Comparing Different Concrete Construction Techniques: Modular versus Individual Panel System Methods

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Abstract

Buildings account for a substantial portion of environmental burdens. This study assesses modular concrete Prefabricated Prefinished Volumetric (PPVC) with concrete individual panel system (IPS) concrete construction method. This mode of construction is still nascent in many countries. Therefore, the environmental and economic impacts of PPVC concrete must be determined and compared to IPS concrete. The results show that material production is the most significant phase, as it contributes to 60% of total global warming potential (GWP) and 70% of the total cost. Furthermore, the results indicate that PPVC is associated with a 5% decrease in GWP emissions when compared to IPS; further, the cost of IPS for a single-family house is 1.3% higher than that of PPVC. The leading factor that influences the cost of PPVC is the design process, which is 2.5 times more expensive than IPS design. However, the assessment of multi-story buildings shows the opposite result. This regard shows that PPVC is 1% cheaper and 3% more environmentally friendly than IPS. Therefore, PPVC might be a more sustainable construction method than IPS.

Keywords: Concrete building; Prefabricated Prefinished Volumetric Construction (PPVC); Individual Panel System (IPS); Life cycle Cost; Life cycle Assessment;

1. Introduction

Increasing efforts have been directed toward climate change mitigation. The building sector has become one of the most popular targets for reducing global warming potential (GWP) emissions (Mamo Fufa et al. 2018). Zero-emission building (ZEB) from the Norwegian ZEB research center case studies show that building envelope (65%) and production and replacement of material (87%) are the main contributors to total GWP emissions (Wiik et al. 2018). Prefabrication or offsite manufacturing has been efficient in enhancing productivity in the construction sector (Khalfan et al. 2014). It offers significant benefits such as reduced project defects and improved health and safety (Pan, 2102). The first construction method is PPVC, i.e., a method in which freestanding volumetric modules complete with finishes for walls, floors, ceilings, and prefabricated bathroom units (PBU) are prefabricated and then erected on-site. The second concrete structure is IPS which entails walls, floors, and ceilings built in the factory and then transferred on-site for the erection. All other building materials such as plumbing, wiring, and sanitary are applied to the building on-site.

This study fills the gap by comparing prefabricated prefinished volumetric construction (PPVC) with individual panel system (IPS) (Vieira et al. 2016) in two categories, namely GWP and cost. Thus, housemakers will have a clear vision of choosing the proper construction method in the future. Despite the many advantages of PPVC (or modular volumetric system), many countries refuse to implement this system and still use the panel system in their construction. The fundamental reason for the refusal of house makers to use the module is the lack of understanding of offsite projects' benefits (Pasquire, 2002). A small number of researchers have recently addressed the subject of prefabricated construction (Tavares, 2019). Based on Rahman et al. (2018), IPS produces less productivity than PPVC and involves lots of on-site activities such as electrical services works and mechanical works.

Some studies refer to modular construction (Shi et al. 2012) based on country needs or resources. However, the literature review shows that most LCA studies for modular buildings have entailed on-site assembly while PPVC is accomplished in the factory. Kamali et al. (2017) claimed that a modular building provides environmental, economic, and social advantages; therefore, it can contribute to achieving sustainability goals (Ortiz et al. 2009). Pan et al. (2011) studied the cost barriers to offsite construction. The result shows that PPVC can bring tangible cost savings by reducing on-site labor and equipment requirements compared to conventional construction methods. In addition, the result of the seismic behavior of precast concrete structures indicates that the buildings designed performed remarkably well (Khare et al. 2011) compared to traditional construction. Liu et al. (2019) conducted a study on the social life cycle (SLCA) performance of two construction methods, namely PPVC and semi-prefabrication projects. The result showed that PPVC has better performance due to its capability to contribute to technology development. Balasbaneh et al. (2021) assessed the sustainability triple bottom line of three different concrete construction methods. The result revealed that modular is the best alternative method.

Additionally, prefabrication also brought tangible cost savings by reducing labor and on-site equipment compared to traditional construction (W. Pan et al. 2011). In single-family houses, embodied energy is often shown to account up to 25% (Cabeza et al. 2014) of the overall energy demand; however, nowadays, this percentage has increased by increasing the use of passive technology in buildings profoundly. Stephan et al. (2013) carried out a life cycle assessment (LCA) on single-family passive houses. The result showed that the embodied energy accounted for 77% of the whole energy consumption of the building over its lifespan of 100 years. This indicates that embodied energy is vital in controlling emissions from the construction sector. Most house makers of today are still using conventional building strategies, while those interested in using an alternative method are still not clear on which ones are the best. However, to our knowledge, there is yet no study so far assessing the complete LCA of PPVC. Thus, this study can contribute to the body of knowledge of offsite PPVC.

2. Methodology

2.1. Life Cycle Assessment and Databases

LCA is a tool for evaluating the product or building process from the early stage of production and construction to the final stage, which is the end of life of that product. The boundary of the current life cycle research is cradle-to-grave. The boundary includes the raw material production and construction, machinery and logistics, and finally, end of life (demolition). In this study, a single-family house in Johor Bahru represents the architecture model, i.e., a Malaysian city located in the south, neighboring Singapore. The model was assessed using SimaPro 8 software for environment carbon emissions. The limitation is related to the end of life, assumed to be the landfill for all the material. The scope of this research involves the manufacturing, construction, and execution phase of PPVC and IPS technology in the construction site. The LCA is calculated by summing up all emissions produced in all the stages, i.e., extraction of raw material and transportation of building components, maintenance, and demolition (EPA, 2006).

The functional unit for the LCA must be appropriately described in order to validate the study. Based on ISO 14040 (Reston, 2006), the functional unit encompasses all attributed input material and all the output emissions to the system. For the functional unit of LCA for the life span of a building (Shao et al. 2014), the parameters were assigned as the mass of material for 1 m2 of building wall (Balasbaneh et al. 2017). The service life of research was estimated to be 50 years for the current case study, as suggested by previous research (Balasbaneh et al. 2020a; Balasbaneh et al. 2020b).

Life cycle inventory (LCI) is a process of data input and output (Ekvall, 2004) that starts from the construction phase. The production of electricity used in the factory for the construction process, such as the mixer, comes from fossil fuel, contributing around 96%. At the same time, the rest is produced by other energy sources. Therefore, the electricity effect in Malaysia is quite different from other countries in Europe. In the current research, the Ecoinvent v3.01 database, one of the most applicable databases in the literature study, was adopted following the suggestion of previous research (Balasbaneh et al. 2020c) using local electricity mix data to describe the Malaysian input and output results. The next step in the LCA study entails the life cycle Impact Assessment (LCIA). LCIA represents the environmental impacts of PPVC by converting the outcome of the LCI analysis into different environmental impacts. The midpoint was chosen for interpretation of results because using the endpoint method or even a single-score indicator (IPPC) would result in a high variation and difficulties in understanding the assessment of the different impact categories (Dahlbo, 2013). The limitation of this research is related to the transportation of PPVC, which is not suitable for all countries and big cities. GWP emissions were based on the Intergovernmental Panel on Climate Change (IPCC) method v1.02, with a 100-year time horizon (IPCC, 2007).

2.2 Economic Assessment, Life Cycle Cost (LCC)

Sustainability in a holistic view is currently required to balance the environment and cost for the construction sector. In the current case studies, LCC was performed using an Excel spreadsheet for the 50 years cost of the building system while the estimation was based on the standard construction cost guide handbook (Construction Cost Handbook MALAYSIA, 2017) and National Construction Cost Centre (CIDB Malaysia Official Portal) in Malaysian Ringgit (MYR). In this study, five major LCC elements were assessed: material, wages, transportation, maintenance, and end of life for each alternative floor system based on the construction cost data from the official portal of the Department of Statistics Malaysia and Malaysia's official portal (CIDB). The base year for analysis is 2019, the year the study was undertaken. The future cost and discounted present value were calculated using equations 1 and 2, respectively.

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

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

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

3. Case Study

For concrete PPVC, prefabricated modules are completed with mechanical, electrical, and plumbing (MEP) installed at the factory (Mao et al. 2016; O'Brien, 2000). After the in-factory manufacturing process is completed, the volumetric is transported by truck to the related site for installation on the foundation (Kawecki, 2011). The prefabrication panel system comprises various precast (Dong et al. 2015) elements such as walls, beams, slabs, columns, staircases, landings, and some other customized elements. Similar to PPVC, this technology is suitable for the construction of high-rise buildings. IPS prefabricate manufactured in a precast yard or site and installed in the building during construction. Table 1 shows the quantity of raw material used for assessment.

Table 1 Characterization of building component schemes.

Buildings Scheme	Components	Thickness (M)/ Length	Total Weight (Kg)
Building material weight	Concrete wall	90mm	14331
	Concrete floor	130 mm	6032
	Concrete ceiling	70mm	3728
	Steel bar	-	1964.8
	Tile floor	5mm	675
	wiring	2mm	5
	Polyethylene pipe	110 mm	64

4. Results

4.1 GWP Emission Comparaison

Table 2 shows the result of both construction strategies in terms of carbon emission. The first stage of assessment is related to the GWP emission for both strategies during Material Production. The higher emission is related to Material Production with 78% of the whole emission compared to IPS with 77%, although the emission of IPS is higher than PPVC. This shows that other stages of IPS have a higher contribution to total emissions, such as Off-site interior work or Waste. The next stage is construction in the factory (Figure 1) which includes mechanical and electrical installations, interior wall finishing, and exterior/interior painting for PPVC – all of which are accomplished before the modular is transported to the site. This stage of the PPVC contributes 16% to the total emission compared to only 0.3% for IPS, which only involves fixing cracks or covering surface walls after the completion of the prefabricated components. Other activities related to PPVC on-site are contributed mainly by the concretion for modules, electrical and mechanical works, or damage repair.

Table 2 life cycle carbon emission for PPVC & IPS

Stages	**Unit**	**PPVC**	**% of total**	**IPS**	**% of total**
Material Production	Greenhouse Gases (GWP) $kgCO_2eq$	19705	78%	20573	77%
Construction In Factory		4120	16%	72	0.3%
Off-site interior work		200	1%	4440	17%
Transportation		65	0.5%	165.6	0.6%
Waste		540	2%	809.4	3%
Erected on Site		120	0.5%	90	0.3%
Maintenance		210	1%	210	0.8%
Demolish		340	1%	340	1%

Another stage is the Off-site interior works which contribute only 1% for PPVC in cases of any damage repair, with grout. Meanwhile, IPS contributed about 17% to the total emission via electrical and mechanical installation and connection, interior and drywall finishing, and interior/exterior painting. Transportation for both strategies shows that emission from IPS is 2.5 times higher than PPVC with 165.6 kgCO2eq versus 65 kgCO2eq. The justification for this is that for PPVC, one whole module can be transferred on-site in one trip, while for IPS, only two components can be transported in one trip due to their size and weight. However, the contribution to the total emission for both Systems is negligible at respectively 0.5% and 0.6% for transportation, respectively for PPVC and IPS.

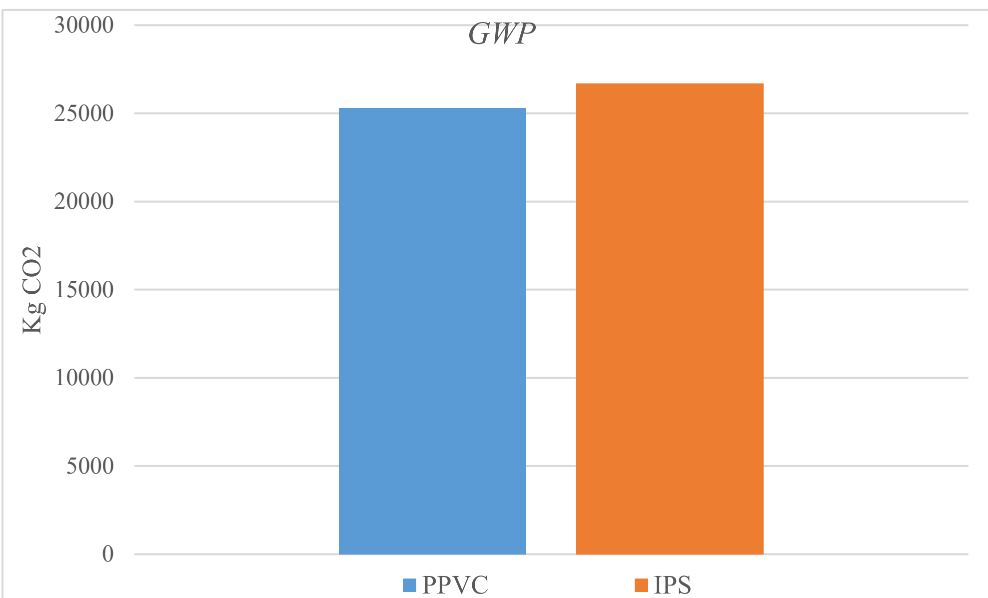

Figure 1 life cycle carbon emission for PPVC & IPS

The next item is emission related to waste. The result shows that emission from IPS is almost two times higher than PPVC, which confirms the result from previous research (Hartley et al. 2007). The emissions related to the waste scenario are 809.4 kgCO2eq and 540 kgCO2eq for IPS and PPVC; however, the contribution of this stage compared to others is only 2% to 3%. The wastage breakdown for PPVC is 4%, 1%, and 5%, respectively for concrete, ceramic tile, and plasterboard, and 9%, 7%, and 25% for IPS.

The next stage of emission is related to the on-site erection with the crane. The emission from the PPVC structure for this stage contributed only 1% of the total emission, i.e., equaling 200 kgCO2eq related to machinery fuel consumption. The PPVC activity in this stage only involves fastening the modules together, while for IPS, the assembly is more complicated and requires more workers, leading to more cost. In addition, PPVC needs a heavier and stronger crane due to the module's heavier weight, leading to the need for more fuel and energy. The emission-related to this stage is 120 kgCO2eq and 90 kgCO2eq, respectively, for PPVC and IPS. The emission from the Maintenance stage is equal for both structures since both are made up of the same concrete material, and the cracks need to be covered up with grout and a fresh coat of paint. The emission contribution of this stage is 1% and 0.8%, respectively, for PPVC and IPS. The final stage entails Demolition, which contributed only 1% for both structures since all the material is sent to the landfill. Finally, from the above assessment, as shown in Figure 1, PPVC has a higher contribution to emission in the in-factory construction and on-site erection stages. At the same time, IPS contributes to higher GWP emissions in all the other stages.

4.2 Life Cycle Cost Comparison

One of the most important aspects of any construction project is the economic issue generally neglected in many research papers. In previous research (Rahman, 2018), it has been confirmed that IPS and PPVC have a total cheaper cost compared to traditional construction methods considerably for incurring less wage and less wastage. The details of the cost for each material are Precast concrete wall (m2) 247 MYR, Ready mix concrete grade 35 MYR (216 MYR /M3) Steel bar 25mm diameter 2300 RM per ton, Finishing coat for the skim coat (each bag 25 kg) 15.88 RM, Paint 217 MYR, Pie 24 MYR per M, and Labour 95 MYR per day. Table 3 shows the details of the cost for each system strategy along with their percentages for the whole operation.

Table 3, Life cycle cost for two different concrete structure strategies

Elements of assessment	Unit	PPVC	% of total	IPS	% of total
Design Cost	MYR	5850	9%	2200	3%
Pre-Cast Concrete		47806	74%	47906	75%
Off-Site Interior Work		7500	12%	150	0.4%
On-Site Interior Work		400	0.6%	9200	14%
Labour Cost		4500	2%	5600	4%
Transport Cost		1100	0.8%	1250	2%
Maintenances		340	0.6%	340	0.6%
Demolish		750	1%	750	1%

Typically, in most of the literature research, the design cost is assumed to be negligible and thus not assessed by the researcher. However, there is a big gap between the design fees calculations for both strategies in this current research. The first stage related to the design fees shows a higher cost for PPVC due to its complexity at the beginning of the project. As a result, the cost for designing the PPVC contributed 9% to the cost of the whole project, and this amount is much lower for IPS, i.e., 3%. Hence, the design cost for PPVC is 2.5 times higher than that of IPS. The next stage is pre-cast concrete, which includes the manifesting wall, roof, etc., for both-factory strategies. However, this process continues for PPVC in-factory. As a result, the manufacturing cost of IPS is slightly higher than PPVC and contributed to 74% to 75%.

The following assessment is related to the Off-Site Interior Work or inside factory operation. The process for PPVC includes electrical and mechanical installation and connection, interior and drywall finishing, and interior/exterior painting. The cost of this stage for PPVC is relatively higher than IPS, whereby PPVC contributes 12% to the whole project cost versus only 0.4% for IPS. Figure 2 shows the differences in costs for each stage. The result for the On-Site cost assessment is different from the previous stage. This stage for IPS includes electrical and mechanical installation and connection, interior and drywall finishing, and interior/exterior painting. While for PPVC, the processes include module connection as well as electrical and mechanical connections. Unlike Off-Site construction for IPS, its On-Site construction has a tremendously higher cost of almost 25 times more than PPVC. The cost of IPS contributes to 14% of the entire cost versus only 0.6% for PPVC. The result for Labour cost shows that using labor in the factory for PPVC leads to cost savings. The amount of cost at this stage for PPVC is 2% lower than IPS. Transportation cost for PPVC is low and contributes only 0.8% to the whole project cost. However, IPS transportation cost is about 2.5 times higher than PPVC. The justification for this is that only one or a maximum of two modules can be transported per truck (IPS), implying that more trucks are needed to get to the construction site.

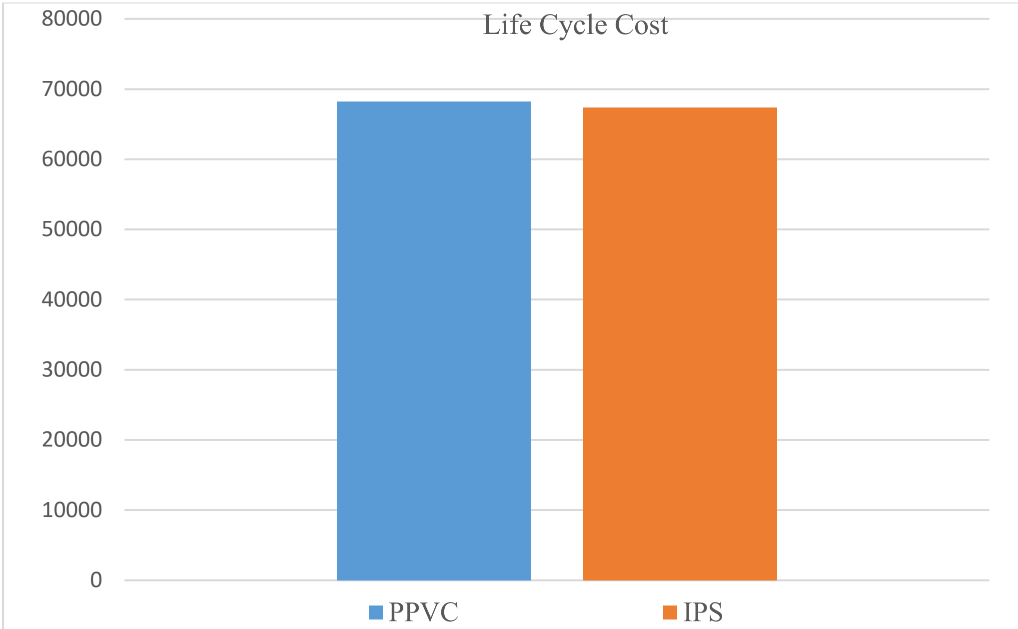

Figure 2, comparison of cost for two different concrete structure strategies

5. Conclusion

In this research, two types of PPVC and prefabricated concrete were assessed and discussed towards having better knowledge and capability to implement both. However, there is a lack of studies to identify the optimum structural system for estimating the GWP emissions and costs involved in implementing both methods. PPVC modules are manufactured off-site complete with internal wall/floor/ceiling finishes, fixtures, and fittings, and transported on-site for installation. PPVC is sometimes referred to as volumetric construction of prefabricated buildings, although strictly speaking, a prefabricated building need not be PPVC. Nevertheless, IPS is completed on-site. Currently, there is a lack of appropriate assessment approaches to capture the differences between PPVC and IPS. Both systems have implications that make them valuable alternatives to traditional construction, but the question of how to determine which one to choose or which one is more suitable for a specific project still prevails. This paper proposes a framework to aid decision-makers in choosing between the construction methods by integrating the aspects of environment and cost. The preliminary result shows that the IPS system requires many on-site activities, which lead to higher emissions. Such occurrence can be reduced significantly by adopting the PPVC system within the whole project. Nevertheless, hoisting the PPVC system is a big challenge that must be carefully considered during the design phase.

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