A COMPARATIVE ANALYSIS OF ENERGY AND LIFECYCLE GREENSHOUSE GAS EMISSIONS PREFABRICATED BUILDING MODULES

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SUMMARY: A method for: 1) quantifying the embodied energy of modular prefabricated steel and timber multi-residential buildings to determine whether prefabricated construction provides improved environmental performance over conventional concrete construction methods; and 2) assessing the potential benefits of material reusability in the context of reducing the space required for landfill and need for additional resource requirements.

ABSTRACTS: Prefabrication is considered to provide improved environmental performance over traditional building construction. This paper provides evidence of the performance improvements of prefab construction by quantifying the embodied energy of modular prefabricated steel and timber multi-residential buildings. To this end, a benchmarking study is performed to ascertain the improved environmental performance of this method over conventional concrete construction methods. Furthermore, this paper assesses the potential benefits of material reusability in terms of reducing the space required for landfill, as well as the need for additional resources. It was found that a steel-structured prefabricated system resulted in reduced material consumption of up to 78% by mass compared to conventional concrete construction. However, the prefabricated steel building resulted in a significant increase (~50%) in embodied energy compared to the concrete building. It was shown that there was significant potential for the reuse of materials in the prefabricated steel building, representing up to an 81% saving in embodied energy and 51% materials saving by mass.

KEYWORDS: Life cycle energy; Embodied energy; Prefabrication; Waste minimization.

1. INTRODUCTION

The construction and operation of buildings contributes significant environmental impacts, mainly through resource consumption, waste production and greenhouse gas emissions. In Australia, the prefabricated building system (i.e., pre-cut, panelized, modular, and mobile home building system) has been recognized as one of the alternative solutions to changing the speed of conventional construction methods at a fast rate. This prefabricated construction system also has been promoted as one of the eight key visions to improving the efficiency and performance of the Australian construction industry vision [1]. It also provides environmental benefits, such as the reduction of construction waste and CO_2 emissions, and reduces disturbance to neighbors of the building site's by minimizing on-site noise and dust [2]. Other benefits include improved quality and accuracy in manufacture, speed of on-site installation, and rapid dismantling and reuse [3].

The importance of considering the life cycle impacts of buildings, given that the environmental impacts of initial construction can be as significant as those associated with their operation, has been established over the past few decades [4]. Specifically, the construction of buildings generates significant quantities of waste, up to 10% of the volume of materials used in constructing the building (on average).

The life cycle environmental impacts can be significantly reduced if the structural components of a building are designed to be durable and reusable. Innovative design of the structural connections at the initial development stage is extremely important to ensure that the deconstruction/demolition process can take place efficiently to maximize the reusability of building components. To this end, this study aims to quantify the potential life cycle environmental benefits of prefabricated modular buildings to determine whether this form of construction provides improved environmental performance over conventional construction methods.

2. METHODOLOGY

2.1. Method for Energy Analysis

In the best-case scenario, studies that have compared the life cycle energy associated with conventional and prefabricated construction methods in the past, have used incomplete methods of embodied energy analysis. These methods are known to exclude up to 87% of the energy requirements associated with construction [5]. There are numerous methods that can be used to estimate the energy consumed in providing goods and services. The accuracy and extent of analysis depends on the method chosen.

The hybrid model developed by Treloar [6] (known as input–output-based hybrid analysis) starts with a disaggregated I–O model, and available process data is integrated in this model. The implication of this is that the truncation errors associated with the use of process analysis are avoided and the analysis is more complete. Various goods and services are allocated according to their appropriate industrial sector in the input–output tables to ensure that similar modelling principles are used. This approach has already been well established and demonstrated for calculating the embodied energy in buildings.

A model utilizing a systemically complete system boundary has seldom been used to assess and compare the embodied energy associated with prefabricated construction. The knowledge gained from previous studies provides little support to industry in terms of their need for environmental comparisons between different construction approaches to inform design decision-making, which is mainly attributed to the known deficiencies in the methods of analysis used. Using the approach developed by Treloar [6], the current study extends similar previous studies by providing a more comprehensive assessment of the embodied energy in prefabricated construction approaches. This substantially resolves the issue of system boundary incompleteness. The information provided by this study will facilitate the design decision-making process and the environmental benefits of prefabrication can be better evaluated to create buildings that are optimized for their environmental performance.

2.2. Case Study Building

2.2.1. Details

A case study was used to conduct a comparative assessment of the embodied and operational energy associated with a multi-residential building for three varying construction approaches, namely prefabricated modular steel and timber structures and a conventional concrete structure. The building modelled has a gross floor area of 3943 m^2 with a total of 63 apartments (58 single-story and five double-story). The first six floors of the building each comprised 9 single-story apartments (Figure 1), and the seventh floor comprised four single-story and five double-story apartments. The floor area of the single-story and double-story apartments is 63 and 118 m^2, respectively. The ground floor comprised seven tenancies together with other utilities. The ground floor and the sub-structure were not considered in this study. The details of the external/internal walls and the floor/ceiling panels are illustrated in Figure 2 (by element for each scenario).

2.2.2. 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

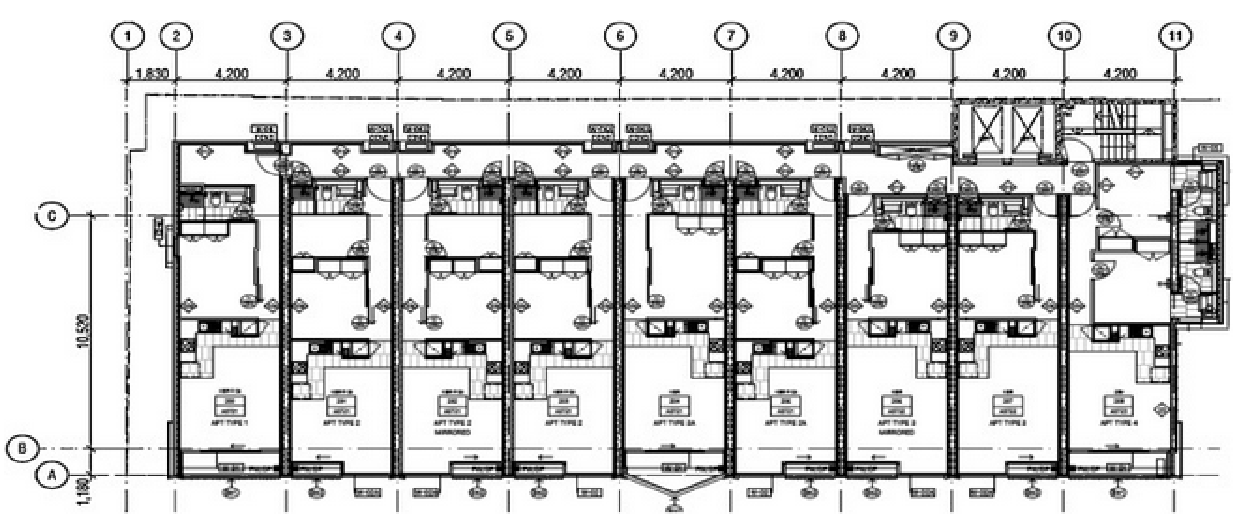

Figure 1. Floor plan for single story apartments

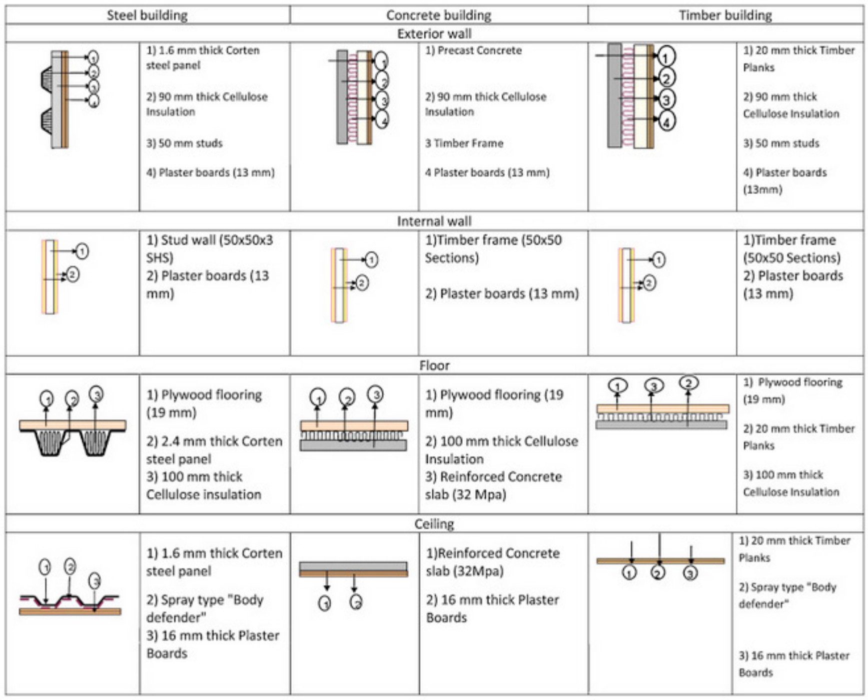

Figure 2. Details (by element) of the main material used in the building for prefab steel, concrete and prefab timber scenarios

this process. For example, the energy embodied in steel products, typically comprise energy for iron ore extraction, transportation, and processing of the iron ore, manufacturing the steel products and delivery to the site. Energy is also embodied in goods and services, including capital utilized during these processes, and so on. 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 the case study building was performed using an input–output–based hybrid analysis [6]. This method is applied using an I–O model of Australian energy use, developed at the Department of Physics at the University of Sydney. The base I–O data was taken from the Australian National Accounts [7] and combined with energy intensity factors by fuel type. The combination of these two sources comprises the I–O model. The model includes the value of capital purchased in previous years, and capital imported from other countries, amortized over the life of the capital item. Capital refers to the equipment and machinery used to make or transport products. The I–O model was used as the basis for the embodied energy analysis of the case study building. The best available process data was incorporated for specific material manufacturers as per the input–output-based hybrid method [6]. Process specific data for the energy from the manufacture of specific materials was obtained from the latest available SimaPro Australian database [8].

The calculation of the energy embodied in the two structural systems for the case study building was based on the embodied energy intensities from Table 1, which includes the energy from fossil fuel consumption. These intensities were calculated using the input–output-based hybrid method, combining available process data for the specific materials with I–O data [9].

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	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
Aluminum	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

The quantities of the materials used for each construction system for the case study building were determined and multiplied by their respective embodied energy intensities. The sum of these results gave the total embodied energy for each structural system. The proportion of materials available for reuse for both construction approaches was determined and the energy embodied in these materials was also calculated using the above approach. The energy associated with the end-of-life demolition, disposal, and reuse processes (e.g., making goods) of materials has not been included in this study. Crowther [10] has shown that the energy associated with this stage of a building's life represents less than 1% of the building's life cycle energy requirement.

2.2.3. Operational Energy Analysis

The operational energy associated with the case study building was estimated using TRNSYS simulation software based on the characteristics of the building and assumed heating and cooling schedules. The simulation was performed using the Melbourne TMY data developed and provided by Morrison and Litvak [11]. The simulation was performed on an hourly basis for a period of one year maintaining an indoor air temperature range of 21–24°C. The detailed occupational schedules and gains were not considered in this study.

The seasonal average heat pump Coefficient of Performance (COP) values of heating (3.0) and cooling (2.2) were used in estimating the electrical energy requirement from the heating and cooling load outputs.

2.2.4. Life Cycle Energy

The life cycle energy requirements associated with the case study building over a 50-year period were calculated for all structural scenarios. This was achieved by combining the initial embodied energy values with total estimated operational energy requirements over 50 years, assuming no heat pump system efficiency losses or improvements over time.

Embodied energy associated with the replacement of materials and building components over the life of the building was not included in the analysis. It is noteworthy that this energy can represent up to 32% of its initial embodied energy during the life of a building. The extent of this depends on several factors, including the useful life of the building and the anticipated life of the individual materials or components. It was assumed that material replacement rates for both building scenarios would be similar as they relate mainly to internal and external finishes, and not to the building structure. Despite this, the study represents a much more comprehensive approach to the embodied energy assessment of a multi-residential building.

2.2.5. GHG Emissions

While 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 this consumption. 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 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.

Embodied energy-related emissions: Due to the difficulties associated with determining the proportion of embodied energy supplied by the various fuel types within the processes involved in manufacturing and supplying the components of the case study building, an average emissions factor of 60 kg CO_2−e per GJ of energy has been used to calculate the GHG emissions related to the embodied energy of all construction types [51].

Operational energy-related emissions: Energy required for heating and cooling was assumed to be provided by brown coal-fired electricity, common for residential buildings in Victoria, Australia. Using the primary energy factor (3.5 for electricity in Victoria, Australia), estimated operational energy figures were converted to primary energy terms to account for the impacts associated with energy production. An emissions factor of 1.35 kg CO_2−e per kWh of electricity was used to estimate the greenhouse gas emissions from the electricity consumption figures.

3. RESULTS AND DISCUSSION

3.1. Embodied Energy Analysis

This section presents the results of the embodied energy analysis of the case study building for both concrete and prefabricated steel construction approaches. Whilst the total mass of the concrete building is over four times greater than that of the prefabricated steel building, the total embodied energy in the steel building is about 50% higher than that of the concrete building. This is predominately due to the much more energy intensive processes involved in steel manufacture as compared to concrete production for an equivalent functional unit (in this case a building's structure). The total embodied energy is about 10% higher than that of concrete building for the timber building with steel columns and beams.

Figure 3 compares the material volume for all construction approaches. This shows that the external walls, followed by the floor panels, contribute the greatest to the overall material volume for all building construction approaches, representing 49%, 47% and 39% of the total material volume, for steel, timber and concrete, respectively. Consequently, the areas can achieve the greatest waste reduction benefits by extending material life and maximizing eventual reuse, thereby minimizing the impact on landfill.

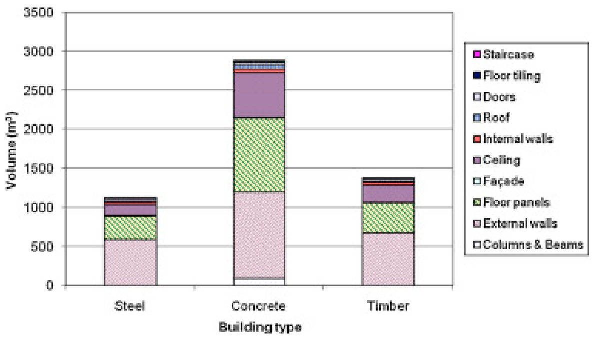

Figure 3. Materials volumes for the three building types, by element.

The breakdown of embodied energy for both concrete and prefabricated steel construction systems is shown in Figure 4. For the case study building, the total embodied energy equates to 14.4, 10.5, 9.6 GJ per m² of floor area for the prefabricated steel, prefabricated timber and concrete construction systems, respectively.

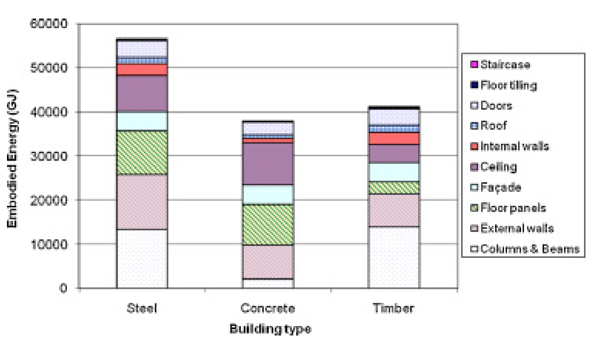

Figure 4. Embodied energy for the three building types, by element.

3.2. Operational Energy Analysis

This section details the annual operational energy requirements associated with the case study building for all construction types investigated. The TRNSYS simulation was conducted to determine the operational energy required for each zone to maintain an indoor air temperature between 21°C and 24°C.

The heating and cooling load patterns behave similarly for all the investigated construction types. The estimated heating and cooling loads were used to calculate the operational energy consumption for all construction scenarios by using the heat pump seasonal average COP values described earlier.

The annual operational energy for the building clearly indicates that in Melbourne, the heating energy requirements are much higher than cooling energy requirements for residential buildings (Figure 5). There is a slight difference in total heating and cooling energy requirements among the three building construction types investigated. The difference shown in operational energy is due to the difference in the thermal mass and heat transfer characteristics of the construction materials selected (Table 2).

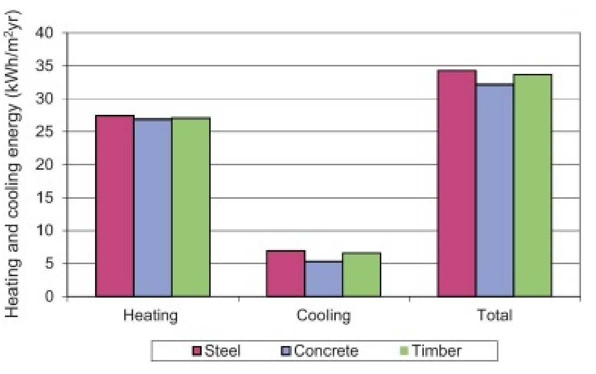

Figure 5. Annual operational energy requirements of the three construction types, per m² of floor area.

Table 2. Annual operational energy requirements for steel and concrete structural scenarios by m² of floor area (NLA = 3943 m²).

Building Type	Annual operational electricity (kWh/m²)	Annual operational primary energy (GJ/m²)
Steel	27.4 (H) 6.9 (C) 3.43 (T)	0.3451 (H) 0.0865 (C) 0.4316 (T)
Concrete	26.9 (H) 5.3 (C) 32.2 (T)	0.3386 (H) 0.0666 (C) 0.4052 (T)
Timber	27.0 (H) 6.5 (C) 33.5 (T)	0.3408 (H) 0.0825 (C) 0.4233 (T)

* Heating (H); Cooling (C); Total (T)

3.3. Life Cycle Energy

The embodied and annual operational energy requirements calculated above were combined to determine the life cycle energy requirements of the case study building for both concrete and prefabricated steel construction types over a 50-year period. The findings are presented in Table 3 and Figure 6. The life cycle energy requirements were shown to be greater for the prefabricated steel scenario at 36 GJ/m^2, compared to 30 GJ/m^2 for the concrete scenario. For all scenarios, the total heating and cooling energy represents a larger component of the total life cycle energy requirements compared to the embodied energy requirements.

Table 3. Total life cycle energy over 50 years (NLA = 3943 m^2); (Life Cycle Energy (LCE)).

Building type	Embodied energy (GJ)	HVAC energy over 50 years (GJ)			LCE over 50 years (GJ)
		Heating	Cooling	Total	
Steel	56,778	68,036	17,049	85,086	141,864
Concrete	38,008	66,753	13,126	79,879	117,887
Timber	41,373	67,180	16,265	83,445	124,818

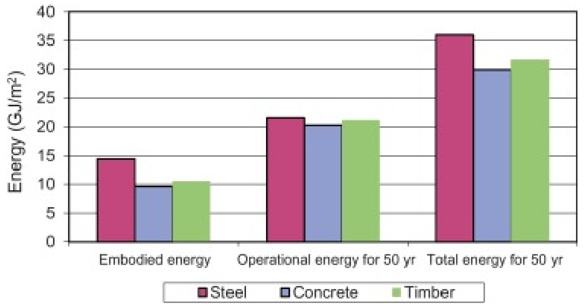

Figure 6. Life cycle energy requirements of the three construction types over 50 years.

3.4. Life cycle greenhouse gas emissions

The embodied and annual heating and cooling electricity requirements estimated above were used to determine the associated GHG emissions for the case study building using primary energy and greenhouse emission factors for Melbourne, Victoria.

3.4.1. Embodied energy-related emissions

The greenhouse gas emissions associated with the energy embodied in the building were 3407, 2482 and 2281 tCO_2−e for the prefabricated steel, prefabricated timber and concrete building types, respectively. The elemental breakdown of embodied GHG emissions for all construction systems is shown in Figure 7. It is evident that the steel framed building has about 50% more embodied GHG emissions compared to the concrete framed alternative. The embodied greenhouse emissions per m^2 of floor area are 864, 630 and 578 kgCO_2−e for the steel, timber and concrete construction systems, respectively.

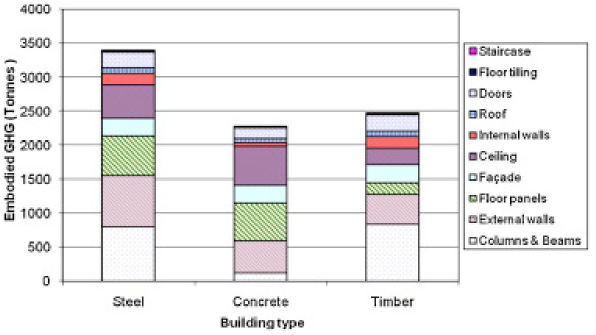

Figure 7. Embodied greenhouse gas emissions of the three building types, by element.

3.4.2. Operational energy-related emissions

The annual heating and cooling energy-related greenhouse emissions are shown in Table 4. This clearly indicates that there is no significant difference in the operational energy-related emissions between the concrete and prefabricated steel and timber buildings. The difference is attributed to the differences in heat transfer characteristics and slight difference in thermal mass. It should be noted that the bulk insulation levels for all building types meet the minimum requirements of the Building Code of Australia.

Table 5 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 13% lower life cycle greenhouse emissions than the prefabricated steel building. The embodied emissions contribute

Table 4. Annual operational energy-related GHG emissions for concrete and prefabricated steel building types (NLA = 3943 m^2).

Structure type	Annual operational emissions (t CO_{2-e})			Annual operational emissions (kg CO_{2-e}/m^2)		
	Heating	Cooling	Total	Heating	Cooling	Total
Steel	145.8	36.5	182.3	37.0	9.3	46.2
Concrete	143.0	28.1	171.2	36.3	7.1	43.4
Timber	144.0	34.9	178.8	36.5	8.8	45.3

Table 5. Total life cycle greenhouse emissions over 50 years (NLA = 3943 m²).

Building type	Embodied emissions (t CO_{2-e})	Operational emissions over 50 years (t CO_{2-e})			LCE over 50 years (t CO_2−e)
		Heating	Cooling	Total	
Steel	3407	7290	1827	9117	12,524
Concrete	2280	7152	1406	8558	10,838
Timber	2482	7198	1734	8941	11,423

* Life Cycle Emissions (LCE)

Table 6. Total volume, mass and embodied energy of concrete and prefabricated steel building scenarios, with the quantity and proportion of potential savings from the reuse of materials.

	Volume (m³)			Mass (t)			Embodied energy (GJ)		
	S	C	T	S	C	T	S	C	T
Initial total	1144	2886	1398	871	3949	996	56,778	38,008	41,373
Qty reused	60	20	35	441	87	335	46,157	12,259	28,584
Saving (%)	5.3	0.7	2.5	50.7	2.2	35.6	81.3	32.3	69.1

* Steel (S); Concrete (C); Timber (T)

between 21% and 27% of the total life cycle emissions. Including the GHG emissions associated with maintenance and replacement of materials and components over this period would further demonstrate the importance and significance of this embodied GHG emissions component.

3.5. Material Reuse Benefits

Reuse of construction materials can lead to significant resource savings together with other environmental benefits from a reduction in disposed waste in landfill and the energy required to produce 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, while 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 from the reuse of materials for both concrete and steel buildings are shown in Table 6, based on assumptions of the likely materials and respective quantities available for reuse. While the concrete construction system accounts for a greater volume of material than the steel system, and thereby 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.

The potential future reuse of a material can never be guaranteed. For this reason, it does not make sense to allocate any environmental credit to its initial use. However, if a material can be reused after its initial use, the building in which the material is reused should be credited with the embodied energy saving resulting from the avoidance of the energy required for processing and manufacturing new virgin materials. Designers should always attempt to use materials that have the potential to be reused rather than disposed of at the end of a building's useful life.

Table 6 shows the comparison between the proportions of total material volume, mass and embodied energy savings from the reuse of building components for both the concrete and steel building scenarios.

The study revealed that the reuse of even a small proportion (by volume) of embodied energy intensive materials at the end of the building's useful life can result in a substantial saving in embodied energy for both concrete and prefabricated steel and timber systems. The proportion of embodied energy that can be saved by reusing existing materials in a new building is up to 81.3% or 46,157 GJ for the prefabricated steel building, up to 69.1% or 28,584 GJ for the prefabricated timber building and up to 32.3% or 12,259 GJ for a concrete building. It should be noted that these figures do not account for the ability to recycle materials, such as concrete into aggregate, for use in new buildings, which can also save substantial quantities of virgin materials and embodied energy.

4. CONCLUSIONS

This study has assessed the life cycle energy requirements of three forms of construction for a multi-residential building, namely conventional concrete construction, prefabricated steel construction and prefabricated timber construction, to determine the environmental benefits offered by modularized prefabrications. An innovative hybrid embodied energy assessment approach was used to make this comparison. The study demonstrated 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 embodied energy in the prefabricated steel building is up to 50% greater than that for the concrete building. However, the additional benefit of the prefabricated system is the ability to reuse a significant portion 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.

Only a minor variance in the operational energy requirements associated with the construction types was also observed. 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 building operational efficiency performance, thereby further increasing the relative significance of embodied energy.

From a life cycle energy perspective, the prefabricated steel scenario was shown to consume 16% more energy over a 50-year period than conventional concrete construction. Despite this, the study has clearly indicated that prefabricated construction can result in 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 optimized in the broader life cycle context, considering also the operational, recurrent, maintenance, and end-of-life energy requirements and impacts associated with buildings.

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