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RESEARCH ARTICLE

A comparative life cycle assessment (LCA) of concrete and steel-prefabricated prefinished volumetric construction structures in Malaysia

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Abstract
In recent years, off-site volumetric construction has been promoted as a viable strategy for improving the sustainability of the construction industry. Most prefabricated prefinished volumetric construction (PPVC) structures are composed of either steel or concrete; thus, it is imperative to carry out life cycle assessments (LCAs) for both types of structures. PPVC is a method by which free-standing volumetric modules—complete with finishes for walls, floors, and ceilings—are prefabricated and then transferred and erected on-site. Although many studies have examined these structures, few have combined economic and environmental life cycle analyses, particularly for prefinished volumetric construction buildings. The purpose of this study is to utilize LCA and life cycle cost (LCC) methods to compare the environmental impacts and costs of steel and concrete PPVCs "from cradle to grave." The results show that steel necessitates higher electricity usage than concrete in all environmental categories, while concrete has a higher emission rate. Steel outperforms concrete by approximately 37% in non-renewable energy measures, 38% in respiratory inorganics, 43% in land occupation, and 40% in mineral extraction. Concrete, on the other hand, performs 54% better on average in terms of measures adopted for greenhouse gas (GHG) emissions. Steel incurs a higher cost in the construction stage but is ultimately the more economical choice, costing 4% less than concrete PPVC owing to the recovery, recycling, and reuse of materials. In general, steel PPVC exhibits better performance, both in terms of cost and environmental factors (excluding GHG emissions). This study endeavors to improve the implementation and general understanding of PPVC.

Keywords Prefabricated prefinished volumetric construction · Environmental assessment · Life cycle cost · Life cycle assessment · Sensitivity analysis

Introduction

Many recent studies have focused on reducing the environmental impact of the emissions produced during the construction of buildings (Dong et al. 2015). Prefabricated construction offers many environmental and economic advantages, thus keeping with current sustainability goals. This research examines volumetric construction in Malaysia—a practice that recently became mandatory with an advisory from the Building and Construction Authority that requires companies in the construction sector to apply prefabricated prefinished volumetric construction (PPVC) components to their units (Ministry of National Development 2016). PPVC's environmental impacts and costs are among the most important factors in the development of sustainable construction; thus, evaluating performance in these areas is vital. This research also comes at a time when the construction industry in Malaysia has been labeled "unproductive" for its reliance on a large labor force and its use of non-prefabricated strategies at a proper scale.

Despite its widespread acceptance within the global construction community, PPVC remains in its infancy. Considerable research has been conducted on off-site construction (Johnsson and Meiling 2009; Dong et al. 2015), but few studies have explored PPVC; in fact, most previous

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research has simply compared precast and cast-in situ concrete buildings (Omar et al. 2014) without analyzing their different volumetric systems. This paper systematically assesses the two most common types of PPVC—namely, concrete and steel—by examining their emissions and costs related to prefabrication and modular construction while also identifying gaps in the existing knowledge. Blismas and Wakefield (2009) have shown that inadequate knowledge of off-site manufacturing is the most influential barrier in construction. Indeed, there is limited research on the environmental impacts of modular housing, and the research that has been done—such as that of Paya-Marin et al. (2013)—focuses only on wooden modular buildings. Recent government recommendations point to a sophisticated PPVC method without the limitations of conventional methods. This PPVC method will be assessed in this study. Modular structures are more environmentally friendly and generate fewer emissions than conventional ones (Quale et al. 2012).

Several advantages of modular building construction have been reported. For example, Kamali et al. (2018) carried out an LCA study that showed that modular buildings have desirable life cycle performance. Rahman and Sobuz (2018) found that total construction time was reduced by 75% with the use of PPVC compared to the conventional industrial panel system (IPS). In a study on the financial barriers to off-site construction, Pan and Sidwell (2011) showed that PPVC offers more tangible cost savings than traditional construction strategies by reducing on-site manpower and equipment requirements. BCA S (2009) pointed out that PPVC can reduce manpower costs by up to 40% compared to when constructing precast concrete walls. Su and Zhang (2016) assessed the life cycles of three steel residential buildings in China and found that the building envelope contributed the highest embodied carbon emissions (50–55%), while on-site construction accounted for only 3–4%.

In the PPVC building industry, prefabricated modules are installed in a factory—complete with mechanical, electrical, and plumbing fittings (MEP) (Mao et al. 2016). This paper will explore the PPVC building process in full, both for concrete and steel structures. Although PPVC has become well-known in Malaysia and Singapore over the past 2 years, other countries in Asia—like Thailand and Hong Kong—have been reluctant to embrace this technique due to its limitation of characterization. Nonetheless, PPVC offers tangible cost savings due to reduced on-site manpower and equipment requirements compared to traditional construction methods (Bernstein et al. 2011). PPVC also expedites the construction process more effectively than conventional IPS. However, PPVC has its own challenges as well, including transportation and hoisting issues. Rigorous assessments of the PPVC module are necessary to fully understand the impact of these issues (Rahman and Sobuz 2018).

On-site building construction is not always effective and may generate unnecessary carbon emissions (Wu et al. 2013); modular construction is seen as a more environmentally-friendly option. As demand for construction and construction materials increases worldwide, concrete (which is the most common material in modern construction) is continually used for a wide range of purposes and in many adverse conditions. Modular construction refers to the fabrication of a structural unit in a manufacturing plant away from the job site. Precast construction plays a vital role in the contemporary construction industry. However, the utilization of PPVC has not been properly assessed. Steel PPVC consists of steel framing that is infilled with wall, floor, and ceiling boards. This system is lightweight and suitable for high-rise buildings. Several studies have been performed on these structures. For instance, Stephan et al. (2013) carried out a life cycle assessment (LCA) on a single-family passive house and found that embodied energy accounted for 77% of the building's total energy consumption over its 100-year life span. This indicates that embodied energy is vital to controlling emissions generated by the construction sector. Some studies recommend the use of specific materials or structures (Balasbaneh et al. 2019), while others content that modular construction (Shi et al. 2012) aligns with the needs or resources of a country.

Mao et al. (2013) assessed the greenhouse gas (GHG) emissions of off-site prefabrication in comparison to those of conventional construction. The assessment showed that prefabrication reduces GHG emissions and that prefabricated concrete constructions produce higher emissions than prefabricated steel constructions. Xing et al. (2008) also compared LCAs for steel and concrete office buildings and determined that their CO_2 emissions were 41,434 kg and 36,065 kg, respectively. Zhong and Wu (2015) assessed steel and concrete projects in Singapore and suggested that economic and environmental performance should be considered when selecting materials, with concrete exhibiting a higher cost than steel. However, opinions remain varied on the extent to which LCA reductions can be achieved through prefabrication. Caruso et al. (2018) carried out an LCA-based comparison of the environmental impact of building materials and found that concrete structures had higher carbon emissions than steel structures. In contrast, Alshamrani (2015) reported that concrete buildings have a lower environmental impact.

Most studies have focused on steel structures, while only a small fraction have examined reinforced concrete structures or compared the two (Paya-Zaforteza et al. 2009). Teng et al. (2018) assessed the carbon emissions of prefabrication and found that, on average, 15.6% more embodied carbon was produced during prefabrication than in their traditional base cases. Although some studies (e.g., Peyroteo et al. 2007) have shown that steel buildings emit more carbon than concrete buildings, other research (e.g., Zhang et al. 2007) suggests the opposite. This inconsistency makes it difficult to compare reported carbon emissions (Pan and Sidwell 2011).

A holistic view of sustainability is necessary to strike a balance between the environmental and cost-related aspects of construction. One of the main considerations of any successful construction project is cost management. Sim (2007) performed an economic assessment of concrete and steel in Singapore and found that public housing projects that used steel instead of concrete to construct their lift shafts achieved an overall cost savings of 20%. Other studies used integrated LCA and LCC analyses across full life cycles in traditional construction (Islam et al. 2015). Although two recent North American studies have reported LCAs of residential building wall assemblies, they did not evaluate the LCCs of the designs (Kahhat et al. 2009). A study on the cost of building in Malaysia (Akasah et al. 2011) showed that most construction projects were initiated without the implementation of a proper LCC assessment, likely due to their commitment and policy.

Half of the total raw materials extracted from the planet are used in construction, and more than half of the planet's waste is produced by the construction sector (Mourão and Pedro 2007). Thus, sustainable construction—as a subset of sustainable development—can have significant impacts on the environment and the sector's costs. The extent of these impacts is not yet known for either type of volumetric construction. The literature on residential buildings has thus far focused predominantly on either the LCC or the LCA of prefabricated houses or on the life cycle stages of building assemblage style. This research goes a step further by comparing steel prefabrication with concrete prefabrication and assessing variables related to the environment and cost. In general, reference materials on concrete and steel PPVC in the Malaysian construction industry are lacking, largely due to construction challenges and external factors in the adoption of new construction technology. Therefore, builders still utilize conventional building strategies despite uncertainties about the most efficient method. Numerous studies have compared conventional construction with different prefabrication methods and materials; however, to the best of our knowledge, no study has conducted a complete LCA or LCC on PPVC. As such, this study contributes to the body of knowledge about off-site PPVC.

Methodology

Sustainable construction focuses on environmental and economic sustainability. Building for environmental and economic sustainability (BEES) uses environmental and economic sustainability as indicators in evaluation techniques (Zhong and Wu 2015). Figure 1 shows the system boundaries corresponding to the life cycle modules of A1, A2, A3, A4, A5, B2, C1, C2, D1, D3, and D4 of the EN15804 and EN15978 standards (CEN 2011). According to EN15978, the system boundary of the analysis comprises the material production and construction stage, the use stage (maintenance), the end-of-life stage, and, finally, a stage allocated for benefits and loads due to the recycling and reuse of materials.

LCA has been used to assess environmental emissions in many studies (Ortiz et al. 2009). LCA is defined as the "compilation and evaluation of the inputs, outputs and potential environmental impacts of a product system throughout its life cycle" (Henkel 2005). Previous studies have examined building LCA in different life cycles, from raw material extraction to disposal (Suzuki and Oka 1998). Embodied carbon, despite its various definitions, can generally be classified into two groups: (1) carbon emissions generated during the cradle-to-gate stage and (2) carbon emissions generated during the cradle-to-end-of-construction stage (Blengini 2009).

Life cycle assessment and databases

LCA quantifies the environmental performance of a product by considering its complete life cycle, from raw material production through to disposal. Any LCA study needs a defined scope. The scope of this study is cradle-to-grave, meaning that it covers all stages of construction—namely, raw material extraction, construction, transportation, erection, maintenance, and various other stages leading to the product's end of life. The model selected for this study is a residential single-family house located in Johor Bahru. The building model was assessed against the five most applicable environmental emission categories using SimaPro 8 software.

Life cycle inventory and life cycle impact assessment method

Life cycle inventory (LCI) is an analytical step defined by ISO 14040. It involves the collection and completion of inputs and outputs, or flow of life cycle phases, for a product throughout its development (Ekvall and Weidema 2004). By adjusting ecoinvent data to reflect Malaysia's circumstances, we hoped to generate an accurate domestic result that would consider the existing local power electricity mix information. To localize the results, we incorporated the raw materials from the LCI stage—including cement production and fuel for burning in manufacturing—into the Malaysia Life Cycle Inventory Database (MYLCID). By doing this, we obtained the most significant result for the Malaysian context. The LCI database was applied at all stages from the "cradle" onward (i.e., manufacturing and transportation) through to the disposal stage. This was essential, given that 95% of Malaysia's electricity is generated from fossil fuels. For our LCA study to be valid, the input and output data had to be defined per the ISO-14040 standard (Reston 2006). The principles and framework of this standard were used

Fig. 1 A modular building's life cycle stages from EN15804 and EN15978

Product stage			Construction stage		Use stage							End of life				Benefit and loads			
A1	A2	A3	A4	A5	B1	B2	B3	B4	B5	B6	B7	C1	C2	C3	C4	D1	D2	D3	D4
Raw Material Extraction	Transport	Manufacturing in Factory	Transport to Site	Installation and Erected Process	Use	Maintenance	Repair	Replacement	Refurbishment	Operation Energy Use	Operation Water Use	Demolition	Transport	Waste Processing	Disposal	Reuse	Recovery	Recycling	Landfill
X	X	X	X	X		X						X	X			X		X	X

as a reference in alternative product and process comparisons. We selected 1 m^2 of a wall component over 50 years as the functional unit for this research based on prior studies (Balasbaneh et al. 2018; Sameer et al. 2019).

A life cycle impact assessment (LCIA) quantifies the overall impact of resource consumption and environmental emissions at different stages of a product's life cycle (Sivakugan et al. 2016). Based on the study by Yang et al. (2017), we selected 2002+ as the impact assessment methodology for this research. For a simplified LCA, the parameters describing environmental outputs, as defined by BS EN 15978 (European Committee for Standardization 2011), are as follows: GHG kg CO_2eq, non-renewable energy–MJ primary, respiratory inorganics–kg PM2.5eq, land occupation, mineral extraction–MJ surplus. Electricity and fossil fuel (such as coal and oil) consumption during the production and processing stages, both for the steel and concrete mixers, resulted in CO_2 emissions. Thus, the associated global warming potential (GWP) increased. CO_2 equivalent (in kg) is the standard unit for measuring GWP. Factors are expressed as GWP in kg carbon dioxide/kg emission for a time horizon of 100 years (Pachauri 2014).

There is no significant difference in the operational energies of steel and concrete buildings (Ngo et al. 2009). Earlier research (e.g., Balasbaneh and Bin Marsono 2017b) assumed identical cooling requirements for all scenarios assessed, implying that the environmental impact of cooling does not influence the assessment. By that logic, this factor is not influenced by the type of construction technique used. Therefore, it has been excluded from this study. A comparative analysis of wall elements showed equivalent heat transfer coefficients of U¼ 0.10 W/m^{2}K. The LCA interpretation was used to evaluate the findings of either the inventory analysis, the impact assessment, or both, in relation to the defined goals and scope; this, in turn, was used to reach the required conclusions and recommendations (ISO 14040, 2006). A sensitivity analysis was carried out, allowing for several-percent variations in input and output in relation to changes in key processes.

Economic assessment, life cycle cost

In the current case studies, LCC was performed on an Excel spreadsheet using 50 years of cost data from building systems. Estimations were based on information provided in the standard Construction Cost Handbook (Malaysia 2017) and by the National Construction Cost Centre (CIDB Malaysia Official Portal). Applying the cost perspective in the early design stages of construction gives decision-makers a better understanding of costs upfront and allows them to make the best choice among different materials. The building sector relies on long-term investments in which cost and environmental impact play central roles (Cole and Sterner 2000).

Five major LCC elements were assessed for each alternative floor system in this study: material, wages, transportation, maintenance, and end-of-life. The construction cost data used were pulled from the archives of the official portal of the Department of Statistics Malaysia and the Malaysia official portal (CIDB). The base year for analysis was 2018 (i.e., the year the study was conducted). Future cost and discounted present value were calculated using Equations 1 and 2, respectively, according to Islam et al. (2015):

$$\mathrm{FC} = \mathrm{PV} \times (1 + f)^{\mathrm{n}} \tag{1}$$

$$\mathrm{DPV} = \mathrm{FC} \div (1 + d)^{\mathrm{n}} \tag{2}$$

where FC = future cost, PV = present value, f = inflation rate, n = number of years, DPV = discounted present value, and d = discount rate.

Following an earlier study on the cost of building materials by Balasbaneh and Bin Marsono (2017a)' the cost assessment was based on an inflation rate of 3.4% (Malaysia Inflation

Rate data), a discount rate of 4.5% (Malaysia Discount Rate), an electricity cost of 38.53 Sen/kWh (Malaysiakini data), and a lorry transportation cost of 0.31 MYR for each ton per kilometer. Based on the exchange rate at the time (December 2018), 1 Malaysian ringgit was considered equal to 0.25 United States dollars.

Case study

The first structure was a concrete PPVC consisting of prefabricated free-standing volumetric modules—complete with finishes for walls, floors, ceilings, and prefabricated bathroom units (PBUs)—that required on-site assembly (Kyjaková and Bašková 2014). PPVC is a process by which modules complete with finishes (nearly 85–90%) are manufactured in off-site factories and then transported to construction sites for installation. Prefabricated bathroom units (PBU) come with finishes such as copper piping, partial tiling, window frames, and waterproofing. The second structure was made of steel, with prefinished walls, floors, and ceilings—as well as wiring and plumbing—that was simply transferred to the site for installation. The main limitation of precast concrete construction is the high cost of transporting precast members from the yard to the construction site (Asamoah et al. 2016). Figure 2 shows diagrams of the structures used in the case study.

The following primary data (Table 1) was collected from an in-field inquiry (2019). The data accounts for the consumption of raw materials (clay, water, and sand); the consumption of electricity and fuels (biomass and gas-oil) in clay mining and tile production; and fuel consumption in the transportation of raw materials, the transportation of fuels to the firm, and final product delivery.

The modules consist of a steel frame with walls and ceilings of corrugated steel sheet infill and floorboards on steel joists; this system is very robust and lightweight. Like the foundation, the doors and windows can be configured in the same ways, even when buildings are constructed differently. Therefore, the main differences in construction components have to do with the wall and roof elements, which we address with more specificity in this research. The various phases of inventory analysis that translate into data collection for PPVC structures are explained below.

Production phase In this phase, all materials used in the construction of the building were taken into consideration, including electrical and plumbing systems. The life cycle stage of the material production process is considered in A1–A3. Concrete production included the characterization of mixing water (110 kg/m^3), cement (340 kg/m3), and sand (710 kg/m3) (A1); transporting the material to the factory (A2); and manufacturing the module in the factory (A3). The same process (A1–A3) was followed for steel production. The electricity used for cutting the steel was 120 kWh/m^3. In this study, 2300 kg/m^3 and 7850 kg/m^3 were selected as the densities of reinforced concrete (ρc) and rebar (ρr), respectively. The impact of transportation from the manufacturing plant to the building site (A4) was calculated based on an average distance of 50 km for massive materials (Asdrubali et al. 2013). A laden weight of 80 tons was considered. Also, a standard boarding of 10 mm outside the fibrocement with an inside gypsum board of 15 mm was used. Insulation inserted into the cavity. The finishes gave the building an outward aesthetic similar to that of a conventional house. The sizing and arrangement of the cranes were determined by the total lift weight of the module and the reach of the crane. The water system was assumed to be direct; storage tank capacity was not assessed, as most buildings in Malaysia do not use this system. PVC pipe with a 1-inch diameter was used for plumbing. Among the greatest challenges was waste generated during production. The rate of waste generation was assumed to be 3.5% and 4% for concrete and steel PPVC structures, respectively, based on a study by Hong et al. (2016). The electrical consumption of the assembly phase was assumed to be

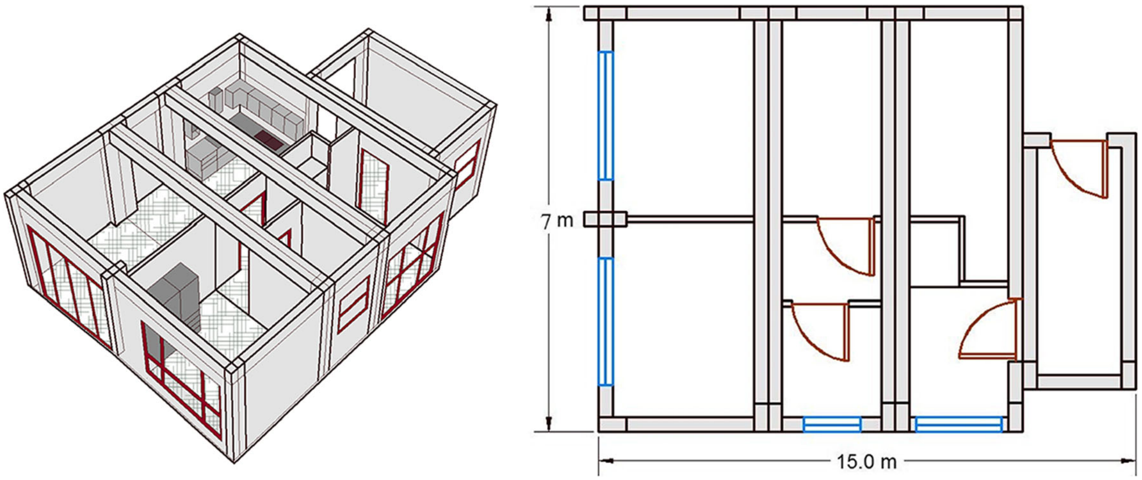


Fig. 2 Architectural scheme of residential building construction

Table 1 Characterization of construction materials for the two structures in the case study

Building scheme	Material	Unit	Thickness	Weight per kg/M^2	Transport to factory	Total weight/kg
Concrete PPVC	Precast concrete	mm	200	291	Lorry 32 ton, 30 km	52380
	Reinforcing steel	Diameter/mm	18	26.4	Lorry 3.5 ton, 7 km	1964.8
	Tile floor	mm	5	6.4	Lorry 16 ton, 25 km	675
	Wiring	Diameter/mm	4.6	0.3	Passenger car, 30 km	7.9
	Polyethylene pipe	Diameter/mm	110	3.2	Lorry 3.5 ton, 7 km	64
	Mineral wool insulation	MM	21	2.3	Lorry 16 ton, 25 km	190
Steel PPVC	Steel stud	MM	200	4.9	Lorry 16 ton, 25 km	4650
	Tile floor	MM	20	6.4	Lorry 16 ton, 25 km	675
	Wiring	Diameter/mm	4.6	0.3	Passenger car, 30 km	7.9
	Polyethylene pipe	Diameter/mm	110	3.2	Lorry 3.5 ton, 7 km	64
	Mineral wool insulation	MM	21	2.3	Lorry 16 ton, 25 km	190

2% of the embodied energy of all building materials (Beccali et al. 2013). The type of hoisting machinery for A5 (considering the use of a mobile crane) is based on the following characterization: crane capacity of 700 tons, lifting capacity of 25–40 tons, and equipment height of 40 m.

Use phase Based on a report by the National Association of Home Builders (NAHB), as suggested by Iyer-Raniga and Wong (2012), regular maintenance activities (B2) include painting wall surfaces, either once every 10 years or four times over a 50-year lifetime.

End of life Assumptions for the end-of-life phase relate to the building demolition (C1) process (i.e., the energy required end emissions released), transportation (C2) to the waste treatment center (50 km), and treatment at the sorting plant (machines for handling, emissions from handling, and electricity consumption). We also considered the impact of landfill (D4) disposal (residual inert masses) and the benefits of recycling and reuse operations. After treatment, all sorted materials were either landfilled, reused, or recycled. Each case study had its own end-of-life scenarios after a lifespan of 50 years. It was assumed that the concrete PPVC would be sent to and left at the landfill based on standard Malaysian demolition statistics—most concrete ends up in landfills, and only 20% of steel bar components are recycled. Conversely, it is assumed that 70% of steel PPVC is recycled as scrap material to produce new steel, of which only 20% is reused (D1 and D3). The remaining components, including insulation, are sent to the landfill, according to Hong et al. (2016). Conventional mechanical demolition was selected for each structure and was to be carried out using a single excavator with a hydraulic hammer (for foundation demolition) and jaw (for structure demolition and inert crashing), a one-wheel loader, and lorries with a 28 m^3 capacity to remove demolition waste from the site.

Additional assumptions and limitations of this research are as follows:

- The cost of designing, setting up, and fabricating molding at the factory was not considered for the LCC assessment outside of its environmental impact. It was assumed that molding would be used without limitations. Such materials were beyond the scope of this study and were not considered in the economic valuation of the finished building.
- Lifting the PPVC modules required a high-capacity crane tower weighing approximately 30 tons.
- The PPVC systems considered for this study were limited to home residences, student hostels, workers' dormitories, and healthcare projects.
- The costs of site foundation and preparation were not considered, as they were assumed to be similar for both strategies.
- The size of a single module was limited to the dimensions permitted for transportation on a public road without special accommodations (e.g., police escort). Height was considered when routes involved overhead bridges.
- Neither the testing of the new designs nor the testing/optimization of the installation process was incorporated into the assessment due to their ambiguous effect on cost.

Results and discussion

PPVC-prefabricated structures offer one main advantage over modular structures: namely, their fabrication and installation are complete and comprehensive. In a prefabricated structure, all features—such as electrical wiring, plumbing, and wall coating—are completed in the factory, as shown in Fig. 3. In modular structures, meanwhile, the cube assembly structure is fabricated in the factory, but the remaining elements—such as the settling of the building with a crane—are performed on-site. When operations like wiring are conducted on-site, affect the outcomes (e.g., higher wages for workers). Therefore, this research focuses on PPVC.

The use of prefabrication methods in construction has been promoted to improve productivity in a traditionally manpower-intensive industry. The key to PPVC is volumetric construction, which involves manufacturing and assembling building components in a factory and subsequently transferring them to a building site. This research proposes PPVC systems using two different primary construction materials. The flowchart in Fig. 3 shows the steps involved in creating the module concrete structure—namely, production and construction, maintenance, and end-of-life processes. The first stage is cement production, which requires factory equipment that consumes electricity. This stage also involves diesel consumption for transportation and water consumption. In this study, both the carbon emissions and the costs of this consumption are assessed. The process continues with concrete manufacturing and wastewater treatment. The second stage involves steel production, which requires the processing of raw materials in the mill and which consumes electricity and water. The steel is then transferred to the factory, where diesel is consumed. Consequently, all the steel and concrete materials provided for the fabrication of reinforcement case in the PPVC factory are ready for assembly off-site.

The next stage is the application of interior finishes, including the MEP installation and other cast-in features, such as plumbing, wiring, tiles, and lightweight panels to separate the interior space. The difference between PPVC and other types of construction is that PPVC uses all these materials in the factory rather than on-site; therefore, the diesel consumption related to transportation must be calculated for different distances. The step that follows entails the installation and attachment of windows and doors. The PPVC unit can then be transported to the site. Setting up the building involves demolding the modules and hoisting them up with a crane, after which the components are assembled. All processes up to this stage comprise the "construction" phase. The "use" phase includes the maintenance of the walls, roof, and other building components. The final stage in the building's lifespan is demolition, during which the concrete materials are sent to a landfill (Balasbaneh et al. 2018).

Figure 4 depicts the sequence by which a steel PPVC module is fabricated. The arrows correspond to the flow of materials and the sequence of the steps. The first stage relates to the production of raw steel in a mill, which consumes raw materials, electricity, and energy. A steel stud is cut and bent in the PPVC factory to obtain appropriate shapes for the wall and roof components. In the next step, machinery is used to assemble the shapes into rooms or units, and to install other components for the wall panels, such as wool insulation and plasterboard. The cost of transporting these materials to the PPVC factory using diesel is considered.

In the next step, other components—such as pipes, wiring, and tiles—are integrated into the assembled unit; the cutting, drilling, and tiling processes consume electricity. At this point,

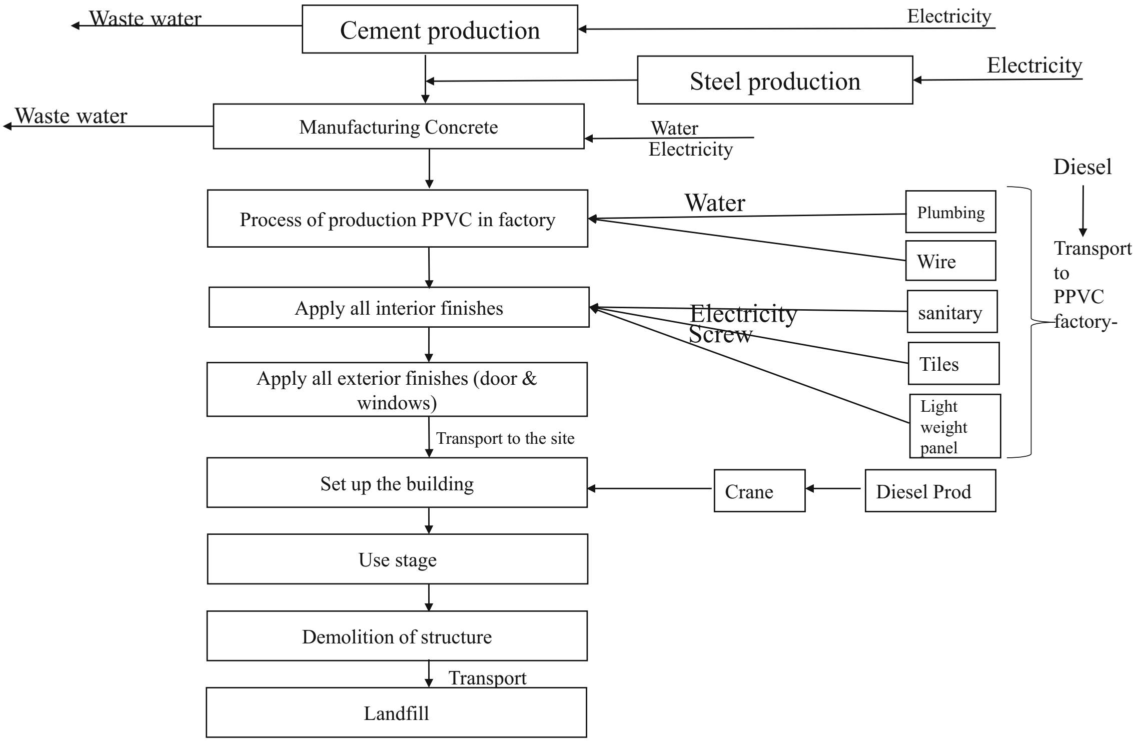


Fig. 3 System boundaries of concrete PPVC

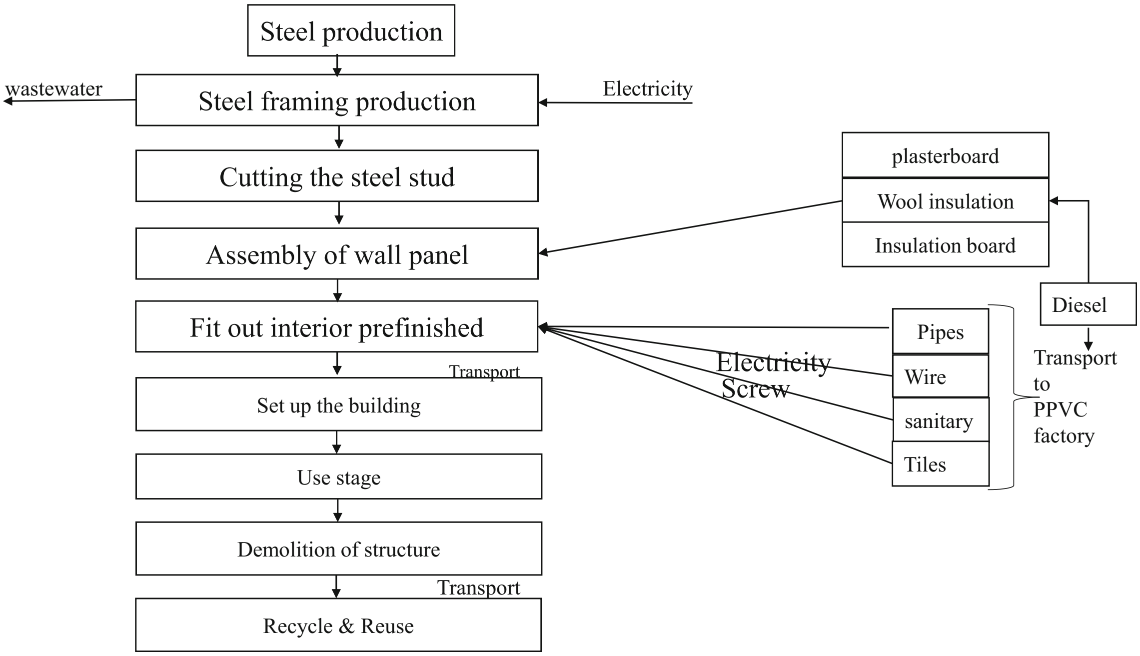


Fig. 4 System boundaries of steel PPVC

the unit is ready to be transported to the site by lorry. Once the unit has been set up using a crane, the "construction" stage is complete. Other stages account for maintenance and repair, as described earlier in the case study. The last step of the building lifespan is demolition, which varies according to the structure and scenario. Demolition also differs significantly between steel structures (S-PPVC) and concrete structures (C-PPVC), as steel is often recycled. The end-of-life stage for a steel structure typically involves recycling (60%) and landfilling (40%).

Environmental impact

The results reveal the different emissions for each material and each stage of the process (production and construction, maintenance, and end-of-life) for the two different scenarios; the full life cycle result is shown in Table 2. The method being considered is known as volumetric construction. This method was recently applied and promoted by the Malaysian government in the construction sector. We have assessed the construction process and the energy consumption during manufacturing for two buildings made with different materials. This study compared the buildings based on their environmental emissions related to electricity usage and the amount of waste each generated to determine which material had a lesser impact. Emissions have been determined at each stage.

The electricity usage for steel produces higher emissions for all environmental criteria (Table 2). In fact, steel uses almost three times more electricity than concrete for GHG; though, the waste from the production of C-PPVC is almost two times greater than that of S-PPVC in the same category. Likewise, regarding non-renewable energy, respiratory inorganics, land occupation, and mineral extraction, the emissions related to electricity are slightly higher for steel than for concrete. Meanwhile, more waste emissions are generated for all categories during concrete production than during steel production.

Figure 5 shows the emissions for the five different environmental categories of steel and concrete PPVCs from cradle to grave. GHG emissions are the first environmental criterion for both construction materials. The results show that the steel structure (S-PPVC) produced more emissions (9623.13 kg CO_2eq) than the concrete building (C-PPVC) (8264.03 kg CO_2eq). As also shown in Fig. 5, the most significant environmental impact of S-PPVC comes from steel stud production, while the most significant impact of C-PPVC comes from concrete production. Embodied emissions at the end of the life cycle account for the environmental impacts associated with the building's demolition, which includes recycling and/or landfilling, depending on the type of material used.

CO_2 emissions and net emission benefits (negative values) vary for the different materials during demolition (Fig. 6). The benefits gained from recycling are more significant for the steel building than for the concrete building, as confirmed by the lower high primary steel emission generated during the production stage. S-PPVC contributed 76%, 10%, and −14% of its total GHG emissions during the production and construction, maintenance, and end-of-life stages, respectively. Meanwhile, C-PPVC's contributions were 81%, 85%, and 11%. The demolition process for concrete has an insignificant impact on the building's life cycle (Fig. 6), indicating that the

Table 2 Environmental emissions for the two modular constructions (concrete and steel)

Materials	Greenhouse gas kg CO_2eq		Non-renewable energy, MJ primary		Respiratory inorganics, kg PM2.5eq		Land occupation, m^2 org.arable		Mineral extraction, MJ surplus	
	S-PPVC	C-PPVC	S-PPVC	C-PPVC	S-PPVC	C-PPVC	S-PPVC	C-PPVC	S-PPVC	C-PPVC
Steel	8500	1170	54000	3630	15.1	0.114	165.3	0.055	4340	3.63
Concrete	-	4860	-	52500	-	22.55	-	191.2	-	5164
Tile	398	398	7380	7380	1.6	1.6	3.16	3.16	1.75	1.75
Coating	-	28.9	-	167	-	0.0118	-	0.55	-	0.266
Pipe	80.8	80.8	1650	1650	0.06	0.057	-	-	0.103	0.103
Wire	14.6	14.6	231	231	0.322	0.322	0.45	0.47	401	401
Wool	206	206	3620	3620	0.422	0.425	2.05	2.05	10.6	10.6
Electricity	550	206	1860	1760	0.398	0.298	0.34	0.144	0.99	0.7
Transport	6.03	6.03	252	254	0.0231	0.0231	1.38	1.38	0.299	0.299
Crane	45.7	38.7	103	193	0.043	0.0128	0.7	0.7	5.92	5.92
Waste	76	110	330	520	0.07	0.14	4.9	5.99	2.1	3.09
Maintenance	45	210	4188	1100	0.52	0.11	8.2	6.3	184	6.27
Recycle	− 250	− 25	− 26800	− 2100	− 3	− 0.005	− 15	− 0.5	− 1192	− 110
Landfill	201	960	2791	4888	0.3	0.34	4	14	128.8	21.1
Reuse	− 250	-	− 3350	-	− 0.8	-	− 7.9	-	− 162	-

end-of-life recovery potential for steel structures is crucial. Considering the S-PPVC, recycling contributes a 15% benefit (− 15%) at the building's end-of-life stage; for C-PPVC, the recycling of steel bars contributes a 1% benefit (− 1%) at the building's end-of-life stage.

In contrast to the GHG assessment, the non-renewable energy assessment showed steel having lower emissions (46,245 MJ) than concrete (77,693 MJ). Although the quantity of emissions in this case is much different than that of C-PPVC, it is almost two times greater than that of S-PPVC. The emissions generated from the production stage are slightly greater for steel than for concrete. However, end-of-life circumstances can profoundly decrease the total emissions produced by a structure. S-PPVC's emissions derived from the production and construction, maintenance, and end-of-life stages were 69%, 4%, and − 27%, respectively. Meanwhile, for C-PPVC, these values were 92%, 2%, and 6%. The emissions related to electricity usage in the production stage were 1860 MJ for steel and 1760 MJ for concrete. However, the waste materials generated were higher for concrete than for steel.

In respiratory inorganics (i.e., the third environmental criterion), steel released fewer emissions (15.0581 kg PM2.5eq) than concrete (26.0037 kg PM2.5eq). Despite the massive impact of steel production on the environment, the end-of-life reuse (− 0.8 kg PM2.5eq) and recycling (− 3 kg PM2.5eq) potential lower the total emissions. Respiratory inorganics have been confirmed in the results of other categories; specifically, emissions for S-PPVC were 2.4 times higher than for C-PPVC. During the construction stage, emissions of 18.0381 m^2 org.arable and 25.5537 m^2 org.arable for S-PPVC and C-PPVC, respectively, were observed. Throughout its life cycle, S-PPVC's emissions from the production and construction, maintenance, and end-of-life stages were 82%, 2%, and − 16%, respectively. Meanwhile, C-PPVC's contributions were 96%, 1%, and 3%. These values highlight that reusability, recycling, and other end-of-life factors play a significant role in reducing emissions. However, difficulties in predicting future impacts of demolition contribute to the ongoing uncertainty about which method is best in terms of waste management.

For the land occupation category, higher emissions were reported for C-PPVC than for S-PPVC (167.58 m^2 org.arable vs. 225.999 m^2 org.arable). In the production and construction, maintenance, and end-of-life stages, S-PPVC exhibited contributions of 87%, 4%, and − 9%, respectively, while C-PPVC exhibited contributions of 91%, 3%, and 6%.

The final environmental category, mineral extraction, showed that S-PPVC caused lower emissions (3721 MJ) than C-PPVC (5618.7 MJ surplus). However, emissions produced in the production stage were higher for steel than for concrete (4340 MJ surplus vs. 4167 MJ surplus). The end-of-life scenario, which incorporates steel recycling, was associated with a net emission benefit (presented as a negative value in the figure) of 1192 MJ surplus, thus resulting in a lower total emission for S-PPVC. The end-of-life recovery potential of steel reduces its total emissions. Based on the results in all categories (except climate change), the S-PPVC structure appears to have a smaller environmental impact.

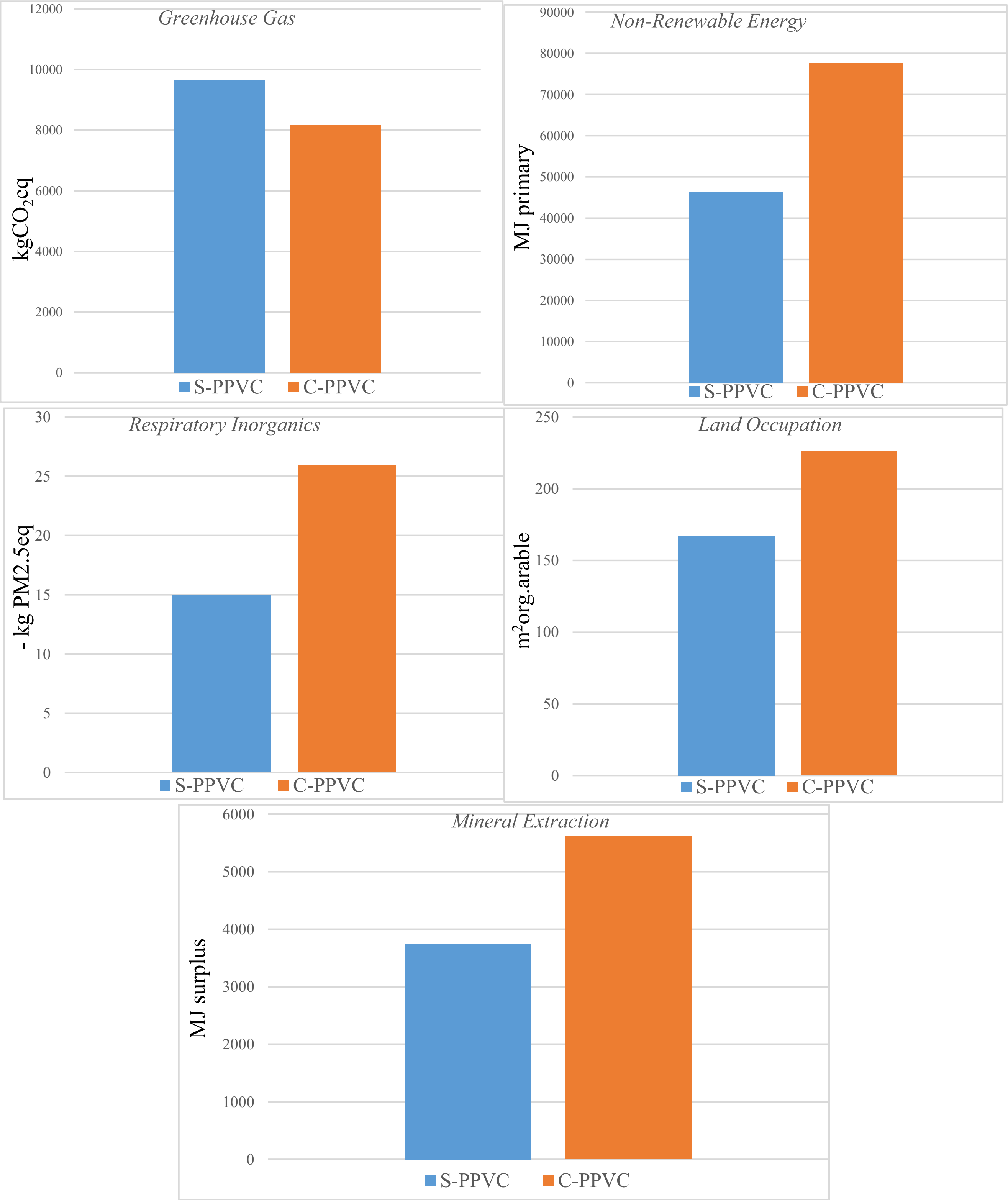


Fig. 5 Comparison of emissions between the two PPVC structures (i.e., steel (S-PPVC) and concrete (C-PPVC))

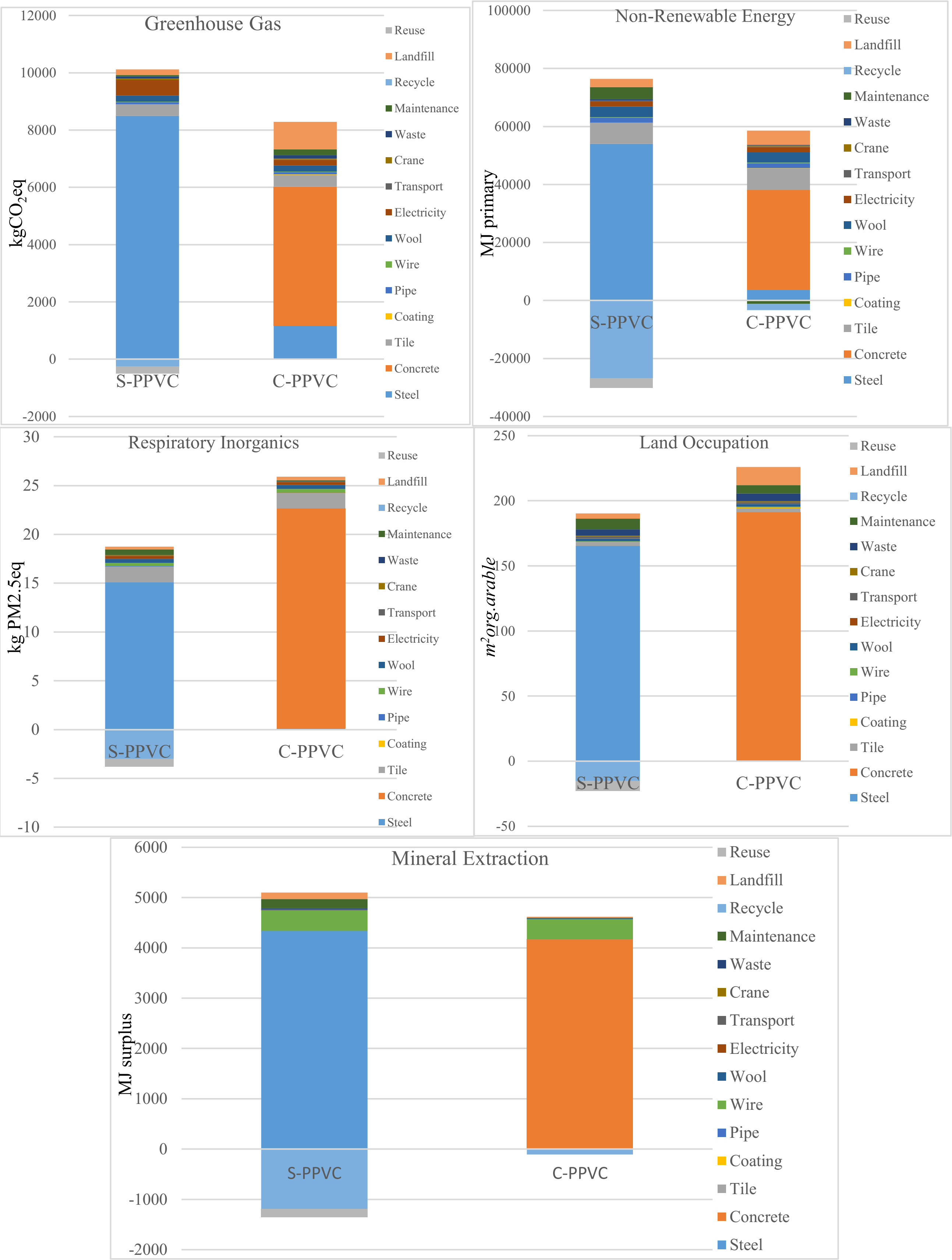


Fig. 6 Detailed comparison of the two PPVC structures (i.e., steel (S-PPVC) and concrete (C-PPVC))

Life cycle cost assessment

When explaining the preferred choice of structure to a house builder, the environmental argument must be supported by cost-related issues. LCC can be used for comparison when more than one design is considered. Traditionally, research on optimum LCC accounts for only the initial cost of the materials; however, a long lifespan can have both environmental implications and long-term financial impacts. In particular, different demolition scenarios can impact the overall project cost. Table 3 presents the costs of all activities related to materials and processes in the manufacturing stage, along with their related percentages.

The highest costs incurred during the construction phase are related to processes that take place in the factory, which excludes the cost of diesel for crane operations (assessed on-site). The highest individual costs for S-PPVC are related to hot rolling stainless steel (78%) and the insulation layer (9%). The C-PPVC structure has different valuations for its materials, including 73%, 8%, and 6% for concrete, steel bars, and insulation, respectively. Labor contributes 6% and 7% of the cost for S-PPVC and C-PPVC, respectively.

Figure 7 shows the cost contributions of each life cycle stage. The results show that the cost of the full construction stage of S-PPVC (226160 MYR) is higher than that of C-PPVC (204,750 MYR), which is primarily due to the cost of steel.

Concrete has slightly higher maintenance costs than steel (26,230 MYR vs. 25,420 MYR). Expenditures at the end-of-life stage differ due to the recycling and reuse of materials. The cost of transporting materials to a landfill is 3500 MYR for S-PPVC and 8400 MYR for C-PPVC. The cost of reusing S-PPVC positively impacts the building's final cost (− 32,500 MYR). Although the construction stage of an S-PPVC is higher (Fig. 8), C-PPVC has a higher overall cost than S-PPVC (222,580 MYR vs. 239,380 MYR).

Sensitivity analysis of key processes

LCA results can be influenced by various elements, including impact assessment methods, system boundaries, initial assumptions, and the quality of available data. Estimating a range of uncertainty is necessary to obtain reliable results and support decision-makers in their selection of different products (Beccali et al. 2013). Sensitivity analysis can provide insights into the influence that certain variables have on assessment results by changing the value of those variables.

In this section, the amount of electricity used by factory machinery is assessed with a 5% variation. Figure 9 shows the results of the sensitivity analysis conducted on the main contributors to electricity usage in the production stage in each environmental category. In the production process for S-PPVC, a 5% variation in the input and output data caused a change in the overall environmental impact. The changes were 19.2 kg CO_2eq for GHG, 62 MJ primary for non-renewable energy, 0.011 kg PM2.5eq for respiratory inorganics, 0.0136 m^2 org.arable for land occupation, and 0.033 MJ surplus for mineral extraction. Likewise, in the production process for C-PPVC, a 5% variation in the input and output data also initiated a change in the overall environmental impact. The changes were 7.1 kg CO_2eq for GHG, 70.4 MJ primary for non-renewable energy, 0.011 kg PM2.5eq for respiratory inorganics, 5.53 E-02 m^2 org.arable for land occupation, and 0.023 MJ surplus for mineral extraction.

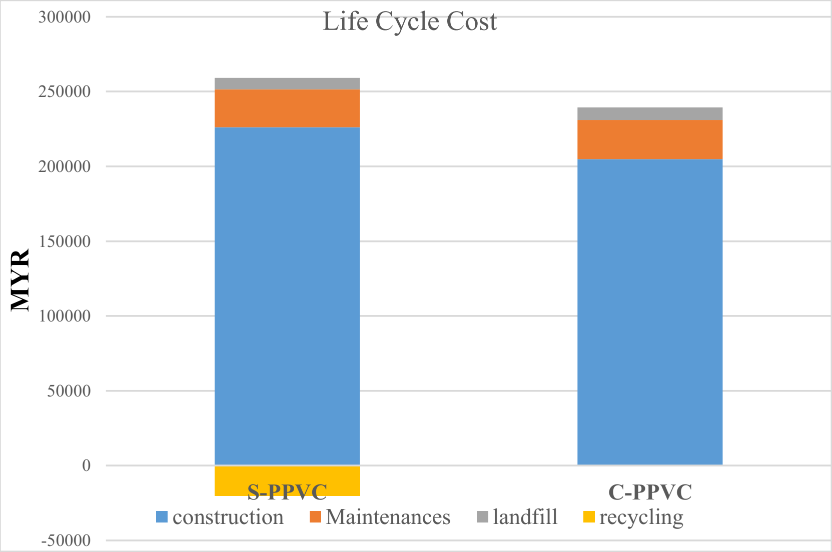
Discussion

An extensive review of the available literature indicates gaps in our understanding of the differences between the two modular PPVC structures regarding cost and environmental emissions. The goal of this study is, firstly, to assess the environmental and economic impacts of the two most common PPVC types—namely, concrete and steel—and, secondly, to assess the waste and electricity usage incurred during factory construction activities. The existing literature fails to draw the necessary comparisons between wastage, electricity usage, and even crane usage, considering that the production setting is the factory. The PPVC construction technologies and processes considered in this study differ from the conventional technologies and processes; their environmental emissions

Table 3 Cost of the construction and manufacturing stage, S-PPVC (steel modular) and C-PPVC (concrete module)

Material and process	S-PPVC (MYR)	% of total	C-PPVC (MYR)	% of total
Concrete	-		150250	73
Steelwork	125600	78	15600	8
Insulation	19680	9	12300	6
Wallboard	5200	2	5200	3
Electricity	3660	2	2980	1
Diesel	4100	3	4100	2
Water	220	0.2	120	0.2
Labor cost	14500	6	14200	7

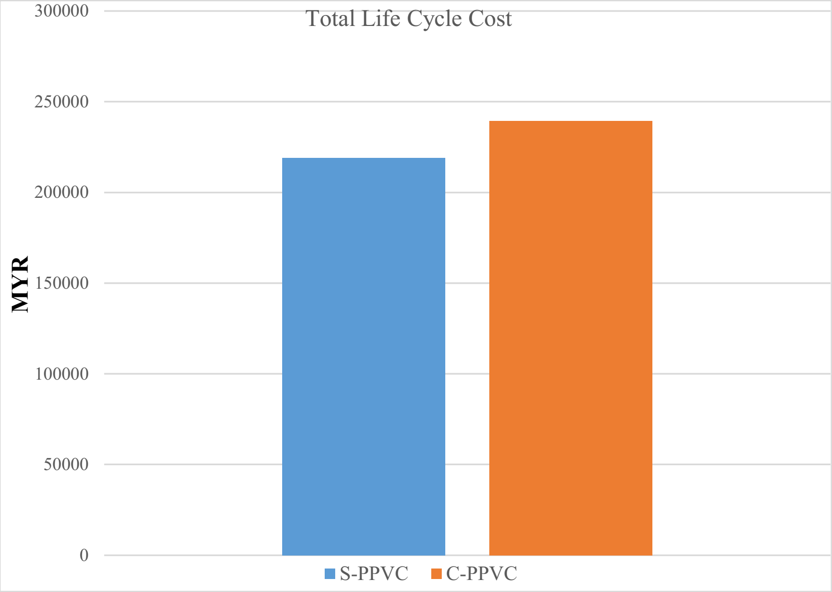
Fig. 7 Cost for S-PPVC (steel lightweight modular) and C-PPVC (concrete module)



and costs differ as well. This study identifies the boundaries of these volumetric structures, which include GHG, non-renewable energy, respiratory inorganics, land occupation and mineral extraction in the stages of manufacturing, transportation of building materials, construction waste, transportation of prefabricated components, equipment operation (electricity), maintenance, and demolition (landfilling, reuse, and recycling). This study also investigates the LCC of such volumetric systems by considering the construction, maintenance, and end-of-life phases. Ultimately, this research employed LCA to evaluate PPVC single residential buildings in Malaysia by utilizing the five midpoint impact category indicators of the Impact 2002 method.

Although many studies have compared modular and conventional constructions, very few have compared these structures' environmental impacts. The results of this research are supported by previous studies (Aye et al. 2012; Xing et al. 2008) that recognized steel prefabricate as having a higher GHG emission rate than concrete (CO_2kgeq). Studies on traditional (on-site) construction methods also confirm the findings of our study concerning environmental impacts. However, their percentages and quantities differ slightly because conventional construction consumes more energy than the construction of modular buildings. For example, Ngo et al. (2009) conducted an LCA of steel and concrete frames for commercial buildings and found that the steel-

Fig. 8 Total cost for S-PPVC (steel lightweight modular) and C-PPVC (concrete module)



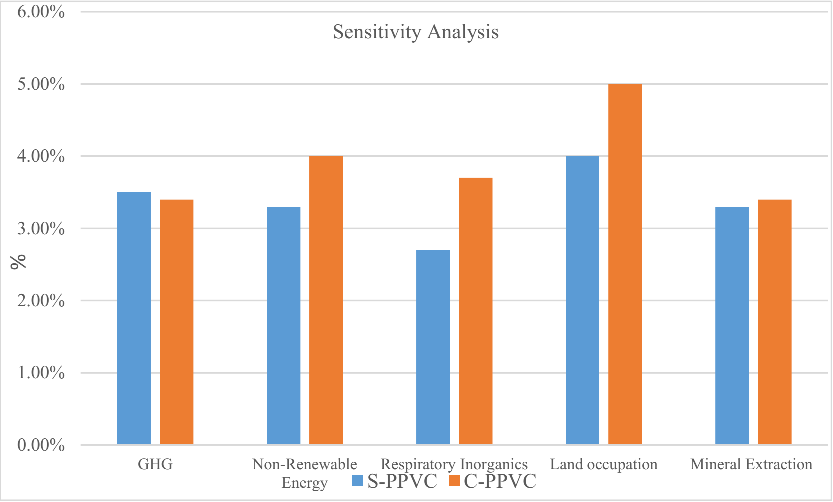


Fig. 9 Sensitivity analysis for environmental impacts. Contribution of electricity usage in the production stage

framed building produced 68% more GHG emissions than the concrete-framed one.

There is still a lack of research comparing the costs of concrete and steel PPVC. A study by Sim (2007) showed the cost of steel to be 20% lower than that of concrete. In our research, PPVC created a cost savings of 26.4%—likely related to the reduced waste associated with off-site construction. Liew (2007) also emphasized that steel is an excellent choice for decreasing overall building costs.

Although most studies support the findings of this research, some do not. This could be the result of research boundaries, transportation distances, or inflation in the costs of specific building materials. Tavares et al. (2019) assessed prefabricated modular structures and found that, contrary to our findings, steel had lower GHG emissions than concrete. However, their research was limited to "cradle-to-site," and maintenance and recycling/reuse were therefore not considered. Regarding waste minimization, the findings of previous research are consistent with the results of our study. For example, Tam (2018) assessed the two building materials and found that steel produces less waste than concrete.

Conclusion

This research offers several valuable insights. The main contributors to the environmental emission rate are the manufacturing and off-site construction of building systems, which account for approximately 69–80% of the overall construction process. The results indicate that steel structures' emissions exceed concrete structures' only in the GHG category, while concrete structures' emissions are higher in the remaining environmental categories. Electricity usage for equipment is greater for steel than for concrete in all categories; however, material wastage is greater for concrete than for steel in all categories. Non-renewable energy has a negative impact of approximately 27% on the total emissions for steel at the end-of-life stage. Additionally, recycling and reuse can decrease the total emissions from steel structures. The results show that electricity usage for production is higher for steel PPVC, whereas the volume of waste materials generated is higher for concrete PPVC in all categories. Concrete PPVC has higher emissions in most categories, while steel PPVC is the cheaper option. Using steel can minimize wastage, as well as the use of materials and electricity—ultimately contributing to a reduced environmental impact.

Meanwhile, the production and construction costs indicated by a survey suggest that steel has a higher economic cost than concrete. Considering different end-of-life scenarios—such as steel recycling—reveals that the concrete PPVC is, in fact, the more costly option by 26.4%. Thus, this study recommends that the differences in the social LCA of PPVC of conventional structures should be explored when conducting future research in other countries. Also, if possible, future work should combine such a study with an environmental and cost assessment. Based on the assumption that concrete is sent to the landfill at the end-of-life stage, future research should also evaluate the impact of concrete recycling on the overall value of concrete PPVC. This study also guides the selection of structural materials for modular PPVC construction based on economic and environmental considerations.

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