sector to their national economies, several countries have undertaken studies to identify the challenges and opportunities that the industry presents. For example, the UK has conducted several prominent studies to document the problems of the construction sector to put in place a program for improvement of the whole-of-the-sector. Sir John Egan, the chair of the Construction Task Force, published his report entitled *Rethinking Construction* in 1998 (Egan, 1998). It was instrumental in laying out a road map for the efficiency improvements within the construction industry in the UK. This came close on the heels of the report, titled ‘Constructing the Team’ authored by Sir Michael Latham and published in 1994. The Latham report identified inefficiencies and made recommendations for enhanced collaboration and coordination in the industry (Latham, 1994). More recently, the UK released a report by Mark Farmer entitled ‘Modernise or Die’ (Farmer, 2016) that used a ‘strong medical process analogy’. Around the time that this study was being conducted, the UK government also released their Construction 2025 industrial strategy with a plan to commit close to £75 million in research and development.

Other countries, such as the US, Australia, Canada, Singapore, and China, have also undertaken sector-wide studies. For example, a similar exercise was conducted in the US, where Construction Users Roundtable produced a detailed report to outline a path to competitive advantage for construction users.

Several developing nations have also undertaken such studies that identify the problems faced and listed the difficulties hindering growth (Al-Momani, 1995b, 1995a; Edmonds, 1979; Manoliadis, Tsolas, and Nakou, 2006; Moavenzadeh, 1978; Moore and Shearer, 2004; Ofori, 1989, 1994, 2000). This is even more important because in developing countries the construction sector’s capacity constraints impact the economic development process (Wells, 2001). These studies have also developed action points necessary for the development of the construction industry (Ofori, 1994, 2000) including the importance of developing key performance indicators (Beatham et al., 2004; Ofori, 2000). A priority-based approach was proposed to rank solutions offered by the researchers and policymakers (Ofori, 1990) with several researchers presenting an optimistic case about the improvement plans (Koenigsberger and Groak, 1978; Turin, 1973).

The repeated nature of these national studies show that there is stagnation and barring some incremental improvements; the industry as a whole has still not managed to show major improvements. The results have been mostly disappointing (Chemillier, 1988; Ofori, 1984, 1990; UNCHS, 1990). Barring a few countries, the problems have persisted over a long period despite efforts made to overcome them. This has been pointed out in the Farmer report that states 'construction has not even made the transition to "industry 3.0" status which is predicated on large scale use of electronics and IT to automate production' (Farmer, 2016; Gerbert et al., 2017). Research has pointed towards a long-term strategic approach to be followed, which is related to the socio-economic needs of the country, often overseen by a steering committee (Farmer, 2016; Ofori, 1994).

The studies described above have generally identified a standard set of challenges or problems that the industry faces. In one such study a list of ten grand challenges (shown in Figure 1.6) faced by the construction sector in India were identified (Sawhney, Agnihotri, and Paul, 2014).

The following are the key challenges that have been collated from these studies (Farmer, 2016; Gerbert et al., 2017; Global Industry Council, 2018; Sawhney and Agnihotri, 2014; Witthoeft and Kosta, 2017):

1. Low levels of research and development leading to a lack of innovation and delayed adoption of technologies.
2. Workforce issues including shortage of young talent due in part to poor industry image.
3. Informal processes and lack of process standardization leading to structural fragmentation.
4. Low levels of cross-functional cooperation and limited collaboration leading to a lack of improvement culture.
5. Low productivity, predictability, and profits.
6. Adversarial transaction-based procurement regime.
7. Insufficient knowledge transfer from project to project.
8. Cultural and mindset issues that act as a blocker to any change.

These issues require a transformational change (Farmer, 2016) in the industry, and we envision that Industry 4.0 can provide a broad framework for such a change.

1.4 Overview of Industry 4.0

During the Hannover Messe in 2011, the German Federal Government released its vision for the future of the manufacturing sector under the broad umbrella term INDUSTRIE 4.0 (Roblek, Meško, and Krapež, 2016). It became part of the 'High-Tech Strategy 2020' project that continues to grow and evolve (MacDougall, 2014). This initiative later became a globally recognized paradigm that was broadly referenced as I4.0, also seen as a precursor to the Fourth Industrial Revolution (Drath and Horch, 2014). Other terms such as smart factory, smart manufacturing, smart production, etc., have also been used to define this broad paradigm (Oesterreich and Teuteberg, 2016).

Similar initiatives have also been launched by other countries. For example, the United States developed the 'Advanced Manufacturing Partnership' in 2014 (Rafael, Jackson, and

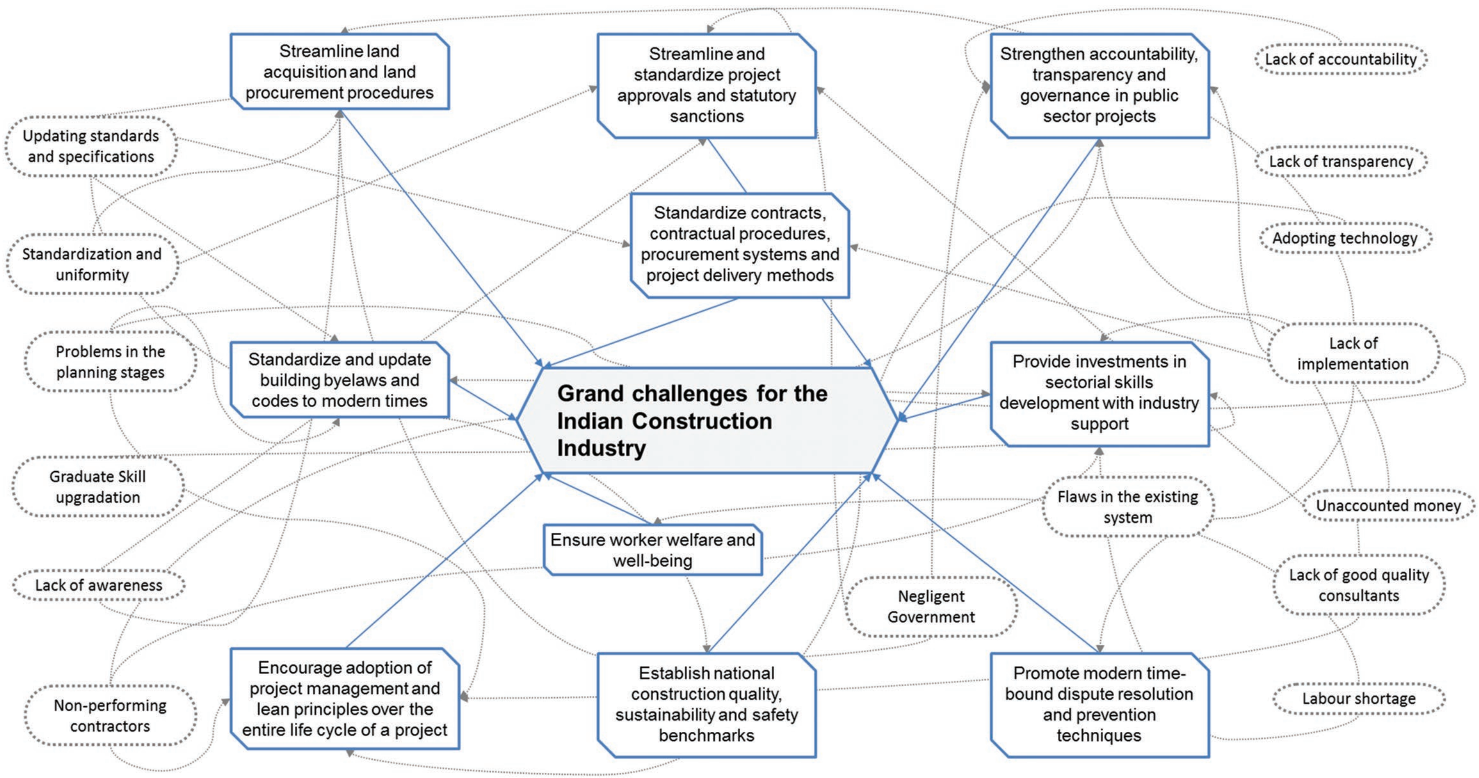

Figure 1.6 Key challenges faced by the construction sector (Sawhney, Agnihotri, and Paul, 2014) reproduced with kind permission of Emerald Publishing

Liveris, 2014) and updated it in 2016, the UK launched an initiative entitled 'Future of Manufacturing' (Foresight, 2013) and China is implementing the 'Made in China 2025' program (Liao et al., 2017).

While the First Industrial Revolution was catalyzed by steam-powered mechanical production, the second was driven by electrical-powered mass production; the third was based on electronics and automation, the Fourth Industrial Revolution has begun with the promulgation of CPS and related technologies (MacDougall, 2014; Pereira and Romero, 2017). It is envisioned that I4.0 will have far-reaching implications on the manufacturing sector that are, in turn, likely to have broad social and economic benefits for nations and societies that embrace this framework (Oesterreich and Teuteberg, 2016). Furthermore, I4.0 uses technologies such as service orientation, smart production, interoperability, cloud computing, big data analytics, and cybersecurity (Vogel-Heuser and Hess, 2016). I4.0 facilitates interconnection and computerization in traditional industries, which makes an automatic and flexible adaptation of the production chain and provides new types of services and business models of interaction in the value chain (Liao et al., 2017; Lu, 2017).

1.4.1 Definition of Industry 4.0

I4.0 is a broad term that has been presented as a 'confluence of trends and technologies promises to reshape the way things are made' (Baur and Wee, 2015). There are several definitions of I4.0 but no globally accepted one because the vision, mission, and components of I4.0 are still emerging and are being connected to more significant and broader themes such as sustainability and circular economy (Lopes de Sousa Jabbour et al., 2018; Müller, Kiel, and Voigt, 2018; Rajput and Singh, 2019).

The German government describes I4.0 as 'a new technological age for manufacturing that uses cyber-physical systems and Internet of Things, Data and Services to connect production technologies with smart production processes' (Kagermann, Wahlster, and Helbig, 2013; MacDougall, 2014) to make manufacturing smart. I4.0 has also been defined at a higher level as 'a new level of value chain organization and management across the lifecycle of products' (Hermann, Pentek, and Otto, 2016; Kagermann, Wahlster, and Helbig, 2013). It is also defined as the integration of machinery and devices with networked sensors and software that can be used to predict, control, and plan for better business and societal outcomes (Shafiq et al., 2015). In a way, I4.0 improves manufacturing organizations, business models that they use, and their production processes through the use of physical and digital technologies.

I4.0 is seen as a cross-cutting paradigm that can have broad social and economic benefits. It is seen as a way to revolutionize manufacturing and other major sectors, such as energy, health, smart cities, and mobility (MacDougall, 2014). The motivation behind this handbook is that I4.0 can also act as catalyst for the future of construction that is more industrialized and automated. We use this motivation to coin the term Construction 4.0.

1.4.2 Key components of I4.0

I4.0 is a very broad and encompassing term. Therefore, it is essential to understand the key components of I4.0. Researchers agree that the push towards I4.0 came from the evolution of embedded systems to more advanced cyber-physical systems (CPS) (Vogel-Heuser and Hess, 2016). This has also formed the basis of the vision developed by the German government. CPS is a set of technologies that connect the virtual and physical worlds together to create a genuinely networked production environment in which intelligent objects communicate and interact with each other (Kagermann, Wahlster, and Helbig, 2013a). The journey towards I4.0 began with the embedded systems and their technological evolution towards CPS and further to provide an Internet of Things (IoT), Data and Services. Figure 1.7 shows this evolution of the embedded systems to CPS.

A CPS is defined as ‘a mechanism that is controlled or monitored by computer-based algorithms, tightly integrated with the Internet and its users’ (Monostori et al., 2016). CPS creates a virtual copy of the physical production system that is also called the digital twin. This is the first step towards I4.0, where a physical-digital-physical loop is created (Rutgers and Sniderman, 2018). The production environment in the factory that is created through this is also known as the Cyber-Physical Production System (CPPS) (Vogel-Heuser and Hess, 2016). CPPS results in a digitalized, smart, optimized, service-oriented, and interoperable production environment upon which other components of I4.0 are built.

Once the digital twin of a manufacturing environment is created, other business and technical aspects of the production process are linked into the I4.0 framework through the Internet of Things, Data and Services. Figure 1.8 shows the key components of I4.0. The very core of I4.0 is formed by the IoT layer that connects physical objects and things, collects data from these connected objects, and allows connected objects to communicate with each other. Based on this core layer are the CPS and CPPS layers of the I4.0. CPS helps create the digital twin of the physical world, in this case, the manufacturing unit. This allows a loop in which the physical components that are connected to each other relay data that can be used for a variety of purposes including decision making. Changes to the physical world can be made via actuators thereby completing the loop.

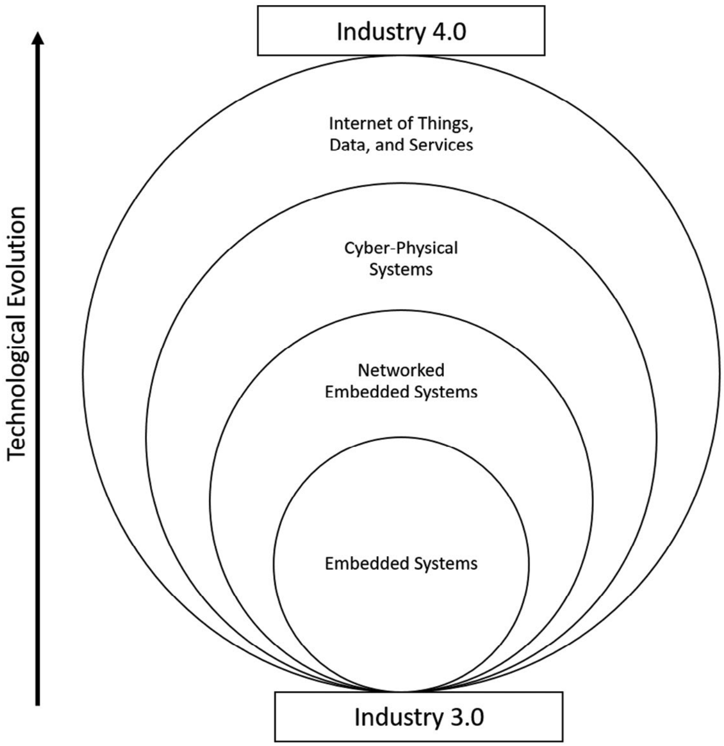

Figure 1.7 Evolution of embedded systems

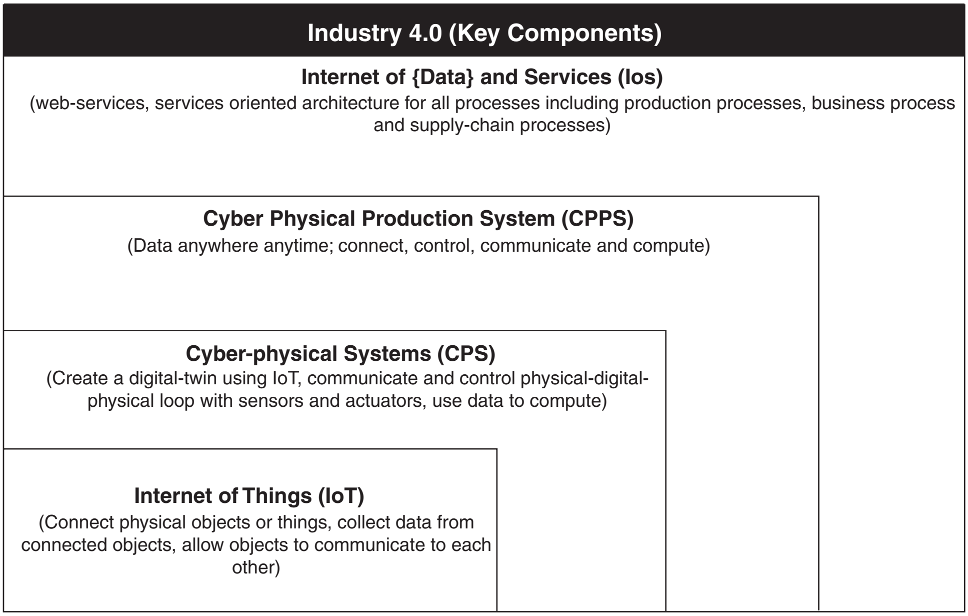

Figure 1.8 Industry 4.0 and its key components

The CPPS sits on top of the CPS layer and provides data about the physical world anywhere and anytime, and helps connect, control, communicate, and compute. CPPS provides an intensive connection with the surrounding physical world and its ongoing processes (Monostori et al., 2016). Finally, the topmost layer is the Internet of Data and Internet of Services (IoS). The IoS creates a service-oriented ecosystem and brings the end-user of customer centricity to the system (Hofmann and Rüsch, 2017). IoS allows the digital tools that support end-user functions to be available as a service on the Internet (Alcácer and Cruz-Machado, 2019). Both internal and cross-organizational services are offered and utilized by participants of the value chain (Reis and Gonçalves, 2018). The IoS helps create networks incorporating the entire manufacturing process that convert factories into a smart environment (Kagermann, Wahlster, and Helbig, 2013a).

1.4.3 Enabling technologies and key features

In addition to defining the I4.0 framework by describing its key components, the framework can also be defined by identifying its enabling technologies and key features. Liao et al. used over 224 research papers published over five years (2012–2016) to determine these technologies and key features of I4.0 (Liao et al., 2017). Figure 1.9 shows the enabling technologies and key features of I4.0 as determined by the literature review. The vision of I4.0 can be accomplished through a collective deployment of several related technologies (Alcácer and Cruz-Machado, 2019). These technologies work in conjunction with the IoT, CPS, CPPS, and IoS as identified in the previous section (Griffor et al., 2017). Based on the frequency of usage and mention in the literature these technologies are rank-ordered in Figure 1.9.

Similarly the key features of I4.0 from literature are also listed in rank order in the figure. From the literature it can be seen that both in research and practice significant attention is given to automation, integration, and collaboration. Less tractable features such as innovation, quality, and sustainability are still not prevalent.

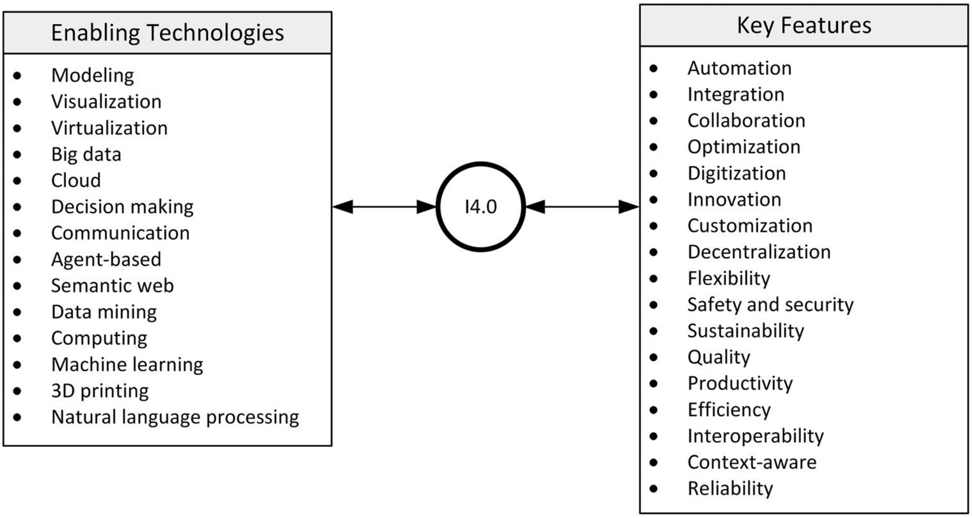

Figure 1.9 Enabling technologies and key features of I4.0

1.4.4 Interoperability and integration in I4.0

Integration and interoperability are two key drivers in the I4.0 framework (Kagermann, Wahlster, and Helbig, 2013a; Vogel-Heuser and Hess, 2016). Interoperability helps two or more systems work with each other to exchange data, information, and knowledge. Interoperability is achieved through a shared understanding of concepts, standards, languages, and relationships (Xu, Da, Xu, and Li, 2018).

I4.0 leads to the integration of processes, systems, applications, and organizations (Oesterreich and Teuteberg, 2016). It is anticipated that I4.0 will allow the following three levels of integration (Kagermann, Wahlster, and Helbig, 2013a):

- Horizontal integration through value networks.
- End-to-end digital integration of engineering across the entire value chain.
- Vertical integration and networked manufacturing systems.

1.4.5 Impact of Industry 4.0

There are several areas that can be impacted and improved by the application of I4.0 at the sector level (Kagermann, Wahlster, and Helbig, 2013; Oesterreich and Teuteberg, 2016; Rose et al., 2016):

1. Productivity improvement: I4.0 provides several improvements such as automation, real-time inventory management, and continuous optimization that lead to productivity enhancement.
2. Increased quality: ongoing monitoring and control of production allows for improved quality of products and services.
3. Increased flexibility: with a customer-centric approach, I4.0 allows manufacturing flexibility through automation and robotics.
4. Increased speed: with enhanced product life cycle management and physical-digital-physical integration, the speed of production is enhanced.

5. Safer and better working conditions: with increased automation, real-time monitoring of incidents, better-designed workstations, and enhanced work structuring, workers have safer and better working conditions.
6. Improved collaboration: as the availability of data is enhanced, and digital layer and physical layer are integrated the intra- and inter-organization collaboration is improved.
7. Sustainability: optimized use of resources, reduction in defects, and other environmental improvements make operations more sustainable.
8. Innovation: I4.0 leads to new ways of creating value and new forms of employment, for example through downstream services.

1.5 Construction 4.0 framework

Figure 1.10 shows the various layers and components of the Construction 4.0 framework. BIM and a cloud-based Common Data Environment (CDE) are central to the Construction 4.0 framework (Cooper, 2018; Oesterreich and Teuteberg, 2016). While BIM provides the modeling and simulation features that are a core component of the I4.0 framework, CDE acts as a repository for storing all the data that relates to the construction project over its life cycle.

The use of BIM and CDE creates a single platform that helps promote:

1. Integration of all phases of the project life cycle (vertical integration), all members of the project team (horizontal integration), and inter-project learning and knowledge management (longitudinal integration).
2. Linkage between the physical and cyber (digital) layer over the entire project life cycle. This allows the implementers of Construction 4.0 to utilize both physical and digital technologies in an integrated manner.

Within the Construction 4.0 framework, the following three transformational trends take place:

1. Industrial production and construction: by using prefabrication, 3D printing, and assembly, offsite manufacture, and automation, the issues and challenges caused by on-site construction techniques are significantly reduced. This type of industrialized process allows production to be digitally linked to BIM and CDE so that instructions can be directly delivered for physical production and any production-related information from the physical layer can be fed back to the digital layer.
2. Cyber-physical systems: the construction site under Construction 4.0 uses robotics and automation for production, transport, and assembly, actuators for converting digital signals into physical actions, and sensors and IoT to sense important information about physical objects (including people) from the physical layer.
3. Digital technologies: the digital transformation relies on the Digital Ecosystem that is developed in the digital layer of the Construction 4.0 framework. BIM and CDE provide the framework upon which integrated digital tools are built. With the help of video and laser scanning technology, artificial intelligence (AI) and cloud computing, big data and data analytics, reality capture, Blockchain, simulation, and augmented reality the delivery and business process is supported in the Construction 4.0 framework. While Digital Ecosystems provide the innovation needed for this support, data standards and interoperability also play an essential role in this overall transformation.

Figure 1.11 shows the components of the Construction 4.0 framework, the role they play in the framework and the layer in which they are present.

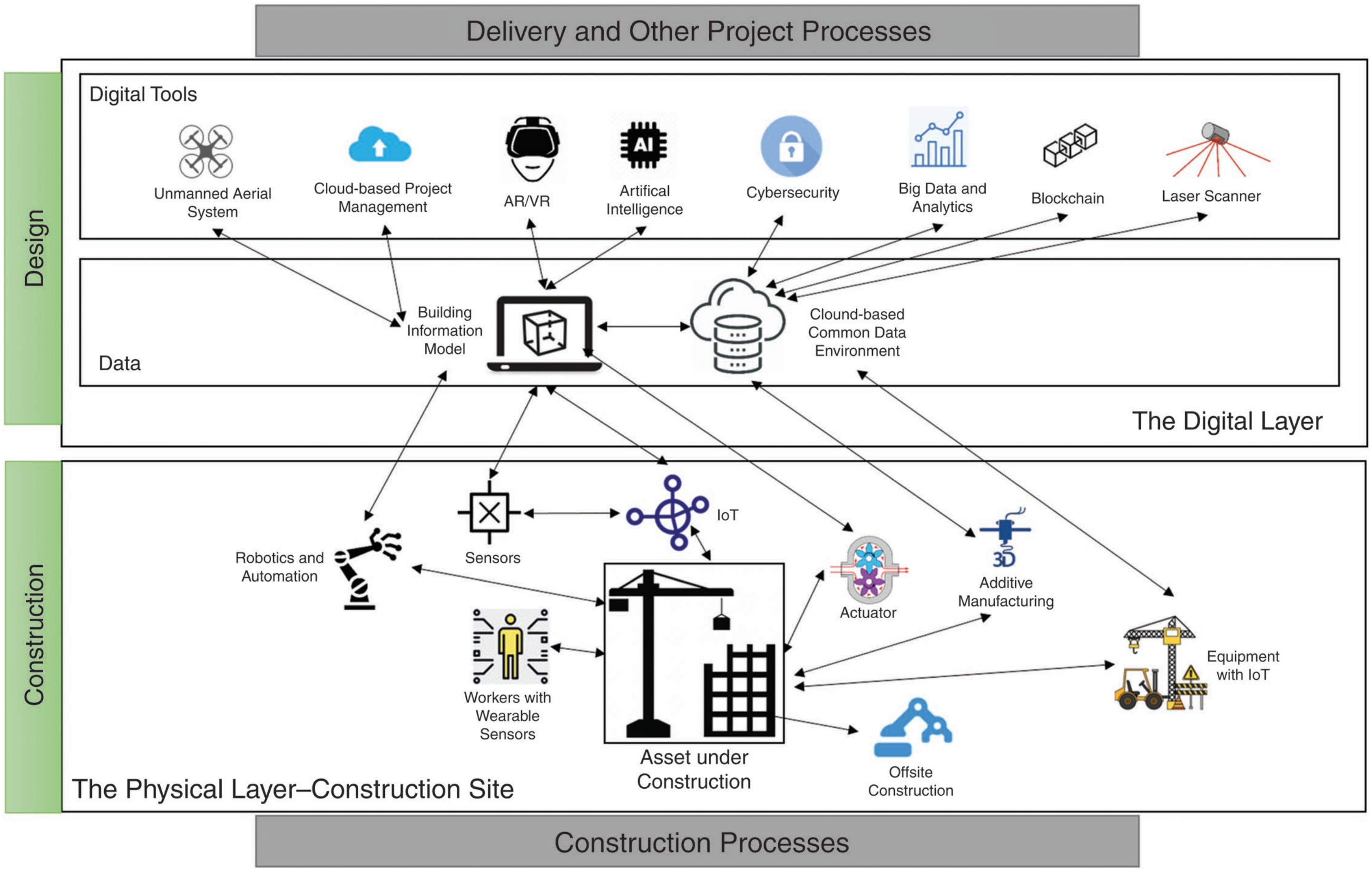

Figure 1.10 Conceptual illustration of Construction 4.0 framework

Emerging Technology or Trend	Construction 4.0 Layer	Construction 4.0 Functions
BIM	Digital	Modeling and simulation
CDE	Digital	Collect, manage and disseminate documentation, the graphical model and non-graphical data for the whole project team
Unmanned Aerial Systems	Digital	Aerial image collection
Cloud-based Project Management	Digital	Digital tools to support delivery and business processes
AR/VR	Digital	Virtual application in all phases and for all team members
Artificial Intelligence	Digital	Classifying, predicting, image processing, mining and problem-solving
Cybersecurity	Digital	Securing the physical-digital-physical loop
Big Data and Analytics	Digital	Trend analysis and business intelligence
Blockchain	Digital	Smart contracts, building trust, and maintaining records
Laser Scanner	Digital	Point-cloud data collection
Robotics and Automation	Physical	Transport, assembly and production
Sensors	Physical	Collect location, temperature, humidity, and movement information
IoT	Physical	Connectivity of things, people and data
Workers with wearable sensors	Physical	Collect location, temperature, humidity, and movement information
Actuators	Physical	Convert digital interactions into physical action
Additive Manufacturing	Physical	Print parts and products using the BIM model
Offsite Construction	Physical	Use manufacturing to produce parts and products
Equipment with Sensors	Physical	Assembly of parts and products in a location aware environment

Figure 1.11 Components of Construction 4.0 framework

1.6 Benefits of Construction 4.0

Several recent studies have attempted to define the I4.0 framework in general and provide a road map for research and implementation based on a detailed literature scan (Alcácer and Cruz-Machado, 2019; Liao et al., 2017; Pereira and Romero, 2017). Similar attempts are being made in regards to Construction 4.0 (Cooper, 2018; Dallasega, Rauch, and Linder, 2018; Oesterreich and Teuteberg, 2016). These studies focus on identifying the sectoral benefits of the Industry 4.0 concept in general and Construction 4.0 in particular. Based on these studies, the benefits of the Construction 4.0 framework are listed below:

1. Enabling an innovative environment: the Construction 4.0 framework may provide the right mix of enablers to allow the innovation mindset to take root in the industry. Through

an integration of the physical and digital layer, it is likely that this innovation will lead to integrated solutions that will strike at the heart of horizontal, vertical, and longitudinal fragmentation that currently dominates the industry.

2. Improving sustainability: the integrated framework of Construction 4.0 allows the industry to fully embrace a life cycle approach and ensure prudent use of resources with a significant reduction in energy usage and emissions.
3. Improving the image of the industry: the construction industry suffers from an image problem caused by several factors. It is well known for its harsh working environment and its low level of automation and digitization (Farmer, 2016; Oesterreich and Teuteberg, 2016). The digital and physical technologies of Construction 4.0 can improve the image of the industry by transforming the work, the worker, and the workplace, and make it more attractive for recruitment and retention of talent.
4. Cost savings: use of industrialized construction supported by digital technologies, BIM, and CDE, can help reduce inefficiencies and waste. Robotics and automation can result in a reduction in direct costs. Real-time access to the physical layer with abundance of data will improve decision making and provide financial incentives for project teams to collaborate and innovate.
5. Time savings: modern methods of construction like prefabrication, additive manufacturing, and on-site assembly will improve the speed of construction. With real-time access to field data, any potential delays can be avoided, resulting in time savings.
6. Enhancing safety: Construction 4.0 will enhance site safety. Augmented Reality/Virtual Reality (AR/VR) based training, wearable technologies, IoT based connectivity of objects, things, and people, image and video processing can enhance safety.
7. Better time and cost predictability: with real-time monitoring, automated site data collection, image processing, AI, and analytics tools the time and cost predictability of ongoing projects can be improved. Availability of large volumes of historical data and information can help set benchmarks for early time and cost prediction of new projects, thereby allowing longitudinal integration.
8. Improving quality: the horizontal and vertical integration resulting from the adoption of Construction 4.0 framework allows the monitoring and control of the design and production processes, thereby improving the quality of construction.
9. Improving collaboration and communication: use of cloud-based project management tools, Blockchain, central repository of information and real-time data access enhances trust among the project team members and enhances communication, coordination, and collaboration.
10. Customer and end-user centric world view: with the reduction in tedious and repetitive tasks, the project team focuses on creating value and focusing on what matters most to the customer.

1.7 Challenges to implementation of Construction 4.0

The Farmer report documented the reluctance of the construction sector to embrace technology and summarized that the industry missed the Industry 3.0 transformation (Farmer, 2016). Dallasega, Rauch, and Linder and Oesterreich and Teuteberg based on an extensive literature review developed the following list of implementation challenges the sector faces while implementing Construction 4.0 framework (Dallasega, Rauch, and Linder, 2018; Oesterreich and Teuteberg, 2016):

1. Resistance to change: the construction sector has a conservative world view when it comes to change. With a considerable resistance, the industry embraces change. Construction 4.0 requires significant change in the way we construct and is likely to face skepticism and resistance.
2. Unclear value proposition: adoption of innovation requires a clear value proposition for all stakeholders. The complex value chain and transactional nature of the sector make it difficult to document benefits and financial gains leading to a hesitation by construction companies to invest.
3. High implementation cost: Construction 4.0 may require high initial investments. This may become a barrier to adoption primarily due to unclear benefits and prediction of cost savings.
4. Low investments in research and development: historically, the construction sector has ignored investments in research and development. This may be a significant blocker of the Construction 4.0 framework.
5. Need for enhanced skills: the industry is already facing a shortage of skilled workforce. Without significant enhancements in education and training, the pipeline of skilled workforce is non-existent. Many aspects of Construction 4.0 may require new roles, new functions, and perhaps new departments or functional teams. This can be a serious threat to implementation.
6. Longitudinal fragmentation: many in the industry believe that we make the same mistakes from one project to the next. This is mainly due to the longitudinal fragmentation in the sector (Fergusson and Teicholz, 1996). To reap benefits from the Construction 4.0 framework it is essential to learn and implement best practices across projects and organizations.
7. Lack of standards: globally agreed standards for the construction sector are important in the transformative processes that are induced by the Construction 4.0 framework. While significant progress has been made on this front, there is still considerable effort needed to embrace data and process standards.
8. Data security, data protection, and cybersecurity: the I4.0 framework mandates that the physical and cyber layers are protected and secured. Lack of security and protection can become a major barrier to the implementation of Construction 4.0.
9. Legal and contractual uncertainty: the construction sector uses a transactional procurement regime that promotes adversarial relationships and limits innovation. The Construction 4.0 framework requires that delivery and procurement processes transform in sync with proposed digital and physical transformations.

1.8 Structure of the handbook

The handbook has the following three parts:

1. Part I: Introduction and overview of Construction 4.0, CPS, Digital Ecosystem, and innovation.
2. Part II: Core components of Construction 4.0.
3. Part III: Practical aspects of Construction 4.0, including case studies and future directions.

Each chapter is structured in such a way that clear and demonstrable linkages to the Construction 4.0 concept and theme of the respective section are provided. The chapters within these three parts and their links to the central theme of the handbook are summarized in Table 1.1.

Table 1.1 Contents of the handbook

Part	*Chapter*	*Chapter title*	*Link to Construction 4.0*
I	1	Construction 4.0: Introduction and overview	Overall vision and description
I	2	Introduction to cyber-physical systems in the built environment	Definition of CPS and its role in the framework
I	3	Digital Ecosystems in the construction industry—current state and future trends	Role of digital tools, platforms and ecosystems
I	4	Innovation in the construction project delivery networks in Construction 4.0	How Construction 4.0 leads to innovation in the industry
II	5	Potential of cyber-physical systems in architecture and construction	Use of CPS in the design and engineering processes
II	6	Applications of cyber-physical systems in construction	Role of CPS in the construction phase
II	7	A review of mixed-reality applications in Construction 4.0	VR and AR applications in Construction 4.0
II	8	Overview of optoelectronic technology in Construction 4.0	Laser scanning of ongoing construction activities
II	9	The potential for additive manufacturing to transform the construction industry	3D Printing of parts, products, and modules
II	10	Digital fabrication in the construction sector	Digital fabrication of parts, products, and modules
II	11	Using BIM for multi-trade prefabrication in construction	BIM for the design and construction phases
II	12	Data standards and data exchange for Construction 4.0	Interoperability
II	13	Computer vision and BIM-driven data analytics for monitoring construction and operation in the built environment	Prediction, forecasting, analytics
II	14	Unmanned Aerial System applications in construction	Data collection, inspection, and imaging
II	15	Future of robotics and automation in construction	Robotics and automation
II	16	Robots in indoor and outdoor environments	Dangerous and repetitive work, inspections and quality control
II	17	Domain-knowledge enriched BIM in Construction 4.0: applications in design-for-safety and crane safety compliance	Knowledge enriched processes and knowledge management
II	18	Internet of Things (IoT) and internet enabled physical devices for Construction 4.0	Machine to machine connectivity
II	19	Cloud-based collaboration and project management	Coordination, communication, and collaboration
II	20	Use of Blockchain for enabling Construction 4.0	Smart contracts and trust building
III	21	Construction 4.0 case studies	Integrated solutions using Construction 4.0 technologies
III	22	Cyber threats and actors confronting the Construction 4.0	Security of physical and digital layers
III	23	Emerging trends and research directions	Research road map

1.9 Conclusion

Construction is a globally significant industry that employs millions of people and contributes massively to the GDP of individual nations and the global economy. However, it is conservative in its approach to innovation and suffers inertia in the face of the need to change. Unlike other industrial sectors such as manufacturing, automotive, and aerospace the construction industry has failed to embrace the opportunities afforded by technology and advances in data management to enhance the efficiency and performance of the sector and the consistency and quality of its outputs. Despite numerous historic attempts to initiate and effect meaningful change the industry still suffers from fragmentation and inefficiencies in process, information flows, and collaborative working. The opportunities afforded by the concepts, principles, and components of I4.0, translated in to a strategic, tactical and operational paradigm as Construction 4.0 have the potential to truly revolutionize the sector. We now approach a potential tipping point at which the concepts generated and applied by forward thinking innovators and early adopters are accepted and applied in the mainstream sector. The effective application of cyber-physical systems and the associated technologies and practices that combine to manifest C4.0 require a new set of skills within the sector workforce. The development of such skills impacts upon the required approaches of educators, employers, and sector leaders to enable a phase shift in the very manner in which construction operates as an industrial and economic domain.

This chapter provides an introduction to the Construction 4.0 framework and its main components. It places them into context with the past and current state of the industry and describes their potential for significant change. The wide adoption of Construction 4.0 related technologies can transform the construction industry into a more efficient and transparent enterprise. Real-time progress monitoring, enhanced quality and safety, and improved communication between stakeholders are just a few of the benefits the industry can enjoy for years to come. It is incumbent on the construction industry to partner with technology innovators, academic institutions, and researchers and educators to make the implementation of Construction 4.0 a reality.

1.10 Summary

- A detailed description of Industry 4.0 and the Fourth Industrial Revolution.
- Key components, technologies, and features of I4.0.
- Benefits of I4.0.
- Description of Construction 4.0.
- Structure of the handbook.
- Future of Construction 4.0.

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NOTES

Chapter 12

1 ISO 10,303 part 28 edition 2

Chapter 15

1 Takenaka, Kajima, Taisei, Obayashi, and Shimizu.
2 www.iaarc.org/publications/search.php.

Chapter 16

1 These are the most significant phases in terms of time, cost, and resources spent compared to the other phases in the life cycle of a construction project (UNEP, 2007).

Chapter 22

1 Industry Foundation Classes.
2 Green Building XML.
3 Comma-separated values.
4 AutoCAD Drawing Database (file extension).
5 Extensible Markup Language.

Chapter 23

1 Idea is loosely used for a new idea, product, or process.
2 In the case of BIM (Building Information Modeling), there is a general consensus in the industry on the benefits and there are many studies quantifying such benefits for various projects with different levels of BIM adoption. These are sufficient conditions for "adoption" under Beal and Bohlen's characterization of the stages and it does not require BIM to be used in the majority of the construction projects.
3 Rate of adoption is understood as a numeric indicator, e.g. number of heavy civil contractors adopting Building Information Modeling per year.
4 Proximity research identifies the distance (physical or cognitive) between two or more entities as a major determinant of knowledge transfer, innovation, and inter-organizational cooperation.

5 *BoKlok* is a housing concept, developed by Skanska and IKEA, www.boklok.com/. *Katerra* is another company revolutionizing the industry with off-site manufacturing, www.katerra.com/en.html.

6 An analogy could be made with "Taylorism" or "scientific management" approaches in the early 19th century when pioneers adopted a similar perspective to improve economic efficiency and labor productivity. For instance, the well-known Gannt chart was discovered and brought into the project management of large public infrastructure projects such as the Hoover Dam.

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