Modular vs Conventional Construction: A Multi-Criteria Framework Approach

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Abstract

The use of modular construction methods for projects offers significant time and environmental improvement relative to conventional construction methods. Currently, there is a lack of appropriate assessment approaches to capture the differences between modular and conventional construction. This paper proposes a framework to aid decision makers in choosing between the latter construction methods through the integration of building information models with material libraries, project schedules and machinery inventory. A fixed set of performance parameters, whose attributes are shared among both construction methods, are defined to allow for a reasonable comparison across multiple criteria, including embodied carbon, productivity and total construction costs expended. The dynamics of the project are incorporated by modelling the various stages of the project within a building information model. The proposed framework is tested on a realistic case example, highlighting its applicability as a decision support tool for construction method selection.

Keywords –

Modular Construction; Construction Methods; Prefabrication; Sustainable Construction; BIM

1 Introduction

The construction sector is known to occupy a significant share of the annual GDP of economies worldwide. The industry is also known for its great deal of environmental breaches. In particular, according to the intergovernmental Panel on Climate Change (IPCC), the construction sector is classified as one of seven dominant sectors responsible for substantial greenhouse gas (GHG) emissions [1]. With the growing awareness of the importance of sustainable construction, such that economic, social and environmental factors are accounted for concurrently, many construction organisations have started to implement greater sustainable measures in their design and construction processes. One of the most critical determinants of the economic and environmental performance of a project is the construction method adopted [2]. As an example, modular construction is known to have major economic advantages compared to conventional construction [3].

Modular construction can be defined as a construction system where volumetric components forming a completed part of a building are produced off-site and transported to the construction site for installation [4]. It is the highest end of prefabrication, where full sets of buildings are constructed off-site, instead of only smaller components being produced during the manufacturing process [5].

Some studies suggest the dominance of semi-prefabrication methods over conventional construction approaches in terms of minimising construction related embodied carbon [6], and greenhouse gas emissions [7]. Though there are studies that have also attempted to contrast separately the economic [8] or environmental impacts [6], [9] of construction methods, no attempt has however been made to contrast volumetric construction methods such as modular with conventional methods using an encompassing approach. A study undertaken to highlight an exact quantification approach for comparing between modular and conventional construction across multiple criteria is therefore lacking.

The idea of modular construction has been around since the 1960s, though its effective adoption as a construction method has not been as wide as was expected [10]. It is always challenging to incorporate changes to the conventional construction methods, which have been widely tested and used for long periods [11]. Having said that, plenty of the research conducted indicates that a controlled environment, such as the one presented in modular construction methods, where components are manufactured off-site in a continuous flow process, allows a lot of benefits to be achieved. These advantages can be realised in terms of productivity, safety and environmental performance [4], [12].

Motivated by the lack of a systematic procedure to compare the trade-offs between modular and conventional construction methods, this paper proposes a methodology for integrating Building Information Modelling (BIM), equipment libraries and environmental databases, within a framework for use in construction method selection, both for residential and commercial buildings. The analysis forming the framework is based on the life cycle cost assessment, where economic considerations are embedded along with the common environmental factors, to quantify the overall building performance during all stages of a project's life excluding its operational phase.

The rest of the paper is organised as follows: Section 2 introduces the major components making up the proposed framework. Section 3 presents a brief case study on a realistic project for showcasing the applicability of the proposed framework. Results are discussed in Section 4. Finally, concluding remarks and future work recommendations are presented.

2 Construction Method Comparison Framework

This section describes the different modules making up the proposed framework. Figure 1 depicts the overall framework which is comprised of 4 principle modules; the first set of modules incorporates the input data required for the analysis; the second module is a BIM representation of the project to be constructed and which aggregates the input data. Associated with the BIM is a Comparative Module that specifies the different material composition that would be required for each construction method adopted. The last of the modules is a Criteria Analysis Module which embeds the conditions necessary to perform a comparison between the construction methods.

2.1 Input Module

Data is required to assess the differences between the construction methods available. Modular construction relies on an environment which is drastically different to that of conventional construction. As a result, differences would arise in the project information regarding site preparation and building layout, material to be used, equipment deployed during the construction process, carbon factors of the associated material with each construction method, and the cost element related to the building components. Each of the aforementioned information forms a separate database which get utilised by the constructed BIM.

2.2 BIM

As a form for linking the various information from the input database, a BIM is associated with each construction method. Depending on the size of the project and its use type, different construction methods will need different material compositions and hence the building model produced for each method can vary. Modular construction places large emphasis on the use of timber and light gauge steel framing, as opposed to brick and mortar in conventional construction. As a result, the BIM produced for each construction method will have to reflect this difference in element composition. Materials and equipment can be mapped according to the construction method use, and information for the latter databases can then be associated with the BIM of each construction method.

2.3 Comparative Module

The Comparative Module is where the BIM for modular and conventional construction is used to extract the necessary data required to evaluate the multiple criteria defined. The criteria is evaluated in a way where economic and environmental factors influenced by both construction methods can be assessed. A total of 3 criteria are incorporated within the Comparative Module of the framework, as discussed below.

2.3.1 Embodied Carbon

The first criteria, Eq. (1) minimises the total embodied carbon emissions. Operational carbon is neglected since it is assumed that irrespective of the construction method used, the building will be operated in the same manner; hence the operational carbon is expected to stay be the same for both construction methods.

$$\sum_c Q_c M_c + \sum_t E_t TD + \sum_c \sum_e R_{e,c} P_e \qquad (1)$$

where Q_c is the quantity of material making up each building component $c \in C$, M_c is the emission factor associated with each material component due to its manufacturing phase within its life cycle, as obtained from emission databases, E_t is the emission factor associated with transportation truck t, D is the travel distance traversed by the truck t, T is the number of trips that need to be conducted by the associated truck, $R_{e,c}$ is the emission factor associated with equipment e deployed on building component c, while P_e represents the duration of operation of equipment e.

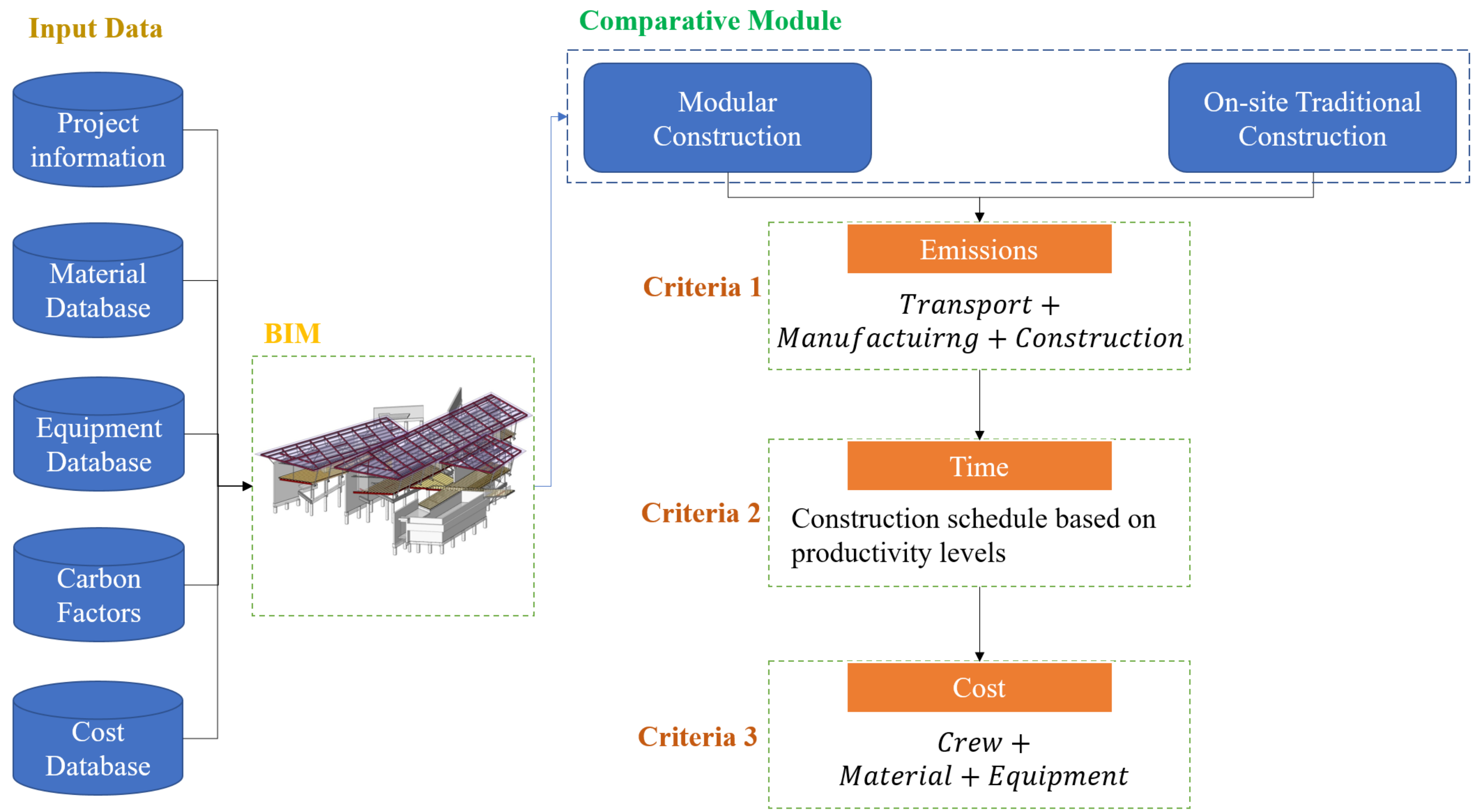

Figure 1. Framework for comparing between modular and conventional construction methods

If on-site construction is used then the distance parameter is calculated by summing the distance of travel between material suppliers i and construction site, d_i:

$$D = \sum_i d_i \tag{2}$$

On the other hand, if modular construction is to be used then the distance is equal to that between the manufacturing place of modular components and the construction site $\overline{d}$:

$$D = \overline{d} \tag{3}$$

2.3.2 Construction Project Duration

The different construction methods will have different project durations, due to the nature of operations and machinery used. To evaluate the schedule duration of each construction method, a second criteria is defined, Eq. (4).

$$\sum_e \sum_c \frac{Q_e}{F_{ce}} \tag{4}$$

where Q_e is the quantity of material to complete activity e while F_{ce} is the productivity rate of crew c working on activity e.

2.3.3 Construction Cost

The third criteria, Eq. (5), computes the cost estimate of each construction method. Each building component is associated with a set of tasks.

$$\sum_q \sum_a N_{qa} CC_{qa}$$

where N_{qa} is the crew size of type q assigned to task a, which reflects the total number of machinery deployed on the respective activities, while CC_{qa} is the unit cost of crew q assigned to task a.

3 Case Example

A project in the North-West of Sydney involves the construction of a granny flat, with dimensions 14 m by 16 m. The builder has the choice of selecting between modular and conventional construction methods; each method is associated with a set of building components as shown in Table 1. The framework of Figure 1 is applied to compare between the two available construction methods. Embodied carbon emission factors are derived from databases such as [13], [14], whereas cost rates and crew productivity rates are obtained from RSMeans and Cordell [15], [16]. Common workflow patterns adopted for both construction operations are shown in Figure 2.

Table 1. Material Composition associated with each construction method

	Modular	Conventional
Interior Walls	Steel frame studs with 5 mm poly sheets	Partition walls with wood studs and 10 mm gypsum wallboards
Exterior Walls	PFC cage with light gauge enclosed framing and colourbond cladding	Double masonry units with bitumen insulation and brick veneer cladding
Floor	Purlin joists with CFC sheeting	Concrete slab on grade with tile finishes
Roof	Light gauge ceiling, with plaster ceiling panel, roof packers and corrugated ceiling sheeting	Timber framing with metal tiling

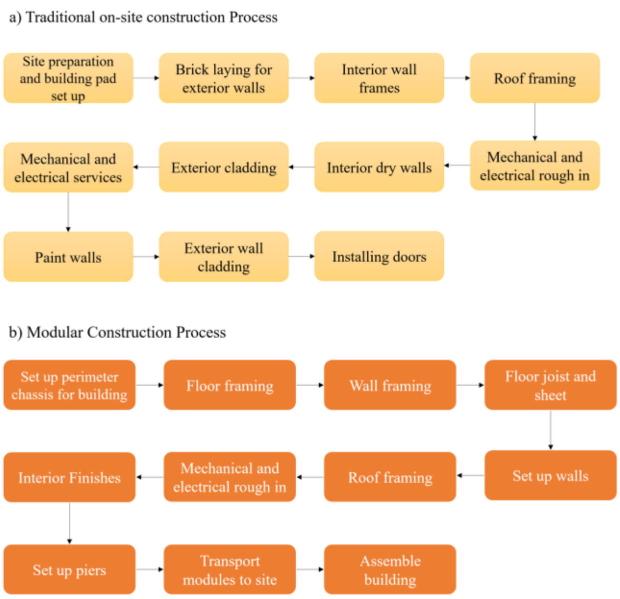

Figure 2. Workflow process of construction

A workflow is adopted to evaluate material use, crew requirement and resource utilization at each stage of the project. A representation of the BIM used to obtain all the required data for the project is given in Figure 3. Piers are assumed to be adopted as the substructure for supporting the granny flat in the case of modular construction, whereas a simple flat slab acts as the building pad for a granny flat constructed using on-site methods. Site preparation for both methods is assumed to be similar; as a result, the analysis excludes substructure construction.

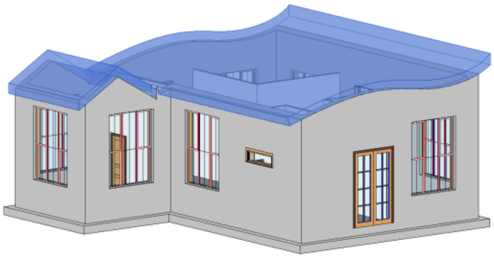

Figure 3. BIM model used for case study

4 Results and Discussion

Each criterion is analysed and the associated results are given in Figures 3 – 5.

4.1.1 Embodied Carbon Emissions

Figure 4 shows the difference in total embodied carbon of both construction methods, adopting the material components of Table 1. The resulting embodied carbon is a direct result of the quantities derived from BIM along with the embodied carbon factors obtained from databases listed above. It is important to note that a total of 302 $kg-CO_2/m^2$ and 378 $kg-CO_2/m^2$ of embodied carbon is associated with modular and conventional construction for the granny flat project, respectively. Overall, modular construction is responsible for 19% lower embodied carbon in comparison to conventional construction

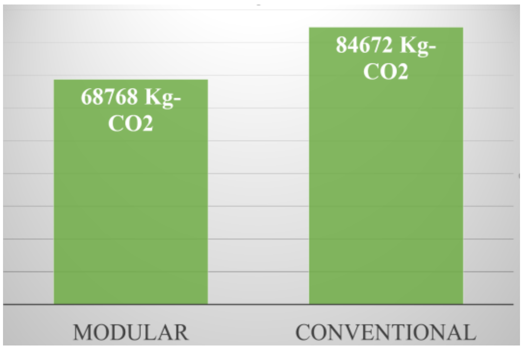

Figure 4. Comparing embodied carbon of the case study using modular *vs* conventional construction

A pie chart showing the average contribution of each material used in both construction methods to total carbon emissions is given in Figure 5. In line with the literature, timber has the highest embodied carbon levels followed by concrete.

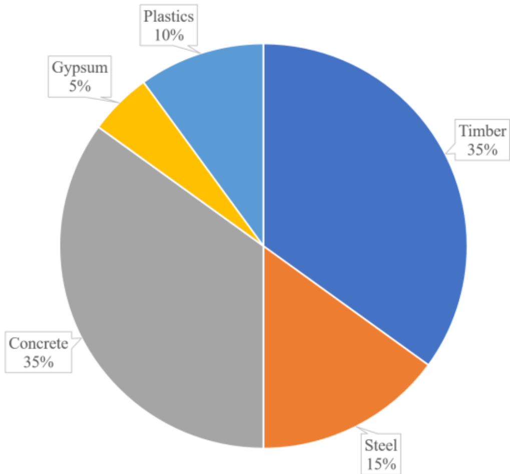

Figure 5. Contribution of material components to total embodied carbon in granny flat case study

4.1.2 Productivity

Based on the crew rate productivity estimates and on the material quantities derived from BIM, the total time taken to complete the project under each construction method is calculated. Results are shown in Figure 6. Modular construction is found to have a 58% advantage in terms of project delivery duration, compared to conventional construction. This is attributed to the influence of weather on work progress, where during rainy conditions, on-site work needed to stop. Such was not the case in the controlled environment of the modular factory.

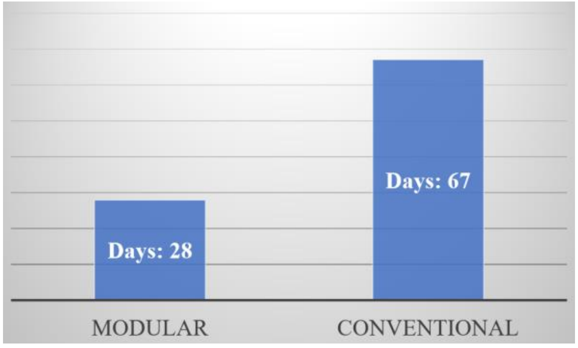

Figure 6. Comparing duration of project using modular *vs* conventional construction

4.1.3 Costs

Total cost estimates for both construction methods rely on the quantities from BIM and the rates associated with the material components. Such rates incorporate labour within them. Based on the flow process delineated in Figure 2, the procedure can be mapped to the cost rates obtained from RSMeans and Cordell. Figure 7 shows the cost estimates of both methods. Modular construction is on average cheaper than conventional methods for this case example. The reason behind this is due to the fewer materials used, and the automated building process in modular construction, which permits economies of scales to be realised.

Figure 7. Comparing cost of project using modular *vs* conventional construction

5 Conclusion

With the growing awareness of sustainable construction, many companies have shifted their focus to sustainable design. This is particularly important given the impact of the construction sector on the economy and on the environment. One way suggested to improve the sustainability of the construction and building industries is through the use of modular construction. This work presented a novel framework to compare the modular construction method against a conventional one. The framework focused on evaluating three main criteria, namely embodied carbon, productivity and monetary cost of the project. Effectiveness of the proposed framework was confirmed by application to a practical construction project. Modular construction was found to be more effective in terms of lower embodied carbon, higher productivity and lower construction costs. Future research will focus on incorporating additional parameters and criteria to compare between the construction methods.

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