A HOLISTIC MODEL FOR DESIGNING AND OPTIMISING SUSTAINABLE PREFABRICATED MODULAR BUILDINGS

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Abstract

Prefabricated Modular Structures are increasingly becoming popular as a strategy that can be used to achieve cost effective and speedy construction. However, there is an absence of detailed engineering research or case studies dealing with the structural performance or building optimisation and integration strategies for this technology. This paper presents a conceptual holistic model that can be used to identify the most optimum structural system in a given scenario. A multi-disciplinary approach will be taken to optimise the building by assessing structural systems, materials, sustainability features, constructability and speed and cost of construction. This paper will discuss types of different optimisation strategies adopted in building designs and how they can be modified to assess a prefabricated modular building and what different variables will dominate as key performance indicators in the search for an optimum solution for a prefabricated modular building.

Keywords: Prefabrication, Modular buildings, Multi-disciplinary, Optimisation, Holistic, Key Performance Indicators

1. Introduction

Due to fast delivery, easy construction 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 stable structure. Most manufacturers will nowadays cater for any architectural design with innovative modular units accordingly.


Figure 1: The 'Little Hero' building in Melbourne, Australia

Modular technology has already been used on low rise structures around the world. A great example among many is the low rise apartment building 'Little Hero' in Melbourne, Australia (Figure 1) which consists of 58 single-storey apartment modules and 5 double-storey apartment modules. The 8 modular stories were assembled with finishes within 8 days and the building was constructed in a site with a very narrow access road demonstrating many advantages of modular construction.

In most cases including the 'Little Hero' building, a cast in-situ concrete or a steel core or a number of cores act as the primary lateral load resisting system. Prefabricated modules are tied to each other and to the core(s) by means of steel connections through which all lateral loads are transferred to the core(s). In other cases very low rise buildings have been constructed using a set of load bearing modules which are stacked on top of a foundation and base slab and connected to it with bolted base plates.

This paper presents a conceptual framework to be used on modular buildings and help designers to find the most optimum solution for a particular modular structure. Key Performance Indicators (KPI) will be identified with respect to a given scenario and will be assessed in integration with each other to arrive at the most optimum solution.

1.1 Features and Benefits 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 features and benefits of modular construction are as follows:

- The modules can incorporate all components of a building including stairs, lift shafts, facades, corridors and services
- The modules are constructed in a quality controlled production facility ensuring better quality than on-site construction
- There is minimal work on site to complete the buildings as the façade and interiors themselves form part of modules
- The modules can easily be removed from the main structure for future reuse or relocation
- Modular construction at present reduces construction time by over 50% from a site-intensive building (Lawson et. al., 2012)
- Reduced construction time means that the building starts generating income for the client, much sooner than it does after a conventional construction.

Further, Jailon et al. (2009) stated that prefabricated buildings reduce construction waste up to 52% compared to traditional methods. Aye et al. (2007) have found out that a steel-structured prefabricated system resulted in a significantly reduced material consumption of up to 78% by mass compared to conventional concrete construction. Quale et al. (2012) showed that Green House Gas (GHG) emissions for conventional constructions is 40% higher than that of modular constructions after comparing a set of modular and conventional residential buildings in USA.

2. Conceptual Framework

2.1 Conceptual Basis

Prefabricated modular structures have a great potential in changing conventional construction methods at a rapid rate. Some key research questions that were identified by conducting a comprehensive literature review.

The basic question to be answered is; 1. "What is the most optimum structural system for a Prefabricated Modular Building?"

This may have varying answers depending on the scenario but from this basic question generates further questions in the form of;

2. Can optimum levels of Construction time and cost and sustainability is achieved by the best structural system?
3. Is it the best structural system in terms of constructability?
4. What are the material properties demanded by the system with respect to walls and connections of the modules and in this sense what materials would best suit the requirements?
5. How are all the parameters integrated for the most optimum solution?

2.2 The Holistic Model

The main aim is to develop a model that can identify the most optimum structural system for a prefabricated modular building. A holistic and integrated approach is taken towards identifying the best system looking at various criteria that it should satisfy (Figure 2).

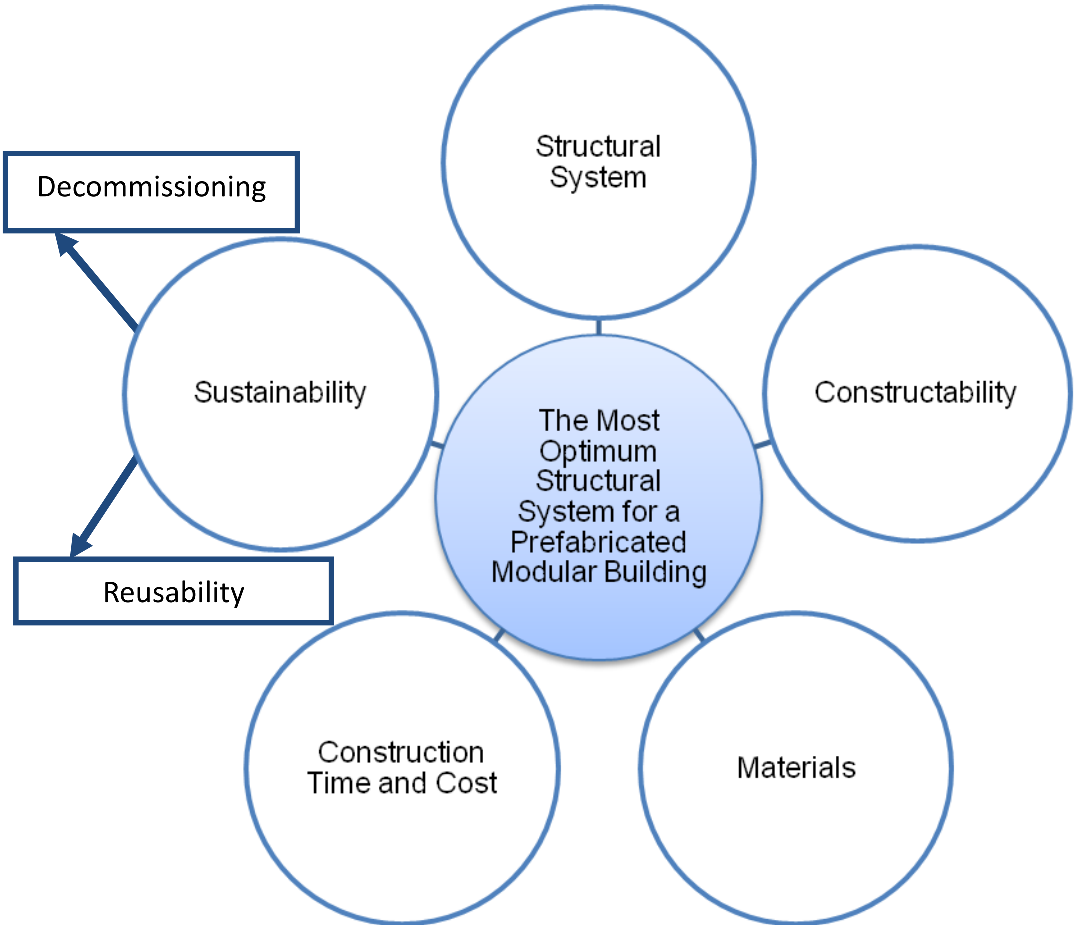

Figure 2: The Holistic Model to identify the most optimum structural system for a prefabricated modular building

The structural system also should by default be constructible, economically feasible and sustainable to be marketable to clients in the industry. These concepts can be explained as follows;

Constructability : The structure needs to be easily constructible on site ensuring worker safety as well. Ability to place cranes and the possibility to use smart auto climbing systems will be assessed especially with respect to medium to high rise buildings.

Economic Feasibility : The structural systems suggested need to be economically feasible. Therefore a basic financial evaluation will be carried out with the input of industry partners.

Sustainability : Sustainability should basically be identified in terms of reusability and ease of decommissioning. Since these are key advantages of modular construction, any structural system that is developed should address these considerations.

All structural aspects that are assessed will eventually be integrated with the non structural considerations that are identified in the Holistic Model (Figure 2) to identify the most optimum solution for a given situation.

3. Multi Disciplinary Optimisation

3.1 Optimisation Strategies and Variables

The Holistic Model as explained previously is a framework to visualise various aspects of a modular building's design and construction which touches all the different disciplines related to the process. Ameli & Gregori (2012) observed that integration could happen at different levels of a building design. It could happen at a more operational level such as integration of functions and components in the form of lighting, hydraulic plant, thermal systems etc. It also could be at a more global level of controls that manage the building as a whole or many buildings together in one system. Once the various parameters are integrated into one framework they could then be manipulated with to come up with an optimum solution.

Once a building design is evaluated with computer models as well as other physical testing if applicable (wind tunnel tests etc.), it will need to follow the Holistic Model (Figure 2) to be evaluated in integration with other non-structural aspects to develop the most optimum design for that modular building. Concepts of building optimisation will need to be closely analysed with regards to the different options of systems considered.

Optimisation can happen at various aspects of design as well. While there may be many forms of optimisation possible for a particular design, a building optimisation can happen mainly in the forms of;

- Geometric Optimisation
- Structural Optimisation
- Energy Optimisation
- Process Optimisation (Manufacturing and Construction - time and cost)

3.2 Geometric Optimisation

Building optimisation could happen as a geometric optimisation, where the geometry of the structure is assessed with variables related to it such as;

- member section sizes and material strengths etc.
- length of continuous spans and cantilevers
- transportability of modules
- provisions for future expansions

3.3 Evaluation of Structural Systems and Materials

As a critical focus, the structural systems shall be evaluated in four key aspects in the form of Structural Connections, Structural Members, Materials, Behaviour under Lateral Loads and Robustness. The structure will be analysed for optimisation on their connections and structural members which are optimised through variables such as;

- performance against lateral loads
- general structural stability
- weight
- required material properties

The vision is to find the requirement for the most optimum modular system that provides all or most of the benefits of modular construction to the client. With this respect, the connections and the main structural elements in the modules for different structural systems have to be analysed thoroughly with advanced finite element analysis software such as Ansys and LS-DYNA. Different materials such as high strength steels and concrete and composites with various mechanical properties will also be evaluated to be used in connections and stiffened walls in modules.

3.4 Energy Analysis

This study involves an assessment of the embodied and operational energy associated with a prefabricated modular building various designs. A full energy analysis will consist of a full lifecycle energy analysis as well. This will give input to the Holistic Model in terms of energy systems in general, mechanical and electrical systems and embodied energy from structural and non structural materials used.

3.4.1 Embodied energy analysis

Embodied energy accounts for the energy consumed during the manufacture of products and materials, including those resulting from the manufacture of goods and services used during this process. For example, the energy embodied in steel products, typically comprise energy for iron ore extraction, transporting and processing the iron ore, manufacturing the steel products and delivery to site. Energy is also embodied in goods and services, including capital, utilised during these processes, and so forth. Many factors (including technology, fuel supply structures, region, product specification and analysis method) can result in considerable variability in embodied energy data.

The embodied energy assessment for this research can be performed using an input-output-based hybrid analysis. This method is applied using an I-O model of Australian energy use, developed by Lenzen and Trealor (2004). Process specific data for the energy from the manufacture of specific materials is available in the latest available SimaPro Australian database (Grant, 2002).

Table 1: Densities and embodied energy intensities of basic construction materials

Material	*Density (kg/m^3)*	*Unit*	*Embodied energy intensity (GJ/unit)*
Concrete (30 MPa)	*2400*	m^3	*5.48*
Concrete (50 MPa)	*2400*	m^3	*8.55*
Structural steel	*7850*	*t*	*85.46*
Glass (4 mm)	*2600*	m^2	*1.72*
Cellulose insulation (R2.5, 100 mm)	*43*	m^2	*2.17*
Plasterboard (10 mm)	*950*	m^2	*2.07*
Plywood	*540*	m^3	*10.92*
Aluminium	*2700*	*t*	*252.60*
Timber (softwood)	*700*	m^3	*10.92*
MDF	*500*	m^3	*30.35*
Mortar	*1900*	*t*	*2.00*
Ceramic tiles	*1700*	m^2	*2.93*
Source: Treloar and Crawford (2010)			

The calculation of the energy embodied for different components in the structural systems can be found from Table 1, which includes the energy from fossil fuel consumption. These intensities are calculated using the input-output-based hybrid method, combining available process data for the specific materials, with I-O data.

3.4.2 Operational energy analysis

The operational energy associated with the usage of a building can be estimated using a tool such as TRNSYS simulation software based on the characteristics of the building as well as assumed heating and cooling schedules.

3.4.3 Life cycle energy

The life cycle energy requirements associated with a building can be calculated for a time period such as 50 years. This can be achieved by combining the initial embodied energy values with total estimated operational energy requirements over the number of years (Aye et al., 2012).

Embodied energy associated with replacement of materials and building components over the life of a building can represent up to 32% of its initial embodied energy (Treloar, 2000). The extent of this depends on a number of factors, including the useful life of the building and the anticipated life of the individual materials or components. The life cycle energy assessment can be carried out considering all the factors and taking reasonable assumptions into account as well.

3.5 Greenhouse gas emissions

Whilst calculating energy consumption is important in identifying areas where significant reductions in consumption may be achieved, energy consumption figures alone do not necessarily give a good indication of the environmental impacts associated with a building. The same quantity of energy, but from different fuel sources (including coal, natural gas, wind and solar) will result in a wide range of impacts on the environment. The greenhouse gas (GHG) emissions produced from the combustion of fossil fuels, which supply over 86% of global energy needs, is one of the main contributors to the world's key current environmental issue, global warming. The quantification of GHG emissions from consumed energy is seen as a good indicator of the overall environmental impact resulting from energy consumption. This assessment can add a great value to the building optimisation study at a global scale.

3.5.1 Embodied energy-related emissions

Due to the difficulties associated with determining the proportion of embodied energy supplied by the various fuel types within all of the processes involved in manufacturing and supplying the components of the case study building, an average emissions factor of 60 kg $CO_{2\text{-e}}$ per GJ of energy can be used to calculate the greenhouse gas emissions related to the embodied energy of all construction types (Treloar, 2000).

3.5.2 Operational energy-related emissions

This takes into account variables such as energy required for heating and cooling. Using the primary energy factor [Example: 3.5 for electricity in Victoria, Australia (Treloar, 1998)], estimated operational energy figures can be converted to primary energy terms to account for the impacts associated with the energy production. An emissions factor depending on the energy source can be used to estimate the greenhouse gas emissions from the electricity consumption figures.

3.6 Process Optimisation

Economy and construction speed will be key criteria that will be integrated into the optimisation study. Results of previous studies on energy performance of modular buildings will also be used to find out sustainability implications.

The process of manufacturing should also be paid a great deal of attention here. The lead times from design to manufacturing and then from manufacturing to delivery can affect the overall time spent on the project. Since most of the construction is replaced by factory manufacturing the critical path will be different to a conventional construction plan. Process optimisation techniques can therefore play a major role in identifying critical activities and reducing the time spent on the entire setup from design to construction.

3.7 Reusability and Waste Management

Ease of disassembly and reusability of entire modules is one key advantage of a modular structural system. Therefore it should be one KPI that needs attention in the optimisation of a building.

Figure 3: Concept of decommissioning and reuse

Reusability of materials in the long run will result in considerable reductions in wastage of materials (Jaillon et al., 2009). Reduction of waste that usually occurs in a traditional demolition of a building is a key feature in the positive environmental impact of modular systems.

Taking these factors into consideration, any structural system that is assessed will be given a higher priority if it has an efficient decommissioning method where complete modules can be reused in other future uses.

4. Concluding Remarks

Prefabricated modular construction is a new and highly sort after technology in the current practice. With key characteristics such as speed of construction, low environmental impact, ease of decommissioning and high reusability this will serve as a highly sustainable construction method.

Although many studies have been done on its sustainability features, very little sound research is available on plausible structural systems and the overall optimisation methods. The holistic model that is presented in this paper is a starting step to finding the optimum solution to a given modular structure. Optimisation techniques such as Monte Carlo method can be used to quantify the multi variable optimisation that is required in this model.

In practice Building Information Models (BIM) can play a major role in integrating design data, manufacturing processes and construction for modular buildings. They can bring all KPIs together for a global optimisation to be carried out. The Holistic Model (Figure 2) will therefore be the fundamental basis for all such techniques to be applied for a given modular design in finding the most optimum structural system.

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