Sustainable Prefabricated Modular Buildings

T. Gunawardena¹*, P. Mendis² and T. Ngo³, L. Aye⁴ and J. Alfano⁵

¹,²,³ & ⁴ The University of Melbourne, Victoria, Australia
² Alfano Architects Pty Ltd, Melbourne, Victoria, Australia
*E-Mail: tharakag@student.unimelb.edu.au, TP: +61423909958

Abstract: Economy, speed of construction and improved environmental performance are critical variables that challenge the modern construction industry to strike a balance between. Employing innovative prefabricated modular structures is one key strategy used to achieve these goals. Therefore, there is an increasing demand for detailed scientific research that deals with the potential environmental benefits of prefabrication, particularly in areas of embodied energy savings resulting from waste reduction and improved efficiency of material usage. This paper gives a brief overview of prefabricated modular structures and aims to highlight the sustainability characteristics of this technology compared to conventional construction methods.

A case study was carried out on an eight-storey, residential building. It was found that a steel-structured prefabricated system resulted in a significantly reduced material consumption of up to 78% by mass compared to conventional concrete construction. However, the prefabricated steel building resulted in an increase in embodied energy compared to the concrete building mainly due to the inherent characteristics of steel manufacturing processes. This form of construction has the potential to contribute significantly towards improved environmental sustainability in the construction industry while providing fast outputs with value for the investments.

Keywords: Lifecycle Energy, Modular Construction, Prefabrication, Sustainable Construction

1. Introduction

Due to fast delivery and convenience on site, prefabricated modular structures have a great potential in changing conventional construction methods at a rapid rate.

Prefabricated building modules (such as apartments, office spaces, stair cases etc.) can be fully constructed with architectural finishes and services inside a quality controlled factory environment, ready to be delivered and assembled on site to form a load bearing structure. Most manufacturers will nowadays cater for any architectural design with innovative modular units accordingly.

1.1 Features of prefabricated modular structures

As modern architecture comes with innovative designs, buildings will not rely on a fixed module. A building designer is free to lay out a building in the conventional manner to suit a client’s desire and the requirements of the market. The building is then adjusted and divided into units that are in width and length suitable for transportation and lifting into position by a crane on site.

The prefabrication of buildings has proven to reduce construction waste by up to 52% (Jaillon et al. [2]) mainly through means of minimised off-cuts (Osmani et al. [5]). This in turn will result in significantly improved energy, cost and time efficiency of construction.

The features of such building units (modules) are as follows:

- All components of a building, including stairs, lift shafts, façades, corridors and services can be incorporated in such modules.
- The modules are mass produced in a quality controlled production facility.
ensuring greater quality control as well as more beneficial economies of scale.

- A module’s shape and size can vary to suit a desired architectural plan, where the dimensions may only be limited according to the transportation arrangements (e.g.: truck dimensions, height restrictions on roads that need to be travelled on during transport of the modules).
- There is minimal work on-site to complete the buildings as the façade and interiors themselves form parts of the modules.
- The modules can easily be removed from the main structure for future reuse or relocation. Many developed economies now have a market for used modular units.
- Modular construction at present reduces construction time by over 50% from a site-intensive building (Lawson et al. [3]).
- Reduced construction time means that the modular houses become habitable for the end users much sooner than it would after a conventional construction.

2. Prefabricated Modular Buildings in Real World Applications

Although the concept of prefabricated modules is only beginning to gain popularity worldwide, quite a few such buildings have already been built and inhabited in many developed countries. Almost all of these buildings are residential, and there is an increasing demand for this construction technique mainly due to the speed at which the final products are realised.

A few examples from around the world are described briefly to observe how prefabricated modular construction has become established as a practical commercial building methodology.

a) Little-Hero Building, Melbourne CBD, Australia

The low-rise apartment building ‘Little Hero’ in Melbourne, Australia (Figure 1) consists of 58 single-storey apartment modules and five double-storey apartment modules. The authors were part of the development team for this project. The eight modular stories were assembled with finishes within eight days, and the building was constructed at a site with a very narrow access road, thereby demonstrating some of the many advantages of modular construction.

b) Domino Housing 21, Spain

This is a four storey structure built in Spain (Figure 2), where modules can be added or dismantled as the client pleases. The time taken to set up the full structure once planned is just 15 days. The building speaks volumes for the speed of construction that modular concepts provide, as the units can be added with additional boxes to add spaces and customise the existing ones even further.

b) Student Housing Building, Wolverhampton, UK

This 25 storey structure (Figure 3) is claimed to have been completed with just 27 weeks of work on-site. Lawson et al. (2012) explains this as a 50% saving from the on-site time estimated for a
site-intensive construction. They have estimated the productivity in terms of man-hours used to be an 80% improvement from a site-intensive construction. In general, Lawson et al. [3] states that modular construction can reduce site wastage up to 70% compared to site-intensive construction methods.

c) Post Katrina Housing, Mississippi, USA

Due to the large housing demand which followed the hurricane Katrina disaster in 2005, much research went into improving on the previously used ‘FEMA Trailers’ and to implement modular construction for temporary housing. A design of Archt. Marianne Cusato inspired this modular design which was named ‘Katrina Cottage’ (Figure 6). It was designed to be installed with a floor area of 27.8m². However this was improved to incorporate a more permanent housing solution with 20 different cottage models that allowed for expansions later on.(McIntosh, [2]).

Further, as discussed by Gunawardena et al., 2014, modular buildings are also suitable for permanent housing solutions for post-disaster situations. This is an efficient way to provide quick but permanent relief to disaster affected communities.

3. Sustainability – Case Study

3.1 General

Sustainability in general is defined through three main paths, namely;
- Social Sustainability
- Economic Sustainability
- Environmental Sustainability

As shown in Figure 5 below, the United Nations (2005) identifies that these three main constituents need to act in harmony to achieve a meaningfully sustainable outcome.

3.1 Case Study

A case study was carried out for the ‘Little Hero’ building (Figure 1) in Melbourne which is introduced in section 2 of this paper.
This study involved an assessment of the embodied and operational energy associated with the above mentioned multi-storey building, for three varying construction approaches, a prefabricated modular steel structure and a prefabricated modular timber structure with a conventional concrete structure used for comparative purposes.

The analysed building has a gross floor area of 3,943 m² with a total of 63 apartments consisting of 58 single-storey and five double-storey apartments. The floor areas of the single-storey and double-storey apartments are 63 and 118 m², respectively.

3.2 Case Study Outcome

Embodied Energy Analysis

The embodied energy analysis of the building for concrete, prefabricated steel and timber construction approaches is discussed here. Figure 6 provides a brief comparison of the total building embodied energy for the three building material options.

While the prefabricated concrete building is over four times heavier than the prefabricated steel building, the total embodied energy in the steel building is about 50% greater than that of the concrete building. This is predominately due to the more energy intensive processes involved in the manufacturing of steel members as compared to concrete production, for an equivalent

![Embodied Energy Analysis Results](image)

**Figure 5: Comparison of Total Embodied Energy for the Steel, Concrete and Timber building options**

![Heating & Cooling load in the UB system for Melbourne weather-Steel](image)

**Figure 6: Heating & Cooling load in the UB system for Melbourne weather-Steel**

![Heating & Cooling load in the UB system for Melbourne weather-Concrete](image)

**Figure 7: Heating and Cooling loads (operational energy) for Steel and concrete options considering Melbourne Weather**
A functional unit (in this case a building’s structure). For the prefabricated timber building with steel columns and beams the total embodied energy is about 10% higher than that of concrete building.

**Operational Energy Analysis**

This section discusses the annual operational energy requirements associated with the case building for all three material types considered. A simulation was performed on the software TRNSYS to determine the operational energy required for each zone to maintain an indoor air temperature between 21 & 24°C (Figure 7).

As shown by Figure 8, the heating and cooling loads are similar for all three building systems investigated. The estimated heating and cooling loads were used to calculate operational energy consumption for all construction scenarios by using the heat pump seasonal average COP values described earlier.

**Lifecycle Energy Analysis**

The lifecycle energy of the analysed building was determined by combining the embodied and annual operational energy requirements calculated above for concrete, prefabricated steel and timber options over a 50-year period. The findings are presented in Figure 9. Once calculated for 1m² of building, the life cycle energy requirements were shown to be greater for the steel option at 36 GJ/m², compared to 30 GJ/m² for the concrete option. For all scenarios the total heating and cooling energy represents a larger component of the total life cycle energy requirements than do the embodied energy requirements.

**Lifecycle Greenhouse Gas Emissions – Embodied Energy Related**

The embodied and annual heating and cooling electricity requirements estimated above were used to determine the associated greenhouse gas emissions for the case study building. Primary energy and greenhouse emission factors for Melbourne, Victoria were used. The greenhouse gas emissions associated with the energy embodied in the building were 3407, 2482 and 2281 t CO₂eq for the prefabricated steel, prefabricated timber and concrete building types respectively. The elemental breakdown of embodied greenhouse gas emissions for all construction systems is shown in Figure 10.

It is evident that the steel framed building has about 50% more embodied greenhouse gas emissions compared to the concrete framed building.
alternative. The embodied greenhouse emissions per square metre of floor area are 864, 630 and 578 kg CO₂-e for the steel, timber and concrete construction systems, respectively.

**Lifecycle Greenhouse Gas Emissions – Operational Energy Related**

Figure 11 shows the annual heating and cooling energy-related greenhouse emissions. This clearly indicates that there is little difference in the operational energy-related emissions between the concrete, steel and timber options. The slight differences are mainly due to the differences in heat transfer characteristics and slight difference in thermal mass.

![Operational GHG Distribution over a year](image)

*Figure 11: Operational greenhouse gas emissions of the building over a year*

Figure 12 shows the total life cycle greenhouse emissions for a 50-year life span for each construction type for the case study building. This indicates that the concrete structure results in a 13% less life cycle greenhouse emissions than prefabricated steel building.

4. **Benefit of Material Reuse**

Reuse of construction materials can lead to significant resource savings together with other environmental benefits from a reduction in waste disposed of in landfill and the energy required for the production of virgin materials. A major advantage of prefabricated steel and timber construction is the ability for construction elements to be disassembled at the end of their useful life and reused in a new building. On the other hand, whilst concrete can be recycled as aggregate in new concrete, it is typically not possible to reuse structural elements from one building in a subsequent building.

The potential material resource and embodied energy savings possible from the reuse of materials for both concrete and steel buildings are based on assumptions of the likely materials and respective quantities available for reuse. Whilst the concrete construction system accounts for a greater volume of material than the steel system, and thus a greater potential for reducing the quantity of waste sent to landfill, the potential for embodied energy savings from the reuse of materials is significantly greater for the prefabricated steel construction system.

5. **Concluding Remarks**

The presented case-study has assessed the life cycle energy requirements of three forms of construction for a multi-residential building, conventional concrete construction, prefabricated steel construction and prefabricated timber construction to determine the environmental benefits offered by modular construction. The study has shown that the prefabricated steel system results in a significant reduction in the consumption of raw materials of up to 50.7% by weight.

Despite this, the energy embodied in the prefabricated steel building is up to 50% greater than that for the concrete building. However, the key benefit of the prefabricated system is the ability to reuse a significant proportion of the structure at the end of the building’s life. This may result in a significant reduction in waste being sent to landfill and reduced requirements for additional virgin materials. At the end of the building’s useful life, up to 81.3% of the
embodied energy of the initial steel building can be saved by reusing the main steel structure of the prefabricated modules and other components in another new building. The resulting advantages through reduction in construction waste as well as construction time are well depicted through the real world examples discussed in section 2 of this paper.

There was also shown to be only a minor variance in the operational energy requirements associated with the construction types. Additionally, the embodied energy component for all construction types investigated was shown to represent at least 32% of the total life cycle primary energy requirements. This reinforces the importance of building embodied energy, particularly as rapid improvements are made in buildings operational efficiency performance, further increasing the relative significance of embodied energy.

As far as life cycle energy is concerned, the prefabricated steel scenario was shown to consume more energy than for conventional concrete construction over a 50-year period. However, despite this the study has clearly indicated that prefabricated construction is capable of providing improved environmental performance over conventional construction methods if they are initially designed to be reused, either adaptively or through disassembly.

The reuse of materials may reduce the space required for landfill and the requirement for additional virgin raw materials. The choice of materials in the construction of buildings has a significant impact on the embodied energy requirements of construction. However, embodied energy should be optimised in the broader life cycle context, considering also the operational, recurrent, maintenance and end-of-life energy requirements and impacts associated with buildings.

References


Minerva Access is the Institutional Repository of The University of Melbourne

Author/s:
Gunawardena, D; Mendis, P; Ngo, D; Aye, L; Alfano, J

Title:
Sustainable Prefabricated Modular Buildings

Date:
2014

Citation:

Persistent Link:
http://hdl.handle.net/11343/208884

File Description:
Published version