**Integrating three Pillars of Sustainability for Evaluating the Modular Construction Building**

**ABSTRACT**

**Design/methodology/approach:** Transitioning the built environment to a circular economy is vital to achieving sustainability goals. Modular construction is perceived as the future of the construction industry, and in combination with objective sustainability, it is still in the evaluation phase.

**Purpose:** So far, the sustainability performance of modular buildings was explored through a life cycle viewpoint. In this paper, a life cycle sustainability performance including the three-pillar evaluation framework was developed for different modular buildings. The materials are concrete, steel, and timber constructed as a modular construction method. The Multi-Criteria Decision-Making (MCDM) method was used to calculate the outranking streams for each modular.

**Findings:** The calculated embodied impacts, and Global Warming Potential (GWP) showed that material production is the most critical phase (65-88% of embodied energy & 64-86% of GWP). The result of embodied energy and GWP shows timber as an ideal choice. The result of the economic revealed that concrete is the most economical choice, while the social assessment shows that steel is the ideal material. The cost calculation shows that timber has a higher total cost by 7% and 11% higher than steel and concrete structures. Finally, MCDM revealed that steel has the best overall performance.

**Originality/value**: This research is valuable for construction professionals since it gives a deliberate framework for modular buildings' life cycle sustainability performance and assists with sustainable construction materials.

***Keyword:***Multi-criteria decision-making; Modular Construction; Life Cycle Sustainability Analysis; Life Cycle Cost; Social Life Cycle Assessment; Life cycle assessment.

1. **Introduction**

Over the past few decades, new buildings have been constructed at a faster rate due to an increasing population. By 2030, the value of construction is expected to rise by 14.41 trillion, up from 7.3 trillion in 2021 (Industry Forecast 2022-2030). Around 40% of all global resources are used by the building industry, along with 33% of all emissions and 40% of all waste (United Nations Environmental Program (UNEP), 2011; Levermore, G. 2008). Due to this, construction industry CO2 emissions account for almost 40% of annual emissions. Respect for nature, environmental protection, and responsible economic and social management are the principles of sustainable development. According to the above statistic, sustainability is considered a vital strategy and tool for controlling resource consumption in the construction industry..

The appropriate term for sustainability is not limited to the environmental impact of products or materials. Still, it covers all three aspects: environment, cost and social well-being. The most appropriate choice must be balanced among these three criteria (Balasbaneh & Sher, 2021c; Finkbeiner et al., 2010). Life cycle sustainability assessment (LCSA) is comprised of three individual dimensions, namely, social life cycle assessment (S-LCA), life cycle costing (LCC), and life cycle assessment (LCA) (Zeug et al., 2022). Baleta et al., (2019) assessed that environmental issues alone are not enough to encourage the construction sector to use specific materials or products. Other sustainability criteria need to be considered and analyzed to justify the use of a specific product for home contractors or consumers (Balasbaneh & Sher, 2022). Modular PPVC (Balasbaneh & Sher, 2021a; Lawson et al., 2014) is a new technique for construction in many countries around the world, and this trend has seen a recent increase of interest. However, only a few studies have focused on modular home construction and the ones that do exist have contradictory findings (Tavares et al., 2019b).

In view of the points above, it is clear that significant attention should be made towards improving the construction industry in terms of sustainability and reducing its negative impacts towards the environment, economy, and society (Tighnavard Balasbaneh et al., 2022). Construction techniques can be grouped into two major categories: modular and onsite. Onsite construction is a conventional method in which all raw materials are sent to a site for building construction. Conversely, off-site construction refers to manufacturing building elements that are then transported to a site for final installation. The scope of this research assessed the modular construction recognized as off-site building manufacturing (Srisangeerthanan et al., 2020). A limited number of studies have addressed and compared different modular prefabricated buildings. For example, a comparison by Atmaca & Atmaca (2016) between prefabricated and container houses constructed with steel showed that prefabricated houses have 25% lower environmental impact and 30% lower cost.

Reviewing previous research on prefabricated construction, some indicated that steel has the highest environmental impact (Bonamente et al., 2014), while others introduced concrete as having the highest environmental impact (Tavares et al., 2019). Pons et al. (2011) believed that prefabricated concrete has a higher impact during production and construction while timber and steel has a higher impact in the maintenance phase of a building. Shinde & Darade (2018) compared the prefabricated evaluation of steel and reinforced concrete. Their results showed that concrete contributes higher CO2 emission than steel in the stage of material production. Aye et al. (2012) believe that prefabricated steel has higher embodied energy than modular concrete. This led to a comprehensive assessment of modular buildings constructed with alternative materials for the complete cradle to grave life span of the building.

Previous attempts on the evaluation of off-site construction includes research by Kawecki (2010) on the GWP of modular timber during its production stage. The study revealed that electricity was found to be the largest energy source during the fabrication process. Life Cycle Assessment (LCA) by Faludi et al. (2012) on prefabricated modular commercial buildings in California showed that transportation and end-of-life disposal impacts are of low to negligible importance. Aye, et al. (2012) compared the cradle to grave material environmental impact of modular construction by steel and timber against conventional concrete construction. The result showed that although modular steel reduced material consumption by up to 78% compared to conventional concrete, it increased embodied energy. Kamali et al. (2019) compared modular construction versus conventional production materials (material production stage). Their results showed that while some modular buildings have a lower environmental impact, none of conventional or modular methods have absolute zero-emissions. The focus of most modular buildings are limited towards the production stage. For example, Tavares et al. (2019) compared four modular buildings using different materials within the production stage boundary. Their findings revealed that lightweight steel frames (LSF) and timber have lower CO2 emissions than steel and concrete.

Limited research is available in the literature relating to the Social Life Cycle Assessment (SLCA) assessment of modular buildings. SLCA is regarded as equally important to life cycle assessment in terms of both the environment and costs. Hosseinijou et al. (2014) assessed the SLCA of steel and concrete materials for in-site construction, and their results showed that steel has a better performance in this category. Hammad et al. (2019) compared some SLCA factors such as injury risk and noise pollution. Their results revealed that modular construction has a better overall performance compared to the conventional method. Liu et al. (2019) assessed two construction methods: the semi-prefabricated reinforced concrete and PPVC structure. The first case study was manufactured in Singapore and the second was sent from China. Results showed that PPVC has a better performance during the material extraction phase.

Nevertheless, there are some limitations on the application of modular building, such as the transportation (Choi et al. 2019) and making the components fit together (Bildsten, 2011). However, numerous advantages over offsite construction such as lower construction material wastage, fewer number of workers on-site, lower energy consumption, higher construction safety, faster construction process and faster construction speed (Kyjaková and Bašková 2014 & Quale et al. 2012) make it preferable to be used by the construction sector. There is a lack of comprehensive research in the literature to assess other sustainability criteria, such as the cost and social aspects of different modular PPVC. This research evaluates alternative materials for modular construction methods (PPVC) by considering different sustainability criteria (GWP, cost, social, etc.) to reveal the best options.

1. **Methodology**

The standard building was chosen as a case study to assess the modular building construction in Malaysia to fill current gaps in research. All case studies have a high degree of modular prefabrication. Data was collected for alternative materials using the same house plan and size to accurately reveal the differences between each material. Hence, the scenarios used in the analysis could be generalized to a broader capacity, representing modular buildings currently manufactured in South Asia countries. The methodological framework used in this research is presented and shown in Figure 1. The sustainability research seeks to distinguish a method to accurately measure not only the environmental and social impacts but also cost to be compatible with proper terms towards the best outcome.

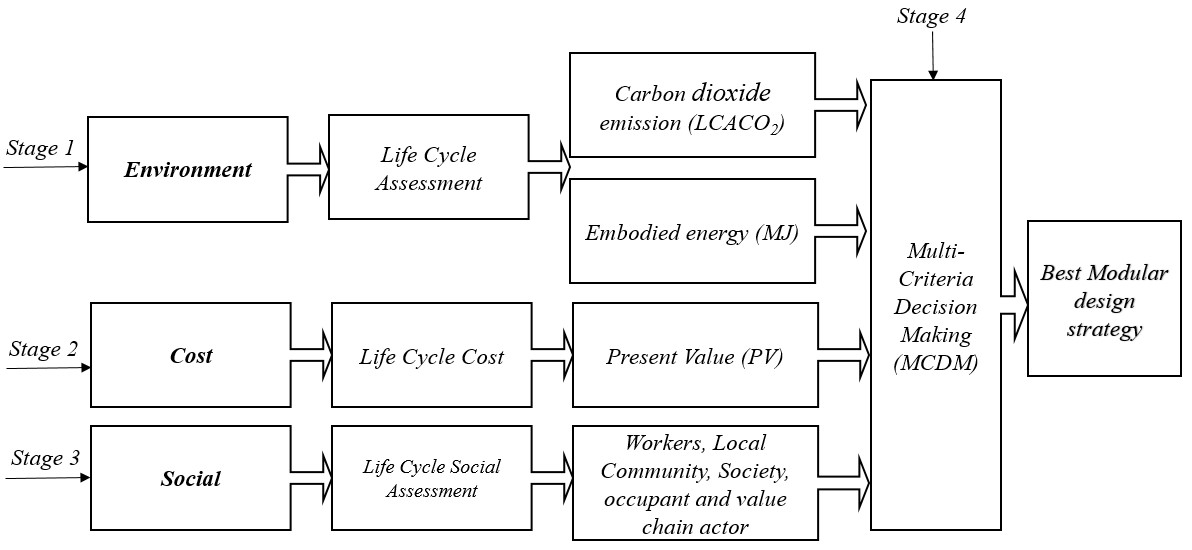


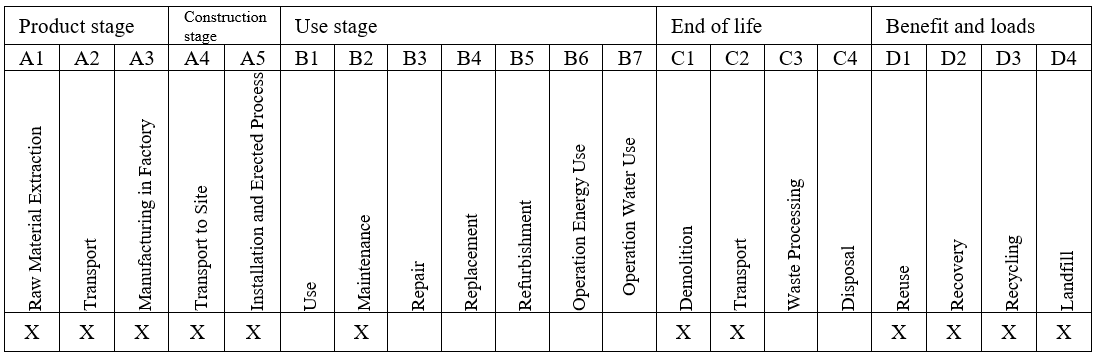
Figure 1: Methodological framework of life cycle study illustrating the steps of this study.

Performing a quantitative evaluation of all environmental impacts could be time-consuming and requires a level of proficiency to analyze all the numerous impacts. This study consists of four stages. In stage 1, two environmental issues are covered: embodied energy and GWP (carbon dioxide emissions) in order to evaluate the environmental burden. The intent is not to replace those two environmental impacts with other impacts but to give fast and reliable results to those designing modular units. Stage 2 is related to the Life Cycle Cost (LCC) evaluation of three different case studies and the economical options. Subsequently, stage 3 evaluates the SLCA of different scenarios to consider the best choice for workers and consumers. Materials selection for construction could be a complex decision-oriented with problem-solving in which an expert's opinion is needed along with comparative validations (Zarandi et al., 2011). Finally, the Multi-criteria decision-making (MCDM) with PROMETHEE (Preference Ranking Organization Method for Enrichment Evaluation) method is used to find the most optimum solution (Brans et al., 1986).

* 1. ***Life Cycle Assessment***

Life cycle assessment (LCA) was conducted to evaluate the CE of wooden materials for two construction cycles. Analyzing processes, products and alternative activities with LCA has become a recognized international approach. Environmental performance and loads are assessed throughout the life cycle of products using this methodology (Allan & Phillips, 2021; Balasbaneh et al., 2022). LCA is currently used to assess impact and sustainability. Table 1 shows the system boundaries corresponding to the life cycle modules.

Table 1: A modular building's life cycle stages EN 15804 and EN 15978



Based on ISO 14040 and ISO 14044 standards, the LCA study consists of four stages. These stages are goal and scope, inventory analysis (section 2.2.1), impact assessment (section 2.2.2), and interpretation. The main goal of this study is to evaluate three different types of volumetric construction materials to provide an accurate sustainability evaluation at the beginning of product development decision-making. The three materials selected were steel, concrete and timber. Concrete and timber used were prefabricated prefinished volumetric construction materials. Life cycle interpretation is the final step in the LCA study, and results are presented in sections 4.1 and 4.2 respectively. LCA is a systematic method whereby the outcomes of the life cycle inventory (LCI) and the life cycle impact assessment (LCIA) are categorized, quantified, checked, and evaluated. Interpretations will result in appropriate conclusions and recommendations.

* + 1. ***Life Cycle Inventory (LCI)***

In product life cycle analyses (LCIs), input and output flows are accounted for as part of a life cycle inventory. Several inputs and outputs are involved, including inputs of water, energy, and raw materials and outputs of air, land, and water. Using Ecoinvent (a database that supports sustainability assessments) certain variables can be altered based on site-specific information. It is possible to modify the wood dataset at the batching plant by changing the amounts and types of materials, as well as the methods of waste treatment. The life cycle inventory used in this study contains process data collected from Malaysian sources and Ecoinvent data supplemented with Malaysian data (Frischknecht & Rebitzer, 2005).

This model is based on the consequential life cycle inventory principle and is decision-based. An environmental impact assessment of changing multiple products is taken into account in consequential LCA (Ghose et al., 2017). A consequential LCA perspective is appropriate when considering economic cause-and-effect chains arising from changing production systems. This is important when evaluating future environmental impact policies. Reuse and recycling at the end of life are included in the system boundary of the consequential approach. Using an attributional (cut-off) approach, the first producer does not receive any credit for materials that are recycled (D3) at the end of a building's life (Taufiq et al., 2021). During the primary stage of the life cycle, the benefits and loads of recycled wood are not considered. The consequential model differs from attributional modeling and is based on multi-output products. Consequently, recyclable materials are reused for other purposes. All emissions to land, water, and air from a specific substance are included. To produce an accurate local result, the Ecoinvent database was adjusted to Malaysian circumstances using mixed local electricity information as recommended by (Horváth & Szalay, n.d.)

* + 1. ***Life Cycle Impact Assessment (LCIA)***

LCIA evaluation is based on the results of inventory investigation to determine the environmental impact of buildings (Henkel, 2005). LCIA is the third phase of the LCA, and its purpose is to provide additional information to help assess a product system’s LCI results to better understand its environmental significance. The LCIA method is used by the ReCiPe Midpoint (H) to assess the GWP. LCA evaluates and reports GWP to indicate the degree to which a building may contribute to climate change over its lifetime. Different fuel sources for producing materials including renewable sources and non-renewable sources such as coal result in various impacts on GWP or embodied energy. In Malaysia, the electricity consumed in producing materials such as prefabricated concrete is mainly generated from of fossil fuels, apportioned as 96.63% of the national electricity produced in 2014. In Malaysia, fossil fuels are the primary source of electricity generation (Balasbaneh et al., 2020b).

* 1. ***Life Cycle Cost Analysis***

The CE offers an approach to create a more sustainable environment. With regard to the construction industry, such an approach should not be limited to an environmental assessment but should include an economic assessment aligned to the CE LCC model (Wouterszoon Jansen et al., 2020). For this study the economic value of alternative methods of salvaging waste wood were analysed. The total yearly economic profit (revenues minus cost) was calculated for each sector. The cost of demolition is represented by the labour cost and the cost of transporting waste materials to a factory. Both the LCC model and the LCA model used in this investigation have been divided into four main phases based on the most crucial cost items: the acquisition of raw materials; the costs associated with production, transportation, and finally the costs associated with dismantling or deconstructing the product. LCC as applied here, refers to all the costs and incomes of a particular waste incurred by the owner of the waste.

* 1. **S-LCA**

Sustainability assessment includes SLCA as the third pillar. An Analytic Hierarchy Process (AHP) is a method of ranking the importance of all criteria related to modular systems in line with UNEP/SETAC "guidelines for SLCA of products." The AHP evaluates all criteria pertaining to modular systems based on UNEP/SETAC "guidelines for SLCA of products." AHP is a method of determining and ranking all criteria related to modular systems. Thus, it was used in evaluating the life cycle effect of three modular materials and comparing them. In this study, workers, local communities, society, and consumers were selected as appropriate items for the social aspect (Benoît et al., 2010). In this assessment, four groups of stakeholders were identified, whereas in previous assessments, only three stakeholders were taken into account. According to UNEP/SETAC (2009), the questions for social aspects of alternative modular materials were derived from their research, which considered more specific questions, such as cleaning comfort, reduced sound production, or beauty.

In order to produce a single index of SLCA subcategories, pairwise comparisons of elements in the problem hierarchy were performed. On the social network, a scoring system ranging from 1 to 9 was applied, with each number indicating how significant (inclination) every component is relative to the others. In the hierarchy, the following scoring system is used for pairwise comparison: 1 is unconcerned, 3 is moderately important, 5 is important, 7 is important, and 9 is extremely important. As a result, the best choice had the highest score. The selection of specialists was based on their ability to cover all aspects.

* 1. ***Multi-Criteria Decision-making***

The MCDA method involves allocating priorities based on a set of individual criteria with different units when many alternatives are available (Hermann et al., 2007). Kaklauskas et al. (2006) applied AHP and MCDM methods to discover the best modular construction option. Using an AHP model, Turskis et al. (2009) investigated the system of values and weights of criteria based on case studies. By using PROMETHEE, we were able to characterize the best and most appropriate material for modules in the construction sector using the four parameters (GWP, embodied energy, LCC, and S-LCA).

Sixty-two specialists from three specializations in the construction sector from Johor Bahru state in Malaysia were analyzed to determine three distinct modular parameters. For the evaluation of their priorities, the specialists filled out the questionnaire about the weighting of the criteria. Comparative analyses were carried out using an outright discernment scale, which indicates how much one component rules another regarding a specific attribute (Saaty, 2008). In line with Saaty (2008), the criteria that will be used in the pairwise comparison matrix are: CO2 emissions (Y1), embodied energy (Y2), cost (Y3), and social impact (Y4). Table 2 shows the relevant matrix for comparing four different criteria.

Table 2: The matrix for comparing four objectives

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| *Parameters* | *weight* | *Y1* | *Y2* | *Y3* | *Y4* |
| *Y1* | *V1* | *1* |  |  |  |
| *Y2* | *V2* |  | *1* |  |  |
| *Y3* | *V3* |  |  | *1* |  |
| *Y4* | *V4* |  |  |  | *1* |

When comparing two parameters pairwise, the inclination scale ranged from 9 to 1. It is important to ensure that the calculated Consistency Ratio (CR) is less than 0.1 in order to ensure consistency of the comparison framework. Based on a given evaluation matrix and a random matrix, CR is defined as the ratio between consistency. If the CR is much more than 0.1, the judgments are untrustworthy because they are too close and indicate randomness, leading to the exercise being valueless or needing to be repeated. Numerous works in the literature have focused on applying PROMETHEE as a trusted MCDM method for solving environment management. Its steps are as follows:

**Step 1:** Accomplishing the normalization by evaluation matrix that was extracted from each previous step. Equation 2 is related to the beneficial criteria while equation 3 assesses non-beneficial criteria (if any).

Eq (2)

Eq (3)

**Step 2:** calculating and deducting each different alternative with respect to other alternatives.

**Step 3**: calculating the preference function using equations 4 and 6.

Eq (4)

Eq (5)

The is the preference of alternative concerning to alternative b on each criterion.

**Step 4:** calculating the aggregate preferences by using equation 6:

Eq (6)

Where of a over b (from 0 to 1) is defined as a weighted sum for each criterion and is the weight associated with criteriaon.

**Step 5**: Calculating the outranking flows to determine leaving (positive) and entering (negative) flow for *a*th alternatives (equation 7).

Eq (7)

**Stage 6:** Calculating the net outranking flow related to the PROMETHEE II complete ranking by (equation 8).

Eq (8)

Where is the net outranking flow for each alternative.

1. **Case study**

Modular manufacturing consists of pre-assembling volumetric units and transferring the units to a site to be installed as a load-bearing block. The single-story building was chosen for evaluation in this study. The comparative analysis was performed among three common building materials: light steel frame, concrete, and timber. The dimensions of the residential building was 18 m2 by 8 m2. The characterization and detail of every single material attributed to three main modules are depicted in Table 3.

Case study 1 is related to modular lightweight steel frame construction. The first stage consists of material extraction, transportation of material to the factory, on-site construction and installation, and transportation (A1-A6). Connections between modules are made with a bolt and tie plate assembly. The second modular is concrete construction, and its density is 2400 kg/m³. The starter bar comes from underneath the slab and passes through the hollow core. The first stage of concrete evaluation is related to raw material extraction, such as sand, cement, etc., which are transported to the factory. The manufacturing of the entire module occurs in the factory (A1-A3). The next stage consists of transporting all the modules to the construction site located 250 km from the factory (A4). A high-load truck is commonly used as the primary vehicle type for transportation, particularly when considering prefabricated components' large volume and weight. Secondly, the modules were hoisted and assembled using a 260-ton tower crane (A5-A6) and on-site machinery in which the use of a crane was considered for PPVC.

The maintenance phase includes regular painting and maintenance over a building life span of 50 years (B1). Maintenance comprises of minor renovations and painting done every 6 to 25 years, with minor repairs being in intervals up to 25 years, four times over the building’s 50 year lifetime (Szalay, 2007). Due to the unavailability of specific modular maintenance, 5 % of the main components require repairs. The demolition phase (C1-C2) also considers the disassembly and transportation of materials to the landfill (D3). The foundation of the building was not considered in system boundary, and therefore, it is not considered for assessment in this research. However, this item was considered the same for all alternatives since this study compares wall frame materials for construction.

Table 3: Characterization of building material details

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| ***Types*** | ***Material*** | ***Weight per kg/m2*** | ***Thickness (mm)*** | ***Total weight-Kg*** |
| *S-PPVC* | *Light Steel Stud Frame Walls and ceiling* | *14* | *20* | *8174* |
| *Plasterboards* | *5.4* | *10* | *1166.4* |
| *Mineral wool* | *40* | *35* | *8640* |
| *OSB sheathing boards* | *7.7* | *10* | *1663.2* |
| *C-PPVC* | *Concrete panels & slab* | *320* | *20* | *194,560* |
| *Reinforcing bars at both faces of all walls* | *1024* | *200 mm centers* | *45056* |
| *Reinforcing bars both faces of ceiling* | *1024* | *200 mm centers* | *18022.4* |
| *T-PPVC* | *Wooden planks & structures* | *70* | *22* | *40310.4* |
| *Waterproof membrane* | *1.4* | *10* | *31350* |
| *OSB panels for floor* | *7.7* | *10* | *71136* |
| *Internal insulation* | *25* | *15* | *12320* |
| *Vapor control layer* | *2.1* | *10* | *13000* |
| *Plasterboard* | *5.4* | *10* | *7931.52* |

Modular timber typically consists of the wall stud and a layer of plasterboard attached to the interior side, also sheathed with orientated strand board (OSB) applied for the floor. Timber panels have to be adequately tied at their strong points (typically corners) to lift them from the factory and transported to the site for installation. Based on consultations with demolition contractors and scholars specializing in this field, timber combustion and steel recycling were identified as the most probable scenarios for each material. It is assumed that 75% of mineral wool was considered for recycling, and the rest sent to landfill.

To avoid inconsistencies in results, it was assumed that 50% of wood would be reused and 50% used to replace fossil fuels. The concrete was crushed and exposed to the atmosphere for four months to increase carbonation and later used for below-ground filling. The steel bar was also recycled for end-of-life scenarios. The data for electricity production in Malaysia was taken from Energy Commission Malaysia (2019). The electricity input for the prefabrication of one module at the plant was calculated based on the plant’s electricity bill and the number of produced modules. A factor that was not included in this assessment was the wastage of materials. The amount of waste was not being considered due to the lack of information about this particular stage. In addition, system activities (e.g., refurbishment) were also ignored as there was a lack of information regarding this stage.

1. ***Results and Discussion***

As previously mentioned, three modular prefabricated buildings were chosen for the sustainability assessment: lightweight steel frame prefabricated prefinished volumetric construction (S-PPVC), concrete prefabricated prefinished volumetric construction (C-PPVC), and timber prefabricated prefinished volumetric construction (T-PPVC), in which four criteria were assessed.

* 1. ***Global warming potential***

The LCA results are discussed in this section to identify which modular building assemblage has minimum cradle to grave environmental impacts. The result of LCA on GWP for different life cycle phases is shown in Table 4. The result shows that the production stage for all modular buildings contribute to the highest emission. In this stage, steel contributes 17% higher emissions compared to concrete and 30% higher than timber modules. Transportation is one of the critical stages of modular building construction and contributed between 9% to 12% of production emissions. Emissions during the transportation phase is highly dependent on the distance of the modular factory and the weight of components.

The end-of-life stage involves the recycling of steel, mineral wool, and plasterboard for S-PPVC. It was assumed that the materials were recycled, having net emission benefits (negative values). The end of life of S-PPVC potentially decreases the overall emission from the module. Steel contributes the highest emission reduction benefits at its end-of-life stage compared to modular timber and concrete. The end of life of C-PPVC has a positive impact on its GWP emissions, contributed from the recycling of reinforcing steel bars after being transferred to a recycling factory, and the concrete is sent to a landfill. As mentioned above, timber recovered during demolition and combusted to recover energy that provides positive emission benefits. The end-of-life scenario contributes to 36%, 8%, and 18% of overall production emissions for S-PPVC, C-PPVC, and T-PPVC respectively. Therefore, it can be expressed that steel contributes the highest emission reduction benefits impact from its final stage. The results in Table 4 is summarize the product stage (A1, A2, and A3), transportation (A4), On-site (A5), maintenance (B2), and end of life emissions, which come along with benefits and loads (C1, C2, D1, D2, D3, and D4).

Table 4: Global warming potential emission of modular steel, concrete and timber (PPVC)

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| *GWP* | Unit | *Production* | *Transport* | *On-site* | *Maintenance* | *End of life* |
| *S-PPVC* | Kg CO2eq | *11256.5* | *1014.04* | *210.526* | *562.8229297* | *-4100* |
| *C-PPVC* | *9294.15* | *1014.04* | *210.526* | *464.7073684* | *-800* |
| *T-PPVC* | *7890* | *1014.04* | *210.526* | *294.5438596* | *-1456.14* |

Figure 2 shows the GWP emissions for each stage of modular building construction over a 50-year life span. The total emission GWP emissions for the case studies are 8043 Kg CO2eq, 10183 Kg CO2eq, and 7953 Kg CO2eq for S-PPVC C-PPVC and T-PPVC respectively. The highest emissions are contributed by modular concrete, followed by modular steel and timber. The emission from steel and the modular building has a negligible difference despite their significant differences in the production stage. This is due to the end-of-life scenario for steel recycling with a positive net of its total carbon emission. The concrete production stage had a lower emission compared to steel. However, its entire life cycle, such as maintenance and end of life, was ultimately revealed as having the highest modular structure compared to the alternatives. Steel modular has 13% higher carbon emission as opposed to modular timber. Timber is the most preferred choice as it has less carbon dioxide emission than other alternatives.

Figure 2: Carbon emission of modular steel (S-PPVC), concrete (C-PPVC) and timber (T-PPVC)

* 1. ***Embodied Energy***

To obtain a holistic understanding of energy consumption and its associated GWP emissions, embodied energy must also be considered. Table 5 shows embodied energy emissions from three different modular buildings. Material production and transportation are responsible for most embodied energy (cradle-to-site) followed by an on-site activity. Transportation has a significantly lower impact compared to the production stage (1.7% to 2% of total embodied energy), while on-site construction, which includes cranes, contributed to only 0.07% to 1.2% of total embodied energy. Comparing material production and its cumulative effects when adding modular production shows that it increases 4% of embodied energy for all case studies. In other words, transportation and on-site construction increased the impact by 8275 MJ, 8475 MJ, and 6545 MJ for modular steel, concrete, and timber respectively.

Table 5: Embodied energy of modular steel, concrete and timber (PPVC)

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Embodied energy | Unit | *Production* | *Transport* | *On-site* | *Maintenance* | *End of life* |
| *S-PPVC* | MJ | *320340* | *5687* | *2587.5* | *9441* | *-96000* |
| *C-PPVC* | *283739* | *5687* | *2787.5* | *9352* | *-42000* |
| *T-PPVC* | *240450* | *4687* | *1857.5* | *9086* | *-46000* |

Transportation and onsite processes have similar impacts and contributed to 2.3% and 1.2% of total emissions respectively. The maintenance phase for timber had a higher contribution of 4.3% of total emission and followed by concrete and steel with 3.9% and 3.6% respectively. The result shows that steel has the highest production emissions, followed by modular concrete and timber. S-PPVC has a higher embodied emission than C-PPVC by 11% and 24% higher than T-PPVC. In comparison, the end-of-life scenario significantly impacted total emissions when steel recycling was considered for S-PPVC.

Figure 3*:* Embodied energy of modular steel (S-PPVC), concrete (C-PPVC) and timber (T-PPVC)

The recycling of steel had an offset impact which covered 30% of total production embodied energy, while recycling concrete steel bars only contributed to a 14% offset impact. Timber combustion for energy recovery at the end of life contributed to 20% of production embodied energy. This shows that proper recycling may decrease the total impact of the product for different construction materials. However, steel benefits from a higher offset impact with its recycling. Figure 3 shows the total embodied energy impact for all case studies at each life stage. The results show that despite the higher impact of steel during its production stage, its total impact was lower than concrete primarily due to the end-of-life scenario that considered recycling and reusing of steel. The total embodied energy was 242,057 MJ, 259,566 MJ, and 210,082 for modular steel, concrete, and timber respectively. Modular concrete had 7% higher embodied energy than modular steel and 23% higher than modular timber. Therefore, timber is the most optimum choice as it releases the least embodied energy compared to other alternatives.

* 1. ***Life Cycle Cost***

Table 6 shows the cost of each modular construction building per m2 in MYR. The concrete was a ready mixed grade 40 that costs 36 MYR per m3 plus an extra 2 MYR for pump mix. Preliminary results indicated that although wood is cheaper than concrete and steel for every m2, constructing modular timber is more costly due to the extra material used for timber components. Additionally, the wages for modular timber construction were 22% and 33% higher than steel and concrete respectively for every m2. The construction costs for timber for every m2 were 10% and 13% higher than concrete and steel, respectively. The total construction and production costs to prepare the module in the factory were different for each case study. The cost of the module’s factory preparation before being delivered to the site was 63,846 MYR, and 59,073 MYR and 70,700 MYR for steel, concrete and timber respectively. This shows that modular concrete has a lower preliminary production cost by 7% compared to modular steel.

Table 6, cost estimation of modular steel, concrete and timber (PPVC) construction phase

|  |  |  |  |
| --- | --- | --- | --- |
| ***Types*** | ***Material*** | **Cost of construction per m2 -MYR** | **Total Cost /MYR** |
| *S-PPVC* | *Light Steel Stud Frame Walls and ceiling* | *31* | *105.01* |
| *Plasterboards* | *23* |
| *Mineral wool* | *12* |
| *OSB sheathing boards* | *10.01* |
| *Wages* | *37* |
| *C-PPVC* | *Concrete panels & slab* | *47.8* | *97.16* |
| *Reinforcing bars at both faces of all walls* | *2.18* |
| *Reinforcing bars both faces of ceiling* | *2.18* |
| *Wages* | *45* |
| *T-PPVC* | *Wooden planks & structures* | *18.01* | *116.5* |
| *Waterproof membrane* | *15.5* |
| *OSB panels for floor* | *7.01* |
| *Internal insulation* | *9* |
| *Vapour control layer* | *12* |
| *Plasterboard* | *10* |
| *Wages* | *45* |

The transportation cost was assumed based on the data collection from the site, which equaled to 5,100 MYR. A typical residential building that requires six modules will need at least three trips if two modules are loaded onto the truck at one time (1700\*3). This is multiplied by the number of needed transportations; it is more than the required modules for one building unit. The crane cost was 1,400 MYR for almost 2% of the total construction cost for the onsite operation. The maintenance costs for S-PPVC, C-PPVC, and T-PPVC were 3,192 MYR, 2,953 MYR, and 4,545 MYR respectively. The end-of-life data were collected by visiting the recycling companies and assessed based on each module’s mass and weight. The net return money back to the project from selling the material was 2,100 MYR, 1,200 MYR, and 4,200 MYR, respectively for S-PPVC, C-PPVC, and T-PPVC. This value was deducted from the total building cost. Figure 4 shows the total LCC of all options. It is apparent that concrete modules represents the best option in terms of cost, followed by steel and timber. The results show that despite its lower environmental impact compared to the alternatives as shown in the preceding section, timber has the highest cost.

The total cost for the steel, concert, and timber modules is 71,438 MYR, 68,326 MYR, and 76,535 MYR respectively,. Based on the assumption that the average exchange rate for six years (2014 to 2019) is 4.14 MYR/USD, the cost based on US dollars will be 17,063 USD, 16,320 USD, and 18,280 USD respectively, for steel, concert, and timber modules.

Figure 4: Cost estimation of modular steel (S-PPVC), concrete (C-PPVC) and timber (T-PPVC)

* 1. ***S-LCA***

Table 7 shows the detailed results of scoring from the stakeholders. To obtain preliminary results, the overlapping roles by stakeholders should be eliminated. For example, a worker might be part of a local community, so only specific groups have cooperated to avoid a biased point of view. For the worker category, concrete has a higher normalized value, showing that it is a preferred choice in this category. However, it is not preferred compared to steel in health and safety subcategory. Steel dominates the fair salary and freedom of association subcategories.

In the second category, steel modular construction provides benefits to the local community compared to the alternatives by 4.02 normalized values versus 3.51 and 3.47 for concrete and timber. However, in terms of access to material resources, specifically on the extraction of material resources, timber has a better value at 0.39 compared to 0.31 and 0.3 for concrete and steel respectively. In the waste generation subcategory, concrete has a lower ranking, followed by timber and steel. In the local employment subcategory, job creation, use of technology that generates employment, and local supply network have higher values for modular concrete.

Table 7: Scoring system of social life cycle assessment

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Stakeholder Categories** | ***Subcategories*** | ***Inventory indicators*** | **S-PPVC** | **C-PPVC** | **T-PPVC** |
| **Normalized Value** | | |
| *Workers* | *Freedom of association* | *Respect for freedom of association bargaining* | *0.35* | *0.37* | *0.28* |
| *Health and safety* | *Less Occupational accidents* | *0.38* | *0.32* | *0.3* |
| *Fair salary* | *Living/non-poverty wages* | *0.4* | *0.34* | *0.26* |
| *Local community* | *Access to material resources* | *Changes in land ownership/ land use* | *0.39* | *0.34* | *0.27* |
| *Levels of industrial water use* | *0.38* | *0.24* | *0.38* |
| *Extraction of material resources* | *0.3* | *0.31* | *0.39* |
| *Safe and healthy living conditions* | *Pollution levels* | *0.39* | *0.29* | *0.32* |
| *Waste generations* | *0.4* | *0.22* | *0.38* |
| *Local employment* | *Job creation* | *0.38* | *0.39* | *0.23* |
| *Use of technology that generate employment* | *0.37* | *0.38* | *0.25* |
| *Presence of local supply network* | *0.28* | *0.36* | *0.36* |
| *Easier to install* | *0.34* | *0.33* | *0.33* |
| *Less wastage* | *0.4* | *0.33* | *0.27* |
| *Use of local labor* | *0.39* | *0.32* | *0.29* |
| *Society* | *Technology development* | *Research and development* | *0.34* | *0.33* | *0.33* |
| *Technology transfer* | *0.35* | *0.36* | *0.29* |
| *Contribution to economic & development* | *Functionality and appeal* | *0.33* | *0.37* | *0.3* |
| *Contribution of product to economic (GDP)* | *0.35* | *0.34* | *0.31* |
| *Maintenance cost and frequency* | *0.4* | *0.36* | *0.24* |
| *Consumers* | *Satisfaction* | *Durability* | *0.37* | *0.38* | *0.25* |
| *Less sound producing* | *0.34* | *0.34* | *0.32* |
| *More beauty* | *0.39* | *0.27* | *0.34* |
| *Presence of consumer complaints* | *0.35* | *0.34* | *0.31* |

In the third category (society) modular steel has a higher normalized value. However, in technology transfer, functionality, and appeal related to contribution to the economy, concrete provides the best score. In the fourth category (consumers), steel has a better score in terms of customer satisfaction of product. In the subcategory of durability, concrete is the best choice. Figure 5 shows that modular steel is the best choice by achieving the highest normalized value (8.37) followed by concrete (7.63) and timber (7) modules.

Figure 5:normalized value of social life cycle assessment of modular steel (S-PPVC), concrete (C-PPVC) and timber (T-PPVC)

* 1. ***MCDM***

Construction companies may find it time-consuming and expensive to choose the right modular building materials when several candidates are available. A MCDM model was used at this stage to identify the best alternative and balance carbon emissions, embodied energy, cost, and social impacts. First, experts with knowledge of construction were consulted to determine the importance of each criteria. It is usually necessary for the decision maker to consider conflicting criteria when choosing between numerous alternatives.

In the MCDM step, importance ranges from 1 to 9 have been applied similarly to the social category (section 2.4). A summary of the results is provided in Table 8. The comparison matrix has a calculated CRa less than 0.1, which indicates consistency. Prioritizing the four research parameters was accomplished by three groups. Considering the construction manager's opinion, cost is assigned first, followed by GWP emissions, embodied energy, and social acceptance. On the other hand, designers have a different perspective. In choosing the appropriate material for modular construction, respondents believe SLCA should be the primary consideration.

As the third group of respondents, we are looking for academics who have contributed to the field of modular construction research. According to this group, embodied energy should be the highest priority in building construction, unlike the previous two groups. GWP is the second most important factor, followed by cost and social categories, as shown in Table 8. Following the cumulative results of the experts' opinions, SLCA is placed first with a weighting of 0.303, followed by cost with a weighting of 0.279. Embodied energy and global warming potential were ranked third and last, respectively, with weights of 0.202 and 0.215.

The two groups of respondents in this survey are from the construction industry who are actively working in modular construction, and they chose SLCA and LCC as the top priorities. This shows that the opinion of those actively working in the construction market is mainly towards cost and customer satisfaction rather than environmental impacts. The cause of this attitude can be analyzed in a future research. However, in a previous study by Balasbaneh, 2020c, when a university lecturer collaborated, their opinions changed and GWP was ranked as a priority. To avoid human subjectivity, this study performed a sensitivity analysis in section 5.1.

Table 8 The results The results of individual and generalized surveys, W represents Weighting and P as priority.

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Parameters** | **60 experts** | | | | | | **Total** | |
| **Construction manager** | | **Designer** | | **Academic/ Professor** | |
| W | P | W | P | W | P | W | P |
| GWP | 0.233 | 3 | 0.132 | 4 | 0.243 | 2 | 0.202 | 4 |
| Embodied Energy | 0.168 | 4 | 0.182 | 3 | 0.295 | 1 | 0.215 | 3 |
| LCC | 0.312 | 1 | 0.287 | 2 | 0.238 | 3 | 0.279 | 2 |
| SLCA | 0.287 | 2 | 0.399 | 1 | 0.224 | 4 | 0.303 | 1 |
|  | CRa= 0.052 <0.1 | | CRa= 0.058 <0.1 | | CRa= 0.034 <0.1 | |  | |

The initial decision-making matrix for different materials is presented in Table 9. This result originated from Figures 2 to 5. Meanwhile, Table 9 shows how different materials for modular construction may impact sustainability criteria such as the environmental, economic, and social lifecycle impacts.

Table 9: Initial decision-making matrix

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| ***Criteria*** | ***Unit*** | ***Weights*** | S-PPVC | C-PPVC | T-PPVC |
| *GWP* | *kgCO2 eq* | *8943.84* | *242057* | *71438.4* | *8.37* |
| *Embodied Energy* | *MJ* | *10183.4* | *259566* | *68326.9* | *7.63* |
| *LCC* | *MYR* | *7952.96* | *210082* | *76535* | *7* |
| *SLCA* | *Normalized* | *8943.84* | *242057* | *71438.4* | *8.37* |

The first stage consisted of determining the beneficial and non-beneficial criteria. Three non-beneficial (indirect) criteria were available with lower desired values, namely the GWP, embodied energy, and cost. In contrast, SLCA was considered as beneficial (direct) criteria to accomplish the PROMETHEE. In this step, the normalized value was assessed using equations 2 and 3. In step 2, the difference was evaluated, and the subtraction of ith alternatives concerning other alternatives was performed. Step 3 involved calculating the preference function using equations (4) and (5) to find the difference between one criterion concerning another. Based on equation 4, if the difference is negligible or zero, it substitutes the preference function value as zero. In equation 5, if the difference of one criterion is significantly more than zero, the difference value is used as the preference function value. Step 4 consists of calculating the aggregate preference by using equation (6). Finally, weights (Table 9) were multiplied to the value achieved from the previous stages, and the results are shown as a new matrix (Table 10). Stage 5 determined the leaving and entering outranking flows using equation seven, as shown in Table 10.

Table 10, the results of the multi-criteria analysis PROMETHEE II

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
|  | S-PPVC | C-PPVC | T-PPVC | Leaving flow | Entering flow |  | Rank |
| S-PPVC | 0 | 0.163844 | 0.476572 | 0.320208 | 0.167361 | 0.152847 | 1 |
| C-PPVC | 0.105761 | 0 | 0.418489 | 0.262125 | 0.290756 | -0.02863 | 2 |
| T-PPVC | 0.228961 | 0.417667 | 0 | 0.323314 | 0.447531 | -0.12422 | 3 |

Finally, equation (8) was used to calculate the net outranking flow for each building construction option. The difference between leaving flow and entering flow had to be deducted. The results of net outranking flow are 0.152847, -0.02863, and -0.12422, respectively for S-PPVC, C-PPVC and T-PPVC. A bigger value represents a better alternative value. Therefore, the result shows that steel PPVC is the best option for prefabricated buildings. Figure 6 shows the PROMETHEE II complete ranking calculated based only on the net outranking flow. From these rankings, it appears that steel PPVC is more sustainable than other alternatives.

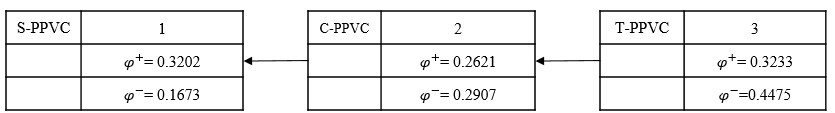


Fig. 6. PROMETHEE II

1. ***Discussion***

In this study, the MCDM tool was implemented in order to compare non-same value parameters. The incentive covered three main criteria: environmental, cost, and social aspects of sustainability, as some materials or systems, might have lower carbon emissions while having a higher cost, which causes the construction sector to shun them. However, the alternatives of modular construction towards environmental and social measurements should not be overlooked. The calculated embodied impacts show that material production is the most critical phase contributing to 65%, 88%, and 83% respectively for modular steel, concrete, and timber compared to the entire cradle-to-grave life cycle stage. Similarly, the calculated GWP shows that material production is the essential phase contributing to 64%, 87%, and 87%, respectively, for modular steel, concrete, and timber than the whole life cycle stage.

Other research by Motuziene et al. (2016) considered GWP, ozone layer depletion, cost, and non-renewable energy sources, while Invidiata et al. (2018) considered GWP, energy, and cost. In contrast, this research has expanded towards more sustainable aspects by incorporating social indicators which have vast results in this category. Therefore, comparing this research with previous studies can form a suitable reference for future research. Most academic research mainly focuses on the environmental impact of the production phase for modular construction (Echeveste et al., 2018). Tavares et al. (2019a) analyzed embodied energy and GWP emissions for modular buildings, and their results are consistent with the current research. However, the boundary of research was only at the construction stage. Hong et al., (2016) showed that the recycling process of prefabricated buildings could achieve up to 24% energy reduction. Based on this research, recycling at end of life shows that different energy reductions could be achieved for different materials, at 16%, 21%, and 40% for concrete, timber, and steel respectively. One aspect of this research was SLCA, and Kamali et al. (2017) also indicated a gap in the literature about the cost and social impact of PPVC. Thus, future studies should focus on social assessments compared to the environmental dimension. Faludi et al. (2012) accomplished LCA for decision making of prefabricated commercial modular building in California. Their results shows that the transportation and end-of-life disposal impacts are of low to negligible importance, which this study agrees with. The cumulative embodied energy for transportation and crane (on-site activity) is about 3% of the total impact, while the cost comparison of for the same matter had an impact of 9%.

Meanwhile, the cost for transportation and crane for prefabricated modular construction equals to 6% to 9% of the total cost. This result is in agreement with previous research by (Kim 2008a). Most previous sustainability studies focused on environmental and economic aspects, and social assessment was neglected.

* 1. **Sensitivity analysis**

Sensitivity analysis aims to determine how sensitive the output of a model is towards uncertain elements of the model. Three different sensitivity analyses were conducted. First, the PROMETHEE I was applied to compare each modular construction technique. In this method, after the preference function was calculated in, it was multiplied with the relative weighting similar to the previous PROMETHEE II method. Next step, in PROMETHEE I, instead of taking the average, the sum was taken. Figure 7 presents the PROMETHEE I partial ranking, which was calculated based on the beneficial and non-beneficial outranking flows. In PROMETHEE I, instead of defining the rank, the references were calculated. The rule is that the alternative with higher leaving flow, and lower entering flow is the best option (preferred). Thus, S-PPVC is preferred against C-PPVC and T-PPVC. The results also show that C-PPVC is incomparable to T-PPVC. Thus, steel modular construction is revealed as the best option again following by concrete and timber.

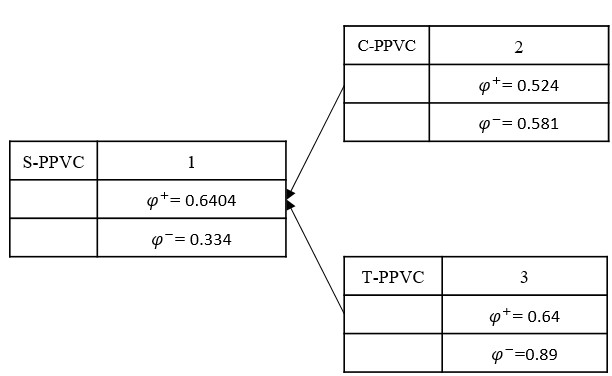
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Fig.7. PROMETHEE I

As shown in Table 6, the weight assessment was collected based on experts’ opinions from different backgrounds. Thus, a sensitivity analysis was performed to overcome human subjectivity in settling the weighs. Therefore, all weighting was changed in this section, the criteria were re-developed for each module structure, and weightings were considered equal to 0.25 (one divided by four). Table 11 shows equal weighting for three case studies and the priorities which were changed. It is interesting to understand how human subjectivity can influence the results. Modular steel is still recognized as the best option, while the timber is replaced by concrete as the second priority.

Table 11, sensitivity analysis same weighting

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| **Alternatives** | S-PPVC | C-PPVC | T-PPVC | Leaving flow | Entering flow |  | Rank |
| S-PPVC | 0 | 0.135036 | 0.405232 | 0.270134 | 0.183686 | 0.086448 | 1 |
| C-PPVC | 0.094768 | 0 | 0.364964 | 0.229866 | 0.317518 | -0.08765 | 3 |
| T-PPVC | 0.272604 | 0.5 | 0 | 0.386302 | 0.385098 | 0.001204 | 2 |

The third sensitivity analysis is related to the SLCA, and social impact was omitted from the evaluation. Due to timber being abandoned by many house makers in Malaysia as a building material over the last forty years (Nor Haniza Ishak, 2012), wooden buildings are only limited to rural houses or bungalows in the countryside (Othuman Mydin, 2016). While, in other countries such as Scotland, wood still is an appropriate option for building construction (NHBC, 2012). In Scotland, up to 70% of construction utilize timber frames. Thus, the response of the building sector could have a considerable impact on the SLCA result. Therefore, there is an opportunity to reevaluate the results without the SLCA criteria explicitly. Table 12 shows that if this sustainability criterion is omitted from the MCDM assessment, then the priority will be changed to timber as the best option following by concrete and steel.

Table 12, sensitivity analysis without SLCA impact

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| **Alternatives** | S-PPVC | C-PPVC | T-PPVC | Leaving flow | Entering flow |  | Rank |
| S-PPVC | 0 | 0 | 0.155232 | 0.077616 | 0.183686 | -0.10607 | 3 |
| C-PPVC | 0.094768 | 0 | 0.25 | 0.172384 | 0.25 | -0.07762 | 2 |
| T-PPVC | 0.272604 | 0.5 | 0 | 0.386302 | 0.202616 | 0.183686 | 1 |

Many other researchers previously focused on the environmental impacts of building (Nwodo & Anumba, 2019). In comparison, this study shows that considering environmental impacts and LCC might not be enough to assess the sustainability of buildings and their materials without considering the social impacts. Based on results presented above, many social considerations could impact choice of the best alternative modular construction material. However, this consideration is influenced by human subjectivity based on the region or country of study and expert opinions on the three pillars of sustainability priorities. In conclusion, covering more criteria such as SLCA could provide more comprehensive results.

1. ***Conclusions***

This study accomplished the life cycle sustainability assessment on three different modular construction buildings. The preliminary result of GWP shows that modular timber is the best option. The end-of-life scenario of steel has a net advantage and reduction in total emissions (37% net emission). In terms of embodied energy of timber has the lowest energy consumption during its lifespan. Cost comparisons revealed that modular timber is the most expensive option, while concrete is the most economical modular building construction material with a 30% lower total cost. Based on respondents in the SLCA, steel is recognized as the most preferable modular building construction material. A MCDM tool by PROMETHEE II was employed to evaluate the differences between modular buildings. The result revealed that steel is the preferred modular construction material among the alternatives followed by concrete and timber.

The sensitivity analysis revealed that the best building material could differ based on changing criteria. All three modular construction materials could be the ideal choice based on specific circumstances. In this study, steel presents the best choice when based on four different criteria: carbon emissions, embodied energy, cost, and social LCA. Sensitivity analysis by equal weighting showed that human subjectivity could significantly impact material selection for constructing the modular house. When the criteria are narrow down to three areas (carbon emission, embodied energy, cost), timber is recognized as the best choice. Results showed that relying on environmental impacts is not sufficient to reveal the best alternative for modular building construction material. Nevertheless, the research needs to incorporate the cost and social impact to achieve comprehensive results. Conversely, the social study results depends on the region of study and human subjectively.

Although the target of this study has been achieved, there are few obstacles that need to be addressed for future research. Firstly, this research was based on the context of Malaysian construction. In this regard, different results might be obtained when encountering other nations due to human subjectivity and transportation distance. However, the findings of this study are still valid and fundamental to the body of knowledge as it considered the three-pillars of sustainability among the variety of materials for modular construction techniques. Also, the results could be vastly applied in all countries in the Asia region which have the same attitudes towards timber as a construction material. Furthermore, the findings of this study can provide a theoretical basis for attempts to enhance the construction management in terms sustainable development. Moreover, the results could be utilized by enterprises and governments to implement better strategies for the future.

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