Feasibility of Reusing Prefabricated Panels from an Embodied Energy and Economics Perspective

Mikael Gilbert[1], Khalegh Barati[1] and Xuesong Shen[1]

[1]School of Civil and Environmental Engineering, The University of New South Wales (UNSW), Sydney, NSW 2052, Australia
mikael.gilbert@student.unsw.edu, khalegh.barati@unsw.edu.au, x.shen@unsw.edu.au

Abstract -

The prevalence of prefabrication in the modern construction industry has highlighted the importance of sustainable management of these new construction materials. Despite reduced emissions through minimizing construction time and production waste, at the end of the building's life, the amount of construction waste produced remains constant. This paper aims to investigate the environmental and economical sustainability impacts from reusing prefabricated concrete and cross laminated timber panels sourced from buildings reaching the end of its service life. The main framework used focuses on applying a lifecycle assessment in terms of embodied energy to a unit of the selected prefabricated material. The results from this analysis are then further expanded to include varying distances between the donor and host building, allowing for a comparison between the embodied energy saved and additional energy consumption from transporting the construction materials. Furthermore, the economic sustainability of this construction practice are calculated. A case study was conducted using a 3D BIM model of a residential structure whereby the materials are quantified and paired with data obtained from the LCA. The results have shown that there are energy savings of 36,628.6 MJ/m^3 and 66.6 MJ/m^3 for concrete and cross laminated timber panels, respectively. Additionally, a trendline showing the correlation between distance and embodied energy savings for both materials were observed. The research contributes to providing alternatives for sustainable waste management and material selection policy in the construction industry.

Keywords –
Embodied Energy, Life Cycle Assessment, Modular Construction, Prefabrication, Sustainability

1 Introduction

As climate change becomes a more significant challenge, it is in the best interest of humanity to combat this phenomenon to minimize the impact of climate change on the global ecosystem. The World Commission on Environment and Development (WCED) defines sustainability as the preservation of the current world for future generations [1]. The construction industry is named one of the major contributors to climate change because of its large greenhouse gas emissions. This is largely caused by an increase in demand for infrastructure, housing and resources as the human population continues to grow and modernize, which ultimately results in the expansion of the construction industry. One of the construction methods that has been implemented to keep up with demand for infrastructure is through prefabrication, which has been proven to be faster to build and more environmentally friendly [2].

A building's lifecycle starts in the pre-building stage where the building is planned and designed, this is the best stage to include any sustainable design principles into the project as nothing physical has been built and can be easily altered as needed. This stage is then followed by the construction stage, where the building is constructed and consequently by the operational stage where the building is used for its intended purpose. Once the building has reached the end of its service life, the building will be demolished or deconstructed to make way for a new building to better suit the needs of society at the time [3]. A major issue of this linear lifecycle is that there will be a large amount of waste produced. Improper demolition waste management reduces reuse potential as the waste will head straight to landfill. Reusing and recycling waste obtained from all the stages of a building's lifecycle ensures the minimization of waste that goes to landfill and thus reduces the harvest of new raw material.

Studies on prefabrication have shown that with prefabricated products, construction waste and time can both be reduced, leading to more sustainable practices [2,4]. Despite these established benefits, there seems to be limited knowledge of methods in which the prefabricated products can be harvested and reused as part of a new building's structure. A major downside to current industrial practices is that significant additional processing energy will be needed, such as when steel is melted and reused [5]. However, reusing already made prefabricated products circumnavigates this problem as these products are relatively ready to use. It appears that a gap in the research exists in finding the benefits of reusing prefabricated materials salvaged from a building's end-of-life stages. Surveys have shown that despite poor public perception of second-hand structural products, this reusing technique may be necessary to ensure responsible use of the Earth's finite resources and promote a sustainable construction industry moving forward.

This paper aims to investigate the environmental and economic feasibility of reusing prefabricated concrete and cross laminated timber panels sourced from buildings reaching the end of its service life. The paper focuses on the comparison of the embodied energy and cost savings from reusing these materials against common transportation methods. In this research, the benefits as well as the limitations of reusing prefabricated concrete and CLT panels were quantified. The benefits to be analyzed will revolve around the two of the three pillars of sustainability, namely environmental, and economic sustainability.

2 Literature Review

Sustainable development is "a development that meets the needs of the present generation without compromising the ability of future generations to meet their own needs" [1]. This concept is commonly separated into three main categories namely, economic, environmental, and social sustainability [6]. When all three sustainability categories are achieved, then total sustainability has been attained.

There are three basic principles that can serve as a basis for sustainable construction such as resource management, life-cycle design, and human design [7]. Resource management involves the efficient use of the Earth's finite resources. This can be done by implementing renewable energy sources, reducing construction wastes, etc. For example, the design of a building's façade can be optimized to reduce its operational energy consumption [8]. Additionally, human design involves both biophysical and social part of the project in which the requirements of the building does not exceed the capacity of the environment to fulfil those needs [7]. This design is usually implemented in the design stage of the building's lifecycle [9]. In life-cycle design, all aspects from the design up to the demolition is to be considered in the planning stage [3].

The promotion of sustainability in the construction industry can also be achieved through optimal material selection. Being one of the most used materials in the construction industry, concrete plays a key role which greatly affects the sustainability of the industry. Another method in which sustainability of concrete can be improved is through the incorporation of waste in less demanding work [10]. For example, an Egyptian case study employed rice stalks can be used as cement fillers for low-cost housing [11]. Another approach in material selection is with the use timber in the form of Cross Laminated Timber (CLT) as a renewable source of material, which has been growing in popularity. The structure of CLTs involves planks which are sawn, glued, and layered wood where the layers are placed perpendicular to one another [12]. The main advantage of CLT is that it is made from timber, a renewable source of material, unlike concrete and steel which are both non-renewable [13].

Prefabrication has also been closely linked to a more sustainable construction practice. In general, there are two types of prefabrication namely 2D and 3D prefabrication [14]. There are both advantages and drawbacks of prefabrication in the construction industry. Advantages of prefabrication includes a reduction in construction time leading to cost savings, lower margin of error and that the modules can be reused or altered as needed [2,4]. When compared to conventional construction, prefabrication has also been shown to reduce the amount of waste by 81.3% and 83.2% for small and large structures, respectively [15]. A case study conducted in Hong Kong has shown that prefabrication can reduce construction waste by 65%, labour requirements by 16%, and construction time by 15% [16]. However, there are also drawbacks such as the need for specialized skill and equipment during assembly, the lack of product variety, etc. Another key drawback is that when an error occurs either during production or assembly, there may be major delays to the project [2,4].

Despite of these advantages during construction, prefabricated buildings are still being decommissioned in a linear manner. Identifying and prioritising the end-of-life solutions for prefabricated buildings are essential to reduce carbon footprint and promote circularity in construction [17]. Research has shown that prefabricated buildings have higher recyclability rates compared to traditional buildings, which drives the possibility of reusing these components in future projects with minimal processing [18]. With regards to these recycled components, BIM has been shown to aid in the deconstruction process by analysing existing conditions, labelling reusable elements and simulating the deconstruction process [19].

The concept of reusing prefabricated components has been applied to multiple projects across the world. One of the concepts is the Pilot Houses in Berlin developed by TU Berlin. In this project, prestressed concrete slabs of type WBS70 were modified by sawing them into the required sizes and then connected to form the external walls of the houses [20]. The façade is then covered with an External Thermal Insulation Composite (ETIC) system. A case study house in Schidlow, Berlin has achieved 245m^3 of concrete saved with a significant reduction in construction time, which has been shown to reduce greenhouse gas emissions such as CO_2, N_2O and CH_4 [20,21]. Other examples can be seen in the BedZED development in London and the UN17 Village in Copenhagen where it successfully implements the basic principles of sustainability. These projects also adopted the practice of reusing second-hand materials as part of an efficient resource management policy and design for human strategy.

As the use of prefabricated components become more widely accepted, steps should be taken to consider the end-of-life stage of these parts [17]. Improper disposal strategies may lead to unsustainable construction techniques which may accelerate the deplet ion of natural resources. Reusing these components may be one of the ways for the industry to process and control the amount of waste being produced. Additionally, it may lower construction costs and preserve finite resources.

3 Research Methodology

In this research, a method known as Life Cycle Assessment (LCA) will be used to measure the benefits brought on by reusing prefabricated concrete and CLT panels to construct new buildings. There are three different methods for LCA. The first of these methods is called Process Analysis where a product is identified and the inputs that go into production of the product is analysed. The second method is called the Input-Output (I/O) analysis where the energy usage of a particular industry in a country is obtained from national survey data. These two methods can be combined to form a "hybrid" LCA to have the simplicity of I/O analysis and the accuracy of process analysis.

A detailed framework of the method used in this paper can be seen in Figure 1. It highlights the major components starting from the LCA, then followed by both environmental and economical sustainability studies. Finally, to show how this method can be applied, a case study involving a 3D BIM model will be conducted. The framework aims to provide a generic plan in which all materials can be analysed and then applied to various case studies.

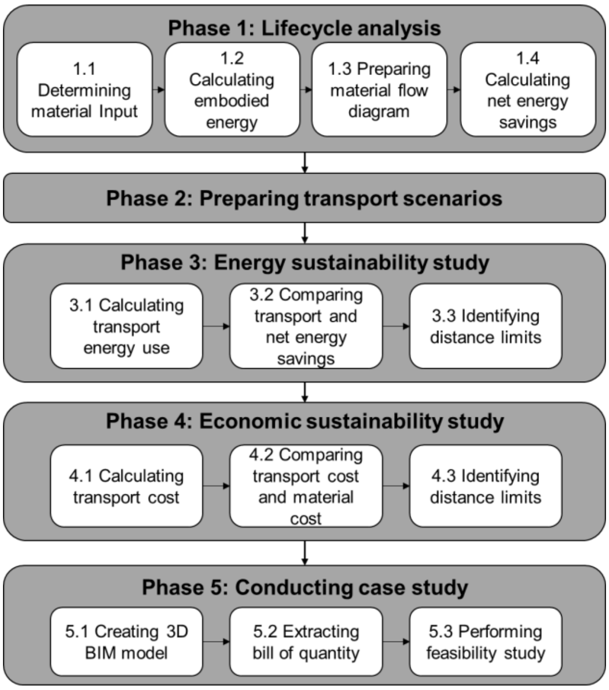

Figure 1. Research framework to quantify feasibility of reusing imported prefabricated components

Firstly, the unit of system processes will be obtained from sources such as research papers, industry examples, databases, etc. The data collection process is followed by the data calculation stage. In this stage, the data obtained is calculated according to the amount of material used. Then, these values are arranged according to the appropriate flow of processes when reusing prefabricated components. The flow will then be based on the law of conservation of energy where the sum of the energy entering a process must be equal to the sum of the energy leaving the process. This stage in the LCA allows for the verification of data energy used throughout the process. This iterative process ensures that the inputs and outputs can be maximally captured to ensure a high-quality and accurate assessment.

In this LCA assessment, data such as the materials being used and their respective processes are first gathered. The respective processes such as transport, assembly and panel cutting will be added onto the analysis. The framework used in this LCA will begin from the material harvesting up to the assembly of the model houses. The maintenance and operation as well as the end-of-life stage of the buildings will not be included in the analysis as it is assumed that the digital model will have similar operational conditions as its real-life counterpart if it is built using new raw materials.

In order to evaluate the framework, a sensitivity analysis is conducted. The aim of the sensitivity analysis is to establish which processes will impart the largest effect on the overall LCA flow diagram. This is done by altering parts of the processes and assessing which of these changes results in a large effect on the overall embodied energy. Sensitivity analysis can then be used to determine which processes to include and exclude from the system boundary. In this study, the sensitivity analysis will revolve around the transportation aspect of the reuse process. This is done by changing the location of the donor building and changing the method of transport accordingly. These scenarios can help determine the limit in which the proposed construction technique is no longer sustainable. By changing the location of the donor building, changes in the feasibility of the project can be seen. Using these changes, trends can be inferred and thus provide a quantitative value to measure the sustainability of reusing these prefabricated panels. This value allows for this technique to be applied to real-life projects and have their sustainability measured.

In Phase 5, a real-life building will be modelled using Revit and then a bill of quantities for the materials used in the house is gathered. The building being modelled draws inspiration from the house mentioned in [20], where the external wall of the house is made from reused concrete panels. In addition to the external walls, the internal walls will also be considered. In this study, it will be assumed that the internal walls will be made from CLT panels. Then, the energy and cost savings value obtained in the LCA can be used to determine the sustainability of the project. This section of the paper is used to verify the framework set out in Figure 1. It shows how the framework can be applied to other projects as the data produced from the LCA is per unit volume.

Finally, an interpretation of the LCA results will be conducted, which includes the verification of the results. This section will highlight the potential limitations of this study and ways in which these limitations can be overcome. It will also show paths in which future research can take to further develop this construction concept and provide a better understanding of material and resource sustainability in the construction industry.

4 Reusing Concrete and CLT Panels

The LCA conducted in this study involves 1 m^3 of reused concrete and CLT panels, where both the donor and host buildings are both located in Sydney. This will include processes starting from the harvesting of these materials up to the assembly of the materials. In this lifecycle analysis, several assumptions will be made. For example, panels harvested from the donor building will be in the exact measurements required by the host building and thus no additional processing of the panels is required. Next, as materials are being reused, the embodied energy of the material itself will no longer be included in the LCA as it has already been included in the LCA of the donor building. Finally, the energy used to assemble 1 m^3 of each material is sourced from [24], where the total energy used for onsite construction is divided by the total volume of material used during construction. This results in the energy consumed for assembly of 294.2 MJ/m^3.

The LCA results suggests that reusing concrete panels requires an additional 1,032.8 MJ/m^3. It is also worth noting that 71.3% of the energy consumed arises from transport which is followed by the energy consumed when assembling of the panels (28.5%). When factoring in the embodied energy of the raw material itself, energy will still be saved. This is because no new material will be required and thus there will be no energy expenditure from the material aspect. The embodied energy of 1 m^3 of tilt up concrete panel which constitutes 95% concrete and 5% steel has an embodied energy of 37,661.4 MJ. Therefore, it can be concluded that the net energy savings for reusing concrete panels is 36,628.6 MJ/m^3.

On the other hand, reusing CLT panels requires an additional energy consumption of 433.4 MJ. In the case of CLT panels, most of the energy consumed comes from the assembly process. It constitutes 67.9% of the additional energy required and then it is followed by transport which contributes to 31.8% of the energy consumed. The embodied energy of 1 m^3 of CLT panels is 5,000 MJ [17]. As there is no new CLT panels being used, the embodied energy of CLT can be considered as energy saved. Thus, it can be inferred that the net energy savings for reusing 1m^3 of CLT panels is 4,566.6 MJ/m^3.

The next section of the journal paper revolves around a cost-benefit analysis of this construction method to fulfil the economical sustainability aspect of this construction technique. The analysis adds eight scenarios in addition to the base scenario previously mentioned. The additional scenarios alter the location of the donor building, leading to increased transportation cost and its environmental impact while keeping the host building in Sydney. The location of the donor building is comprised of cities in Asia, Europe, and North America. The list of scenarios and their respective travel distances can be seen in Table 1. The total distance travelled is the sum of the travel distances of all modes of transport namely, truck, rail, and ships, used during the panel's transportation process. Truck, rail, and ships were selected as the preferred mode of transportation as they are representative of how most construction materials are transported from the factories to the construction site.

Table 1. Scenarios and their respective travel distances

Source	Distance (km)			
	Truck	Rail	Ship	Total
Sydney	120	0	0	120
Perth	182	3,290	0	3,472
Jakarta	170	0	7,119	7,289
Tokyo	150	0	8,043	8,193
Shanghai	270	0	8,579	8,849
San Francisco	70	0	11,957	12,027
London	105	0	21,352	21,457
Stockholm	110	0	23,230	23,340
Moscow	90	631	23,728	24,449

In Table 1, the scenario where Perth is the location of the donor building, Rail is mainly used to transport these panels over the Australian component as it is deemed more efficient than trucks. For the Moscow case, Rail was used to transport the panels from landlocked Moscow to St. Petersburg to be loaded onto ships. This material transfer is assumed to be done by rail. The distances for ships are calculated using distances of typical shipping routes between the locations.

The first part of the result analysis involves comparing the energy consumed during transport of the materials and the energy saved from reusing the material itself. The energy consumption for trucks, rail and ships are 4.6 MJ, 0.9 MJ and 0.4 MJ per ntkm (net-tonne kilometre), respectively [23]. This is done for all scenarios and both concrete and CLT panels and the results are shown in Figure 2. The threshold whereby the transport energy exceeds the saved embodied energy is also included in this figure.

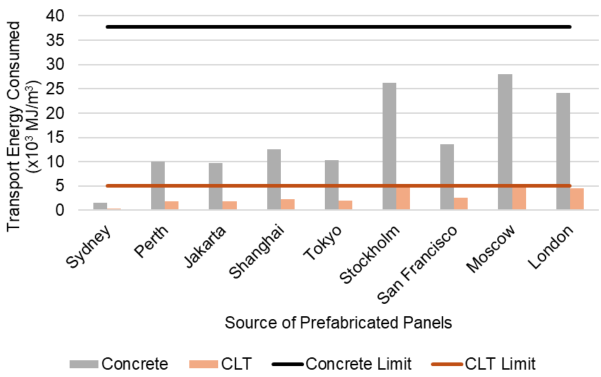

Figure 2. Energy consumed by transport for 1m^3 of (a) concrete panels (b) CLT panels for various locations

When energy consumed by transport (E_t) is plotted against the distance travelled (d) by the material, a linear trendline can be seen. The trendline equations for both concrete panels and CLT panels can be seen in Equations (1) and (2), respectively.

$$E_{t,concrete}\ (MJ/m^3) = 0.989d + 3119.7 \quad (1)$$

$$E_{t,CLT}(MJ/m^3) = 0.185d + 584.2 \quad (2)$$

The maximum distance that a material can be sourced from can be calculated by replacing the energy consumed by transport by the embodied energy of the material being reused including the processes required to reuse them while excluding the energy required for transport. The resulting maximum distance calculated from an environmental perspective (D_{env}) are 34,180.79 km and 22,272.43 km for concrete and CLT, respectively.

The next stage of the cost benefit analysis revolves around comparing the cost of transport and the cost savings brought on by reusing the materials. The price of the material in Australia can be assumed as AU$302 per m^2 of concrete panels and AU$863.32 per m^2 of CLT panels. Assuming the exchange rate for AU$1 is US$0.62, the price of concrete and CLT are US$187.24 per m^2 and $535.26 per m^2, respectively [23]. It is also assumed that the price for material transport is US$0.052, US$0.024, and US$0.018 per ntkm for road, rail, and ships, respectively [25]. Another assumption made in the cost analysis is that the thickness of the concrete panel is 200 mm and the thickness of the CLT panels is 135 mm.

A limit for the distance for the material source from an economic standpoint can be obtained. Table 2 below shows the distance limits for both concrete and CLT panels. From an economical perspective, the maximum distance limit for concrete is 19,180.03 km. This is obtained in the case when the concrete panels are obtained for free or in other words 100% discount. It is also shown that CLT panels can be sourced from all over the world and still be economically sustainable.

Table 2. Distance limit in kilometres depending on material discounts for concrete and CLT panels from an economical perspective

Percentage of Original Cost	Distance Limit (D_{econ}) (km)	
	Concrete Panels	CLT Panels
0%	19,180.03	314,542.25
20%	15,211.30	251,500.00
40%	11,242.84	188,457.75
60%	7,274.11	125,415.49
80%	3,305.39	62,376.06
100%	-663.39	-665.01

The maximum distance between the source of reused materials and the construction site can be obtained from both an environmental and economical perspective. Selecting the larger value from the two distances produces a comprehensive table with the de facto distance limitation. The equation used to decide on which distance to choose is shown below in Equation (3). Where D_{env} and D_{econ} are the distance limit from an environmental and economical perspective, respectively. i is the material that is being analysed and r is the percentage of original cost for the selected material i.

$$D_{i,r} = \min\left(\frac{D_{env,i} + |D_{env,i}|}{2}, \frac{D_{econ,i,r} + |D_{econ,i,r}|}{2}\right) \quad (3)$$

Table 3 shows the distance limit of both economic and environmental sustainability of this construction technique. It is shown that the sustainability of reusing CLT panels is governed by the environmental limitations of the material. While concrete panels are governed by its economics. It is suggested that as the materials density increase, the main barrier for sustainability shifts from being an embodied energy to an economic limitation.

Table 3. Distance limit in kilometres depending on material discounts for concrete and CLT panels from both environmental and economical perspectives

Percentage of Original Cost (r)	Distance Limit (D) (km)	
	Concrete Panels	CLT Panels
0%	19,180.03	22,272.43
20%	15,211.30	22,272.43
40%	11,242.84	22,272.43
60%	7,274.11	22,272.43
80%	3,305.39	22,272.43
100%	0	0

Although this study shows that CLT panels are not environmentally sustainable when sourced from long distances, common industry practice has disregarded this fact. This is because of the significant cost savings that reusing CLT has, as shown in the cost analysis section of this paper. Due to the slim profit margins in the construction industry, cost savings takes priority over environmentally sustainable practices.

The values obtained from this section are unit values for both 1m^3 of concrete and CLT panels. These values can aid designers in extrapolating necessary emission and cost saving calculations for various building types and applications.

5 Case Study

In this case study, an apartment building, located in Sydney, Australia, comprising of seven units was analysed. The apartment block is built on a site with an area of 686.95m^2 and covers five levels ranging from a basement parking level, three levels for apartment units and a rooftop area. the 3D BIM model of the apartment block can be seen in Figures 3. This case study will serve as an example in which the framework developed in this paper is to be implemented in a real-life case study.

Figure 3. 3D BIM model of case apartment

During the analysis of this case study, the external walls are assumed to be made from the reused prefabricated concrete panels, and the internal walls are made of reused CLT panels. The external walls are supposed to be 200 mm thick, and the internal walls are 138 mm thick. The total volume of concrete and CLT panels used in the construction of the apartment are 246.53 m3 and 49.71 m3, respectively. Assuming the material is purchased at 20% of its new price. Table 4 below shows the sustainability of reusing prefabricated panels when implemented into the case study from both an economic and environmental point of view.

Table 4. Sustainability analysis of case building

Material	Concrete	CLT
Building Element	External Walls	Internal Walls
Sydney- Sydney		
Volume of Material (m^3)	246.53	49.71
Distance (km)	120	120
Energy Saved (x10^6 MJ)	9.03	0.23
Cost Savings (thousands of AUD)	291.2	177.8
Environmentally Sustainable?	✓	✓
Economically Feasible?	✓	✓
Stockholm – Sydney		
Volume of Material (m^3)	246.53	49.71
Distance Travelled (km)	23,339.64	23,339.64
Energy Saved (x10^6 MJ)	2.94	-0.23
Cost Savings (thousands of AUD)	-151.7	161.1
Environmentally Sustainable?	✓	×
Economically Feasible?	×	✓

The results from the case study shown in Table 4 shows that when the materials are sourced locally within Sydney, this reusing construction technique is both economical and environmentally sustainable. This is shown by the positive value for both cost and energy savings. The sustainability benefits from the Sydney-to-Sydney case can be attributed to the distance between the donor and host building. Lower distance values lower the corresponding GHG emissions created through transport and minimizes the transport costs. However, this may not be the case for all location sources for these prefabricated materials. Some situations may result in a project being economically viable but not environmentally sustainable as shown in the case where CLT panels are sourced from Stockholm.

6 Conclusions

This research is set to answer the question of whether it is in the best interest of the construction industry to reuse prefabricated panels which can be harvested from buildings reaching the end of its useful life. As more new prefabrication parts are used in the construction industry, the significance of efficiently and sustainably handling a building's construction or demolition waste can no longer be ignored. This paper provides an alternative to project developers to adopt reusability into their design mandate. Additionally, it proves that reusing prefabricated materials has both economic and environmental benefits which can be used in favour of the developer. Lastly, a framework is created to quantify the distance limit in which prefabricated materials can be sourced before being either environmentally or economically unsustainable.

Based on the LCI flow diagram, this construction method has shown that significant energy savings can be achieved when prefabricated panels are reused. However, this energy savings decreases the further the material is sourced. Because there will be a rise in the energy consumption brought on from transporting the panels. Thus, from case studies involving different donor building locations, it is concluded that, environmentally, the maximum distance concrete panels can be sourced from is 34,925.85km and for CLT the distance is 23,869.14km. Apart from energy savings, there are also cost savings to be achieved with varying values. These values depend on the transportation method and cost of the reused panels when sourced from other projects. When factoring in the cost of the method, it is found that the distance in which concrete can be sourced is limited by the transportation cost which increases steeply due to the high density of concrete. In the other hand, the distance in which CLT panels can be sourced from is limited by the energy consumption of transport being higher than the energy saved from reusing the panels. This may result in situations where a product is environmentally sustainable but not economically feasible and vice versa.

The proposed framework provides designers and construction managers with a method to calculate the cost and embodied energy savings from reusing prefabricated panels. Reusing prefabricated panels may not be environmentally and economically sustainable in all cases and which highlights the need to quantify these savings to ensure that the project remains sustainable.

One of the main limitations of this paper is that the only items being analysed are the external and internal walls. When the entire bill of materials is considered for the whole building, the sustainability of the project may not be the same. Different materials have different embodied energies, and some materials may not be worth transporting from any location. Additionally, there are also limitations in terms of the regulations that each country may have regarding the import and export of second-hand construction products as well as different quality standards for these products. These obstacles may affect the viability of a project due to difficulties during the material procurement process. This can be overcome by creating more case scenarios where patterns can be recognized to produce an optimum source for these components. Future studies can the social impacts of using this construction technique, which includes the health impacts of the new construction technique towards the population living in the vicinity of the project. It can also include the inclusion of sustainability impact calculations as well as feasibility studies of using state-of-the-art transportation technologies.

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