Sustainability and Process Benefits of Modular Construction

Lawson, R.M.
The University of Surrey, UK,
(email: m.lawson@surrey.ac.uk)
Ogden, R.G.
Oxford Brookes University, UK,
(email: rgogden@brookes.ac.uk)

Abstract

Modular or volumetric construction has established a strong market in residential buildings and also in health and educational buildings, where the benefits of speed of construction are achieved. As Regulations for sustainability of buildings are introduced in many countries, the continued expansion of this highly industrialised form of construction depends on the quantification of its sustainability and construction process benefits. This paper addresses the constructional and sustainability benefits of modular construction, based on case studies of recent residential projects, including a 25 storey student residence. The factors investigated include; speed of installation, reduced disruption during construction, higher productivity, fewer transport movements, less waste and more recycling of materials, and more reliable thermal performance in comparison to more traditional construction. Data is presented to support these arguments based on the case studies. The different forms of modular construction are also be presented, which illustrate how the manufacturing process can be adapted to suit the particular building form. Guidance on high-rise applications of modular construction is presented.

Keywords: sustainability, construction, modular, industrialised, high-rise

1. Introduction

Modular construction comprises pre-fabricated room-sized volumetric units that are normally fully fitted out in manufacture and are installed on site as load-bearing ‘building blocks’. Its primary economic advantages are: Economy of scale in manufacturing, speed of installation on site and improved quality and accuracy in manufacture.

Potentially, modular buildings can also be dismantled and re-used, thereby effectively maintaining their asset value. The range of applications of modular construction is in cellular-type buildings such as hotels, student residences, military accommodation, and social housing, where the module size is compatible with manufacturing and transportation requirements. The current application of modular construction is reviewed in a recent SCI publication (Lawson). A paper in The Structural Engineer (Lawson, Ogden *et al)*, describes the mixed use of modules, panels and steel frames to create more adaptable building forms.

1.1 Generic forms of modular construction

There are two generic forms of modular construction, which affects directly their range of application:

- Load-bearing modules in which loads are transferred through the side walls of the modules – see Figure 1

- Corner supported modules in which loads are transferred via edge beams to corner posts – see Figure 2

Figure 1: Partially open sided module with load-bearing walls (courtesy PCKO Architects)

In the first case, the compression resistance of the walls (comprising light steel C sections at 300 to 600 mm spacing) is crucial. Current heights of modular buildings for this type of construction are typically limited to 4 to 8 storeys, depending on particular systems and the size and spacing of the

C sections used. In the second case, the compression resistance of the corner posts is the controlling factor and for this reason, Square Hollow Sections (SHS) are often used due to their high buckling resistance. Building heights are limited only by the size of the SHS that may be used for a given module size (150 × 150 × 12.5 SHS is the maximum size of these posts).

Modules are tied at their corners so that structurally they act together to transfer wind loads and to provide for alternative load paths in the event of one module being severely damaged. This is the scenario method presented in Approved Document A (Building Regulations, England and Wales), which leads to minimum tying force requirements.

Figure 2: Open sided module with corner and intermediate posts supported by a structural frame (courtesy Yorkon and Joule Engineers)

1.2 High-rise building forms using modular construction

Modular construction is conventionally used for cellular buildings up to 8 storeys high where the walls are load-bearing and resist shear forces due to wind. However, there is pressure to extend this technology up to 15 storeys or more by using additional concrete cores or structural frames to provide stability and robustness. High-rise modular buildings of 10 to 25 storeys have been completed in the last 3 years.

One technique is to cluster modules around a core to create high-rise buildings without a separate structure in which the modules are designed to resist compression and the core provides overall stability. This concept has been used on one major project called Paragon in west London, shown in Figure 3, in which the modules were constructed with load-bearing corner posts (Cartz). The building form may be elongated laterally provided that wind loads can be transferred to the core. This can be achieved by using in-plane trusses placed within the corridors, or by structural interaction between the modules and their attachment to the core.

Figure 3: Modular building stabilised by a concrete core (courtesy Caledonian Building Systems)

Bond Street, Bristol is a 12 storey student residence and commercial building in which 8 to 10 storeys of modules sit on a 2 storey steel framed podium (see Figure 4). The 400 bedroom modules are 2.7 m external width, but approximately 100 modules are combined in pairs to form ‘premium’ studios consisting of 2 rooms. The kitchen modules are 3.6 m external width. Stability is provided by four braced steel cores, as illustrated in the plan form of Figure 5. The ‘podium’ structure on which the modules are placed provides open space for retail or commercial use or below ground car parking. Support beams align with the walls of the modules and columns are typically arranged on a 6 to 8 m grid (7.2 m is optimum for car parking below)

Figure 4: 12 storey modular student residence at Bond Street, Bristol (courtesy Unite Modular Solutions)

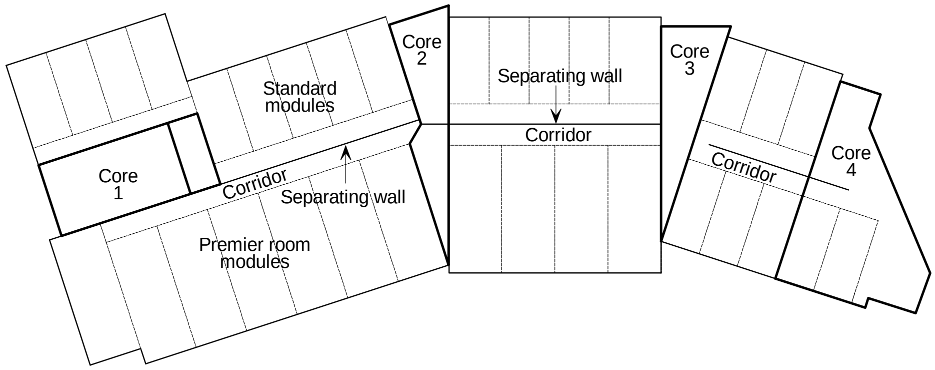

Figure 5: Plan of modular building at Bond Street, Bristol showing the core positions

2. Study of high-rise building using modular construction

2.1 Project description

The modular construction project in Wolverhampton has 3 blocks of 8 to 25 storeys and in total consists of 824 modules. The tallest building is Block A, which is shown in Figure 6. The contractor was Fleming Developments for client Victoria Hall Ltd and the architect was O'Connell East Architects. The modular manufacturer was *Vision*, part of the Fleming Group. The project started on site in July 2008 and was handed over to the client in August 2009 (a total of 59 weeks). The project is located next to the main railway line north of the centre of Wolverhampton. Importantly, the use of off-site technologies meant that the site activities and storage of materials are much less than in traditional construction, which was crucial to the planning of this project.

Figure 6: 25 storey student residence in Wolverhampton during construction
(courtesy Vision Modular Systems)

The total floor area in these three buildings is 20,730 m^2 including a podium level. The total floor area of the modules is 16,340 m^2, which represents 79% of the total floor area. The average module size was 21 m^2, but the maximum size was as large as 37 m^2. The *Vision* modular system uses Square Hollow Section (SHS) corner posts and a concrete floor with perimeter Parallel Flange Channel (PFC) steel sections.

All three blocks are constructed either on a concrete ground slab or first floor podium. The tallest building, Block A, has various set back levels using cantilevered modules. Lightweight cladding was used on all buildings and comprises a mixture of insulated render and composite panels, which are attached directly to the external face of the modules.

2.2 Manufacturing and transport effort

It was estimated that the manufacture and in–house management effort was equivalent to a productivity of 7.5 man -hours per m^2 module floor area (for a 21 m^2 module floor size). This does not take into account the design input of the architect and external consultants, which would probably add about 20% to this total effort.

Allowing for 2 modules in most deliveries, the average travel distance was 300 km (205 miles) on each leg of the journey. The estimated travel time was 20 man-hours per module, which is equivalent to 13% of the manufacturing effort. This reflects the travel distance and a more realistic figure might be 6 to 8% of the manufacturing effort for a modular project in the UK.

The module weights varied from 10 to 25 Tonnes depending on their size. The modules in the first Block C were installed by mobile cane, whereas the modules in Blocks A and C were installed by the tower crane that was supported by the concrete core. The module self weight is approximately 5.7 kN/m^2 floor area. For modules at this higher level, approximately 14% of the module weight is in the steel components and 56% in the concrete floor slab. At the lower levels of the high-rise block, the steel weight increased to 19% of the module weight. The steel usage varied from 67 to 116 kg/m^2 floor area.

The total area of cladding was 10,440 m^2 for the 3 blocks, which included composite panels, metallic cladding and insulated render. The thermal properties of the cladding (U-values) ranged from 0.18 to 0.27 W/m^2 and 1.9 W/m^2 for the glazing, giving an average of 0.45 W/m^2 over the whole façade.

2.3 Construction Data

The installation period for the 824 modules was 32 weeks and the installation team was a total of 8 plus 2 site managers. The average installation rate was 7 modules per day although the maximum achieved was as high as 15 per day. This corresponds to 14.5 man-hours per module (9.5% of the manufacturing effort), or 0.7 man-hours per m^2 of module.

The overall construction team varied from a further 40 to 110 personnel with 3 to 4 site managers for the non-modular components, and the number of personnel increased at the finishing stage of the 59 week project. The total man-hours on site work was estimated as 170,000 (or approximately 8.2 man-hours per m^2 of the completed floor area). It was estimated that the reduction in construction period relative to site-intensive concrete construction was over 50 weeks (or a saving of 45% in construction period).

The estimated breakdown of man effort with respect to the completed building was; 36% in manufacture, 9% in transport and installation, and 55% in construction of the rest of the building. The total effort in manufacturing and constructing the building was approximately 16 man–hours per m^2 completed floor area, which represents an estimated productivity increase of about 80% relative to site-intensive construction.

2.4 Deliveries and waste

Site deliveries were monitored over the construction period. During installation of the modules, approximately 6 major deliveries per day were made, plus the 6 to 12 modules. During concreting of the cores, approximately 6×8 m^3 concrete wagons were scheduled to be pumped to create the core at a rate of one storey every 3 days. Waste was removed from site at a rate of only 2 skips of 6m^3 volume per week during the module installation period and 6 skips per week in the later stages of construction, equivalent to approximately, 3 Tonnes of general waste, including off-cuts and packaging. This is equivalent to about 9 kg of waste per unit floor area.

The manufacturing waste is equivalent to 25 kg/m^2 of the module area of which 43% of this waste was recycled. Allowing for the proportion of module floor area to total area of 79%, this is equivalent to about 5% of the weight of the overall construction. This may be compared to an industry average of 10 to 13% wastage of materials, with little being recycled. It follows that modular construction reduces landfill by at least 70%

2.5 Economic benefits of modular construction

Modular and off-site construction technologies take most of the production away from the construction site, and essentially the slow unproductive site activities are replaced by more efficient faster factory processes. However, the infrastructure for factory production requires greater investment in fixed manufacturing facilities, and repeatability of output to achieve economy of scale in production.

2.6 Economic model

An economic model for modular construction must take into account the following factors:

- Investment costs in the production facility.
- Efficiency gains in manufacture (economy of scale) and in materials use.
- Proportion of on-site construction (in relation to the total build cost).
- Transport and installation costs.
- Benefits in speed of installation
- Savings in site infrastructure and management (preliminaries).

A comparison of the breakdown in the costs of a building constructed using site –intensive processes and fully modular construction is shown in Figure 7. In modular construction, materials use and wastage are reduced and productivity is increased, but conversely, the fixed costs of the manufacturing facility can be as high a proportion as 20% of the total build cost.

Background data may be taken from a recent report '*Using Modern Methods of Construction to Build Homes More Quickly and Efficiently'* (National Audit Office). In this report, the typical as-built cost of a fully modular residential building is stated as £1000/m^2 in relation to a cost-median of £800 to £850/m^2 for traditional housing. However, savings of 7-8% when using modular construction are readily identified in the NAO Report, which offset this cost premium. The economic arguments are presented below.

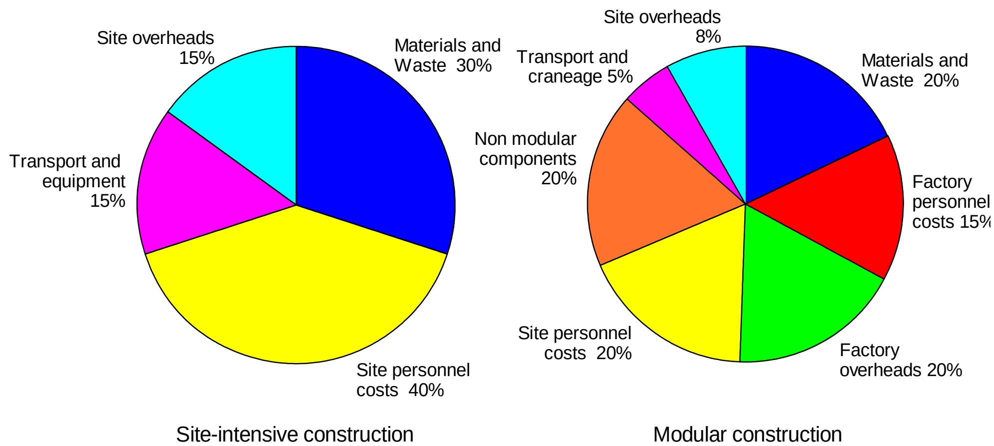

Figure 7: Comparison of breakdown of costs of site-intensive and modular construction)

2.7 Investment costs in manufacturing

The investment in factory production of modules takes into account the following fixed costs:

- Manufacturing machinery and factory infrastructure.
- Storage, materials handling and distribution facilities.
- Heating, lighting and running costs of the factory.
- Skilled personnel involved in manufacture.
- Management and administration overheads
- Design personnel and CAD/CAM facilities.
- Testing and system approvals

A typical advanced modular production facility would require an investment of £8 to 10 million (£9 to £11 million Euros) and running costs could be as high as £4 to 5 million (4 to 5 million Euros) per year including the costs of 80 to 100 personnel. Such a capital investment would be amortized over 5 to 7 years and would require a minimum output of 1500 modules per annum to achieve its ‘pay back’. It follows that the manufacturing cost per typical modular unit is approximately £5,000 excluding materials (or £200/m^2 (220 Euros/ m^2) for a 25m^2 modular unit). This investment must be balanced against other tangible savings, as identified below.

2.8 Efficiency Gains in Manufacture and On-Site

The efficiency gains may be summarised as:

- More efficient materials use and ordering of materials.
- Less wastage and more recycling of materials.
- Higher productivity in factory production
- Less work on site in difficult conditions.
- More reliable performance of the completed building

It may be estimated that off-site production leads to at least 15% saving in materials and wastage. Given that materials cost is about 30% of the total building cost, this is equivalent to about 4% overall saving in build cost.

Productivity benefits are significant, and it may be estimated from the above case study that the labour costs in production are reduced by at least 30% relative to on-site work, and the number of site personnel is reduced by over 70%. This means that overall productivity is increased by at least 50% relative to site-intensive building.

2.9 Design costs

An annual production of 1,500 units may be broken down into 10 to 20 individual projects, with some opportunity for repeatability of components. Design and production costs will decrease with the number in any production run. A nominal 10% increase on production costs for design and management costs may be assumed for a typical modular project. Background testing can lead to efficiency gains by optimising performance and removing waste.

The cost of external consultants is also reduced from typically 6 – 8% in traditional design and tender projects to 3 – 5% in modular projects, as more design work is carried out in-house by the modular supplier. Furthermore, these costs will reduce for repeated projects.

2.10 Proportion of work on-site

Even in a highly modular project, a significant proportion of additional work is carried out on-site. The National Audit Office report estimates that this proportion of on –site cost is approximately 30% of the total for a fully modular building, and may be broken down approximately into Foundations (4%), Services (7%), Cladding (13%) and Finishing etc (6%). However, in many modular projects, the proportion of on-site work can be as high as 55% -see case study. Modular construction also saves on commissioning and 'snagging' costs that can be as high as 3% in traditional construction. Efficiency gains may be achieved by pre-attaching cladding to the modules. Lifts and stairs and service units may also be produced as modules.

2.11 Transport and installation costs

Transport costs are relatively independent of module size and may be taken as £600 (720 Euros) per module for a 200 mile (320km) travel distance (each way to the site). A large mobile crane would normally be required at a cost of up to £2,000 (2200 Euros) per day, and an average installation rate of 6 to 8 modules per day can be achieved. The combined transport and installation cost is therefore approximately £900 per module, which for a 25m^2 module is £36/m^2 (40 Euros m^2) or approximately 4% of the overall construction cost.

2.12 Benefits in Speed of installation

Overall construction periods are reduced by 30 to 50% relative to site intensive building techniques. The financial benefits of speed of installation may be considered to be:

- Reduced interest charges by the client.
- Early 'start-up' of business or rental income.
- Reduced disruption to the locality or existing business.

These business-related benefits are clearly affected by the size and type of the business. The tangible benefits due to reduced interest charges can be 2 to 3% over the shorter building cycle. The NAO report estimates that the total financial savings are as high as 6%.

In traditional construction, site preliminaries may represent 12-15% of the total cost and take into account: Management costs, site facilities, storage and accommodation and equipment. Savings can be achieved due to the reduced number of site personnel (and hence costs) over the reduced construction programme. Site preliminary costs may be taken as 5% for fully modular buildings, leading to a saving of 7 to 10% in comparison to traditional building.

2.13 Overall cost balance

The cost-value balance may be summarised by considering the following savings relative to traditional construction, assuming the same construction cost:

Estimated Saving (% of construction cost)

- Client financial savings 3 – 6%
- Design fees reduction 2 – 3%
- ‘Snagging’ reduction 1 – 2%

Site preliminaries 5 – 7%

Total 11 to 20 %

It follows that the cost premium for modular construction could be up to 10% higher than site intensive construction and still be economic in overall terms.

3. UK code for sustainable homes

Sustainability in the context of construction is presented in terms of various ‘criteria’ of environmental, social and economic performance. In the UK, *BREEAM* is widely used for offices, and the UK Government’s Code for Sustainable Homes (CfSH) has become the environmental standard for use in the residential sector.

The CfSH assessment procedure is based on a number of accepted environmental criteria, which are weighted separately and earn a percentage of available credits. The available credits and weightings for each category of the assessment are presented in Table 1 The point scores are aggregated but certain minimum scores must be satisfied in areas such as energy/CO_2, water saving and material resources, in order to achieve an overall rating.

Table 1 Available credits to the UK Code for Sustainable Homes

Category	*Credits*	*% of Total*
1.Energy and CO2	*29*	*36.4%*
2.Water	*6*	*9%*
3.Materials	*24*	*7.2%*
4.Surface water run-off	*4*	*2.2%*
5.Waste	*7*	*6.4%*
6.Pollution	*4*	*2.8%*
7.Health and well-being	*12*	*14%*
8.Management	*9*	*10%*
9.Ecology	*6*	*12%*

Code Level 3 is the desired standard for most social housing projects. Code Level 6 is 'zero carbon', which is technically very demanding and outside current practice for the vast majority of buildings. A total of 57 points is required to achieve Code level 3 and 90 points for Code level 6.

4. Conclusions on sustainability

The primary use of energy over the building's life is its operational energy due to heating (and in some cases cooling). Modular buildings can be designed to be highly insulating and very air-tight, with a leakage rate of less than $2m^3/m^2/hr$.. Modular construction is lightweight, and the modular structure of a residential building weighs less than 30% of that of a concrete frame. Savings in foundation sizes can be significant on 'brown-field' sites and poor ground.

According to the Building Research Establishment, the UK construction industry average for material wastage on site is 13%. In comparison, site waste in modular construction is greatly reduced and all off-cuts are fully recycled in the factory. Nationally, 98% of all steel is recycled after use and 50% of current steel manufacture in Europe comes from recycled steel (scrap).

Site management is much improved by 'just in time' delivery of the modules and minimal storage of materials is required on site. Noise and other sources of disturbance are also minimised. Site deliveries and site traffic due to construction activities are also reduced by up to 70% relative to more traditional ways of building.

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