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Life cycle assessment and economic analysis of Reusable formwork materials considering the circular economy

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ABSTRACT

Economic development and population growth have impacted on fossil-based energy consumption, contributing to environmental pollution. Adopting circular economy research is more pressing than ever to ease pressure on the environment and the economy. Evaluating the best construction materials is not new. To date, many researchers have assessed materials using various criteria. Formwork differs from other construction materials in terms of serviceability and reusability. These materials may be reused multiple times (from 7 to around 50 times). This raises the question of which material is the best from a sustainability perspective. In this paper we have evaluated four of the most widely-used formwork materials used in the construction of buildings in Malaysia. These include plastic, steel, plywood and timber. Evaluations of life cycle assessment (LCA), embodied energy, and life cycle cost (LCC) were conducted from cradle to cradle. For a single use of formwork, timber is best in all categories except human non-carcinogenic toxicity. However, when 50 reuses are considered for the same wall a completely different result arises. In the environmental category, steel formwork produces the lowest emissions and impact in all categories except global warming potential (GWP). Plastic formwork has the lowest carbon emissions. In terms of embodied energy and cost, plastic formwork presents the best option being approximately 20% lower than steel formwork. Because of the inconsistency in the results for LCA, embodied energy, and LCC for 50-cycles of usage, a multi-criteria decision-making (MCDM) tool was used to normalize the results. The MCDM shows that plastic formwork is an ideal choice for sustainability among the alternatives considered.

1. Introduction

The building sector consumes 40 % of global resources, generates 33 % of all emissions and 40 % of waste globally [34]. The building industry is responsible for a considerable share of resource consumption worldwide as well as the associated waste generation and emissions [29]. CO_2 emissions from the construction industry account for almost 40 % of the industry's annual emissions. Sustainable development is guided by the principles of respecting nature, protecting the environment, and managing economic and social affairs responsibly. A key component of the construction industry's sustainability strategy is resource management. Designing climate-aware and energy-efficient cities can contribute to the sustainability of cities and mitigate the effects of climate change (Hallegatte & Corfee-Morlot, 2011). In construction, formwork systems play an important role, and selecting the right formwork system can lead to a more sustainable result. Formwork is a system that supports and shapes concrete components. They remain in place until structures are capable of supporting themselves. A formwork system is used to cast structural elements like columns, beams, slabs, and shear walls, as well as smaller building components like stairs, etc. It is important to consider cost, time, and quality when selecting formwork for any type of building Mohammed Taher Al-ashwal [30].

The circular economy has become an aspiration of EU policy development, leading to environmentally sustainable consumption and production [19]. Therefore, shifting to a circular construction economy appears to be a fundamental step in developing sustainable cities and societies. The circular economy has attracted the attention of policy communities and the scientific sector in keeping products and materials in circulation by recovering materials, recycling, and/or reusing them [33]. The circular economy's main aim is to increase the efficiency of

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materials and minimise resource depletion [37]. It aspires to provide economic growth while alleviating pressure on the environment [40]. Thus, a circular economy may be defined as a system where waste, emissions, and energy are minimised by reducing the natural resources consumed via iterations of usage [13].

Concrete is one of the most functional materials worldwide [41]. Formwork is a temporary and necessary part for a concrete structure, providing shape to concrete so that it can progressively develop strength [22]. After the concrete has achieved its design strength, the formwork is disassembled for subsequent further use [2]. Different formwork materials have advantages and disadvantages. For instance, plastic and wood are lightweight. Wood formwork can only be used a limited number of times and is prone to swelling, twisting and cracking. However, wood is cheaper than plastic or steel formwork. Steel formwork is strong and durable, but it can also be expensive [22]. In recent years, its potential to be reused has attracted increasing attention [31]. Formwork reuse contributes to cost savings and material waste reduction. Based on previous research, expenditure on formwork is up to 25 % or more than the cost of a building's structure [42]. Furthermore, the formwork system is also one of the main factors determining the success of construction projects, including the cost, quality, speed, and safety of the project. In summary, formwork can significantly impact on construction project cost and duration as well as other activities [46]. In this study, different types of popular formwork used as wall panels have been evaluated to determine sustainable options.

Different types of formwork function in different ways in buildings, and these are investigated in this paper. For example, Prajapati et al. [42] used plastic formwork because of its durability and flexibility. These reasons provide insufficient justification for using this product over another. Additional criteria such as energy consumption and environmental impact need to be considered to identify the best material for the purpose. Rajeshkumar et al. [45] evaluated the factors considered necessary for ideal construction formwork. The results of their questionnaire survey identified other items including capital cost, lifespan, exposure to the environment and labour cost as important factors. However, none of the aforementioned studies considered the environmental impact of formwork materials in parallel with their life span. In this study we explore the life span of different formwork materials (the number of times formwork can be used efficiently) and the impact this has on assessments of their life cycle and economic use.

The consensus reached in previous studies is that timber is the most favourable construction materialBalasbaneh et al. [4], Balasbaneh and Sher [5]. Some studies have characterized timber formwork as the best option [23] but there are some exceptions [7]. Compared to other materials such as steel and plastic, the advantages of timber formwork not clearcut. This is mainly due to the number of uses different materials can sustain. Construction materials including wood have been studied extensively in the context the 3Rs (reduce, reuse and recycle) (Hai, 2020; Stahel, 2019). These align with the circular economy and warrant serious investigation if CO_2 reduction targets are to be achieved. Lo, [24] evaluated formwork used to construct concrete walls and proposed using plastic formwork to reduce the amount of wood used in construction. However, the resulting environmental emissions are unclear. The author simply explored an alternative material to reduce timber use for commercial advantage. Wei-yi Li & Evison [25] evaluated sawn timber and plywood used in China formwork. They showed that timber and plywood consumption rates were 1.7 m^3 and 11.3 m^3 per 1,000 m^2 of wall, respectively. More plywood is thus needed to manufacture formwork than sawn timber for the same area. Yip & Poon, [53] compared the disadvantages and advantages of metal and timber formwork. They showed that traditional timber formwork is the best economic choice compared to steel formwork. However, only one use of formwork was considered. This is unrealistic as common practice is to use formwork multiple times.

Shazwan Ahmad Shah et al., [48] discussed the benefits of plywood formwork over steel formwork as used in Malaysia. They found that wood is cheaper in the short term. However, the authors acknowledged that steel formwork has advantages over wood formwork. Gaddam & Achuthan, [15] evaluated the costs of different types of formwork in India including steel, timber, and aluminium. They showed that aluminium formwork is cheaper than timber formwork. Doka, (2013) compared steel and timber formwork, and found that steel formwork is more costly than timber formwork. Gebrehiwot & Getachew, [16] assessed the cost of the plywood, timber and steel formwork. They showed that most respondents believed that timber was cheaper than the alternatives. Wei Li et al., [22] reviewed research about alternative formwork systems. Their conclusion was that each material has its advantages depending on the type of construction. For example, wood formwork is preferable for structures with regular shapes. In contrast, flexible formwork systems are primarily used for structures with complex geometries. Krawczynska-piechna, [21] evaluated a 'semi-system' and compared it to conventional formwork. They found that conventional methods costed 12 % more than the semi-method.

Approximately 40 % to 60 % of the cost of construction relates to formwork [14]. This warrants further investigation to determine the characteristics of different materials used as formwork. Formwork is expensive, so investigating ways to reduce costs is of interest both to practitioners and researchers. Despite current research on sustainability and life cycle assessment (LCA) for different construction materials, it is not clear which ones are best for formwork regarding environmental, energy, and cost considerations. Some researchers have proposed using plastic formwork over timber formwork, and others have suggested timber over steel. However, there is no consensus. This study addresses this conundrum. Some stakeholders only consider the cheapest materials for formwork. Formwork is, after all, not permanent. This begs the question: are inexpensive formwork materials a sustainable choice? Finally, as far as we can ascertain, there are no published sustainability studies that consider the reusability characteristics and multiple uses of different types of formwork. This research adds to existing knowledge about the use of traditional formwork materials (such as plywood and timber) in the circular economy. It explores the potential environmental and economic implications of these materials when compared to contemporary materials (such as plastic and steel formwork).

2. Materials and method

As the built environment increasingly adopts circular principles, it is necessary to determine which materials contribute to environmentally circular building components. There is therefore a need for a robust assessment methodology. Circular economy frameworks can use LCA to analyze environmental impacts [49]. This paper focuses on using LCA and life cycle costing (LCC) to assess economic costs over the entire life cycle of a building. Fig. 1 shows our research approach to consist of four stages. The first two assess different environmental criteria and embodied energy. Stage3, considers the present value of formwork. All evaluations were conducted twice, first for one use and second for 50 uses of different types of formwork. As each component of sustainability is defined in different units, such as carbon emissions or money, we needed a tool to compare the results of the different case studies (stage 4). We used multi-criteria decision-making (MCDM) to select the optimum wall formwork (stage 4). The criteria chosen facilitate comprehensive evaluations and align with previous studies Balasbaneh and Sher [6].

2.1. Formwork options

Formwork is widely used in concrete construction. It follows that the sustainability of formwork contributes to the overall sustainability of the construction method selected. Therefore, the most popular formwork materials[44] have been evaluated in this study. The key variables relate to their lifespan and ability to be reused. Table 2 shows the number of times each material is assumed to be reused during its productive life. No

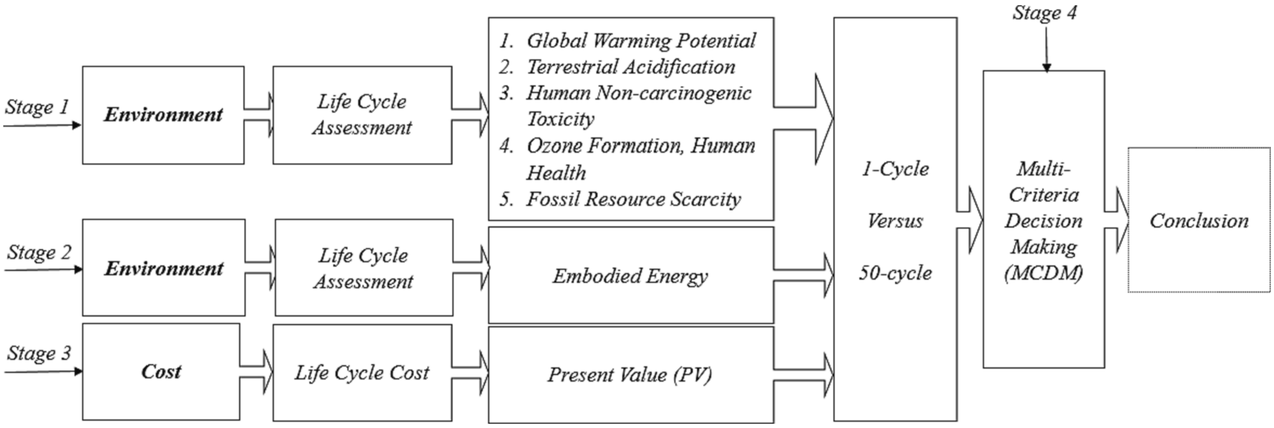

Fig. 1. Flowchart of analysis of environmental factors and costs to enable Decision Making.

alterations resulting from reuse were considered. All options were based on a 20 cm thick concrete wall, 3 m by 3.6 m in size (10.8 m^2 of wall area). Table 1 provides details of the components used in each option for a single use of each formwork type. Construction companies and suppliers were used as the source of data collection. In this data, companies are provided with the quantity and cost of each formwork.

The estimated service life of different formwork materials is debatable. The first option is for plastic formwork [24]. This may be used an average of 50 times and is considered to have one of the longest life expectancies of the options. The plastic used is of polypropylene. The plastic shuttering system (FW1) is novel because of its reusability, lightness, solidity, recyclability, universality, durability and simplicity [39]. Some studies have highlighted the considerable potential for plastic waste to be recycled into formwork to reduce greenhouse gas emissions [10]. Furthermore, when plastic formwork is damaged or decommissioned, it can be crushed and recycled. Suitable clamps (or bolts and nuts) as well as bracing are used to hold the panels together. Our study was based on polypropylene panels 1200 mm by 600 mm. These weigh 11 kg less than timber formwork of the same size (15 kg). The second option is for steel (FW2) with a density of 7850 kg/m^3. This consists of panels fabricated out of thin steel plates stiffened along the edges by small steel angles. The steel units are held together using suitable clamps or bolts and nuts and braced to maintain a stable position. At the end of its life, steel formwork can be recycled. The data in Table 1 were collected from suppliers [54].

Table 1
Materials characterization of different formworks.

Formwork options		*Materials*	*Quantity*	*Weight per unit-kg*	*Total weight-Kg*
Plastic Formwork	*FW1*	Plastic panel	30	9.8	294
		Tie rod	30	1.20	36
		Anchor nut	60	0.85	51
		Pull-push Prop	2	36.91	73.82
		Alignment Bar (Waler)	8	11.2	89.60
		locking Handle	270	0.1	24.3
Steel Formwork	*FW2*	Metal panel	30	34.5	1036
		Bolt and nut	190	0.13	24.7
		Alignment Bar (Waler)	22	11.2	246.4
		Tie rod	30	1.2	36
		Pull-push Prop	2	36.91	73.82
		Plate nut	60	0.85	51
Plywood Formwork	*FW3*	Plywood sheathing panel	30	12	360
		Stud & wale (wooden)	–	2.5	351
		Tie wire	30	1.5	45
		Stringbacks	–	0.85	52
		Pull-push Prop	2	36.91	73.82
Timber Formwork	*FW4*	Wood sheathing panel	30	13	390
		Stud & wale (wooden)	–	2.5	351
		Tie wire	30	1.5	45
		Stringbacks	–	0.85	52
		Pull-push Prop	2	36.91	73.82

Plywood formwork (FW3) 650 kg/m^3 and timber formwork (FW4) 750 kg/m^3 are the other materials considered in this study [26]. If timber formwork is damaged or aged, it reaches its end of life. Construction waste generally includes 20 % waste timber formwork [24]. Wooden panels are frequently assembled using nails and wire. The energy required to manufacture a square meter of timber formwork is 0.1428 kWh [24]. In addition, construction workers' skills and their habit of arbitrarily cutting formwork combine to affect the usability of timber formwork. Spacers are required to maintain the distance between the panel (shuttering) and steel reinforcement. Depending on the system used, when concrete has been cast and formwork is removed, steel fixings may remain embedded in the concrete. This means that for the next formwork job, new fixings need to be used. Timber and plywood are frequently incinerated after 7 uses. Steel and plastic formwork can be used more times than timber or other wood materials. To quantify these uses, data were collected from 15 construction sites and extracted from different studies [24,46]; Prajapati, R., Pitroda, J. and Bhavsar, 2014). Thus, based on literature and a survey, plastic and steel can be reused almost seven times more than wood and plywood.

2.2. Life cycle assessment

2.2.1. Goal and scope

In line with cradle-to-cradle thinking, products and processes may be developed as a perpetual flow of materials [47]; Peña et al., 2021). As a product reaches its end of life, cradle-to-cradle means materials are recycled or repurposed. These materials do not end up as waste, which aligns with the circular economy. This requires a focus on minimizing the environmental impact of the life cycle of these materials whilst improving the circularity of production systems. In this way LCA can be used to promote a circular economy. The first step of a LCA study is to identify the relevant functional units and system boundaries. The functional units used in this study are based on 1 m^2 of concrete wall. This allows different materials to be compared equitably.

The goal of this study was to assess the environmental impacts of different formwork materials and identify their environmental emissions. The results of this study can assist formwork designers and other design professionals to make objective choices about materials. Several recent studies have compared alternative construction materials. Walls can be constructed in various ways (including in-situ concrete, timber or steel frames clad with gypsum boards, fibre cement sheets or similar). This study focusses on the formwork used to construct in-situ concrete walls. These can be constructed from a range of different materials such as those included in Table 1. The results of this study can be used to determine which materials are best suited for formwork for the Malaysian building industry. However, these recommendations are subject to some limitations. It was assumed that the formwork would not require maintenance during its lifetime. Thus, maintenance and repair have not been considered. Fig. 2 shows the system boundaries of the study from cradle to cradle based on life cycle stages from EN15804:2012 + A2:2019.

The boundaries consist of the production stage (A1-A3), construction stage including transporting materials to site and erecting the formwork (A4, A5), and the end of life stage, including demolition, transport, waste processing and disposal (D1, D2, D3, and D4). The last stage is for reuse (D1), recycling (D3), and incineration (D4). Other building elements have not been included as they have no impact on wall materials. Fig. 2 applies to all formwork options. We have not considered C1 because it relates to deconstruction and demolition. Formwork materials are only used during construction and do not form part of finished buildings. They are thus not in place when buildings are deconstructed and / or demolished, hence our decision not to include C1.

2.2.2. *Life-Cycle inventory*

A life cycle inventory analysis involves collecting and synthesising information relating to physical material and energy flows for various stages of a product's lifecycle. SimaPro v9.3 software was used to evaluate the LCA of alternative scenarios and different formwork options. Life cycle inventory (LCI) identifies inputs and outputs for each process or material (Chen et al, 2008). Ecoinvent 3.3 data, currently the most comprehensive and transparent life cycle inventory database available, was used to identify appropriate data for different building materials and services. LCI involves considering the flow of materials, substances, and energy within the system. No distinction was made between combustion systems for secondary, residual, and waste wood. For timber formwork, wood was assumed to be sourced from an unsustainable forest in the local area. Therefore, based on EN15804:2012 + A2:2019, there is no specific requirement to calculate the biogenic carbon for such forests. As a result, wood was considered carbon neutral. The ILCD handbook EUR 24708 (2010) and EN 16449 (2014) were considered since no consensus exists on whether and how the biogenic carbon benefits of wood should be accounted for [35].

As biogenic carbon [17]; Andersen et al., 2021) was not accounted for in this study, there is no consideration of biogenic CO_2 uptake and release from forestry. Thus, the LCA excluded biogenic CO_2 uptake and emissions. The indicator chosen for the assessment was Global Warming Potential (GWP) over 100 years. The carbon absorbed during the plantation stage and stored in trees has not been considered. This is mainly because there are no commonly accepted methods in the life cycle assessment framework for handling changes of biogenic carbon stocks in biomass [28]. Additionally, the biogenic carbon absorbed by forests has not been included because of the lack of data about the Malaysian forestry industry. Data about the negative carbon from biomass are not available.

On the other hand, the biogenic CO_2 from waste incineration, recycling and reuse have been considered to address the end of life scenario [32]. Two scenarios have been defined for the end of life of wood and plywood as shown in Table 2. Firstly, when wood and plywood have served their purpose as formwork, they enter another product system. The biogenic carbon that was stored in the material is thus reported as a positive value. Secondly, when plywood and wood formwork are recovered for energy, all the biogenic carbon that was stored in the combusted material is released directly back into the atmosphere and reported as a positive value [56]. A consequential LCA approach was adopted. Comparing different construction materials should only use consequential life cycle assessment approach. With this approach, the net benefits from recycling and reuse are included [18]. The inventory used for this analysis was adapted from the Ecoinvent database library, available with the Simapro Software. A limitation of this approach is that the transport of material to its end-of-life location was excluded as it was assumed to be similar for all scenarios. By adjusting Ecoinvent to Malaysian circumstances, existing local electricity mix information was included, as recommended by Horv et al. (2012). (SEE Table 3.).

Table 2 shows the scenarios for the end of life for each alternative material. Steel is often recycled, followed by plastics. It was assumed that 10 % of plastic was reused in subsequent projects. Also, it was assumed that 80 % of wood formwork would be incinerated and 20 % was considered to be reused.

The most crucial issue is the life span of each type of formwork. Considering only a single use will give an unreliable result and provide little guidance. Therefore, this assessment has considered the same number of uses for each type of formwork. Specifically, the number of times plastic and steel is assumed to be used is 50 [24], and for plywood and timber seven times [43]. Thus, after seven uses, we have assumed that new formwork needs to be assembled and that 20 % of the wood from previous formwork is used in this new formwork. This loop continues until the formwork is used 50 times (seven cycles). We have further assumed that the transport of plastic and steel is paid once and seven times for plywood and timber. All work is assumed to have been conducted on a single site.

Table 2
Attributes of formwork at the end of their life cycle.

Items	*Plastic Formwork*	*Steel Formwork*	*Plywood Formwork*	*Timber Formwork*
Quantity recycled	*90 %*	*100 %*	–	–
Quantity reused	*10 %*	–	*20 %*	*20 %*
Quantity incinerated	–	–	*80 %*	*80 %*
Number of uses	*50 times*	*50 times*	*7 times*	*7 times*

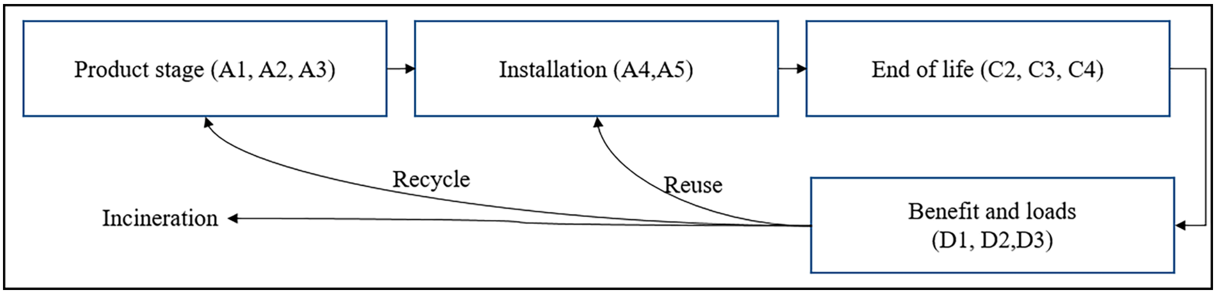

Fig. 2. Conceptual framework of a circular economy.

Table 3
Comparison matrix.

Parameters	weight	Y1	Y2	Y3	Y4	Y5	Y6	Y7
Y1	*W1*	*1*						
Y2	*W2*		*1*					
Y3	*W3*			*1*				
Y4	*W4*				*1*			
Y5	*W5*					*1*		
Y6	*W6*						*1*	
Y7	*W7*							*1*

2.2.3. Life cycle impact assessment

Life cycle impact assessment (LCIA) was conducted using the ReCipe Midpoint (H) method with Simapro Software. Increasing opportunities to use wood waste and residues can assist in the transition to a circular, low-carbon economy [36]. Using waste at the end of the life of formwork can have a marked economic impact in terms of economic efficiency in line with circular principles. Waste wood consists of wood pieces and particles that are generated in the course of industrial or small-scale wood processing, construction and demolition activities, and the recycling of broken-down wood products [38]. The resulting environmental impacts include Global Warming Potential (GWP), Terrestrial acidification potential (TAP), Human non-carcinogenic toxicity (HCT), Ozone formation, human health (OHH), and fossil resource scarcity (FRS).

The LCIA method used to evaluate primary embodied energy was the Cumulative Energy Demand (CED) method 1.04. Results are expressed as non-renewable energy based on the Ecoinvent database incorporated in the SimaPro software (PRé. 2019). These estimate the energy consumption of products along with that of the processes used in their manufacture (Hischier et al., 2010). CED results are expressed in megajoules (MJ) per Kg. However, in a circular economy, all materials need to be incorporated in some way to avoid being sent to landfill. LCI values were sourced from the Ecoinvent database assuming that wood is burned in an incinerator with appropriate emissions controls. Plastics are also assumed to have been incinerated in an incinerator, and ecoinvent has been used for all LCI data.

2.3. Life cycle cost

Estimates of cost were based on information from the National Construction Cost Centre (CIDB Official Portal) as well as data collected from suppliers [11]and field investigations [50]. This stage (3) supersedes other LCC studies based on consequential LCC estimation. In contrast to the attributional and conventional assessment methods, a consequential analysis model uses a different approach. A consequential method involves computing the end-of-life costs of materials for each building stage within a system boundary. In addition to reviewing the benefits of reselling waste materials such as steel plates and plastic panels at the end of a building's life, the differences relate to how reselling waste materials is assessed[3]. As part of assessing the LCC, the firstly involves calculating the total cost of raw materials used in construction. Next, the future costs are determined. Based on the current reference time, it is necessary to discount the future costs, as shown in the following equation.

$$PC+LC+TC=\left(\frac{PC}{(1+r)^{t}}+\frac{LC}{(1+r)^{t}}+\frac{TC}{(1+r)^{t}}\right) \tag{1}$$

In Eq. (1), PC is determined by the material production cost, LC stands for the cost of labour or the wages paid to workers, TC is the cost of transporting formwork to the site, and PC is the cost of materials production. T is for time, and r is for the discounted rates. In addition, when materials reach their end of life as described previously in relation to Table 2, they are sold on. The benefit of resale is considered in Eq. (2). The end-of-life stage has a positive net impact on the total estimated cost, based on the consequential method for LCI assessment.

$$C=\sum EOF \tag{2}$$

EOF is defined as the end-of-life cost of reselling materials using Eq. (2). The assumptions made for evaluating the LCC are as follows; the rate of inflation is 3 % based on the Malaysian inflation rate for 2021, and the discount rate is 3.2 % expressed as the average Malaysian discount rate in 2021.

2.4. MCDMs

An analytic hierarchy process (AHP) was conducted to identify dependencies between the results of the various options and to investigate the values and weights of each formwork criterion (Turskis et al., 2009). We used TOPSIS (Technique for Order of Preference by Similarity to Ideal Solution) to characterize the most suitable material as the seven parameters (criteria) used diverse weights within the construction sector. The informed views of sixty specialists from three development divisions were sought, namely: construction estimators, project engineers and academics. To be included in the study, these parties were required to have experience of the concrete industry related to formwork systems. These professionals were asked to share their opinions about prioritizing the selection of formwork materials based on seven different criteria. They were asked to weigh the criteria based on their assessment of the importance and the value that needed to be considered. Their responses were analyzed using the AHP method. A scale of outright discernment was used to highlight different components' relative weights for a given attribute (Saaty, 2008). The criteria and their corresponding weights (W) were placed in a pairwise comparison matrix, in line with Saaty (2008): GWP (Y1), HTP (Y2), AP (Y3), TE (Y4), FD (Y5), Embodied energy (Y6), and LCC (Y7). Table 1 illustrates the pairwise comparison matrix for the seven criteria.

Only stakeholders with experience in the field of formwork were chosen as respondents. Each criterion addressed by the specialists is different and has a distinctive value. Hence analysis of their opinions is complex and was conducted using the AHP method. This involves the allocation of weights to highlight the significance of each criterion. To determine the weight for different criteria for each of the seven scales, three different expert categories were selected (based on the AHP technique and Saaty's evaluation). The experts were construction estimators, project engineers and academics involved in the timber industry. An objective of the survey was to investigate how the seven different scales and their associated weightings affect MCDM results. A scale of one to nine (the most extreme) was used to establish relative significance. To ensure the consistency of the comparison framework, the computed Consistency Ratio (CR) should not exceed 0.1.

When faced with complex decisions, TOPSIS defines suitable alternatives. Processes and products should be selected according to the shortest distance considering the positive ideal. On the other hand, when solving the decision-making process, the alternative should be one that is at the furthest distance from the negative ideal solution. The following are the six steps used by TOPSIS. It is necessary to normalize the decision matrix to calculate r_{ij} using Eq. (3) first.

$$r_{ij}=\frac{x_{ij}}{\sum_{i=1}^{n}X_{ij}^{2}} \tag{3}$$

Here the weighting described previously is multiplied by the weight of this criterion. The weighted normalised value V_{ij} is calculated using Eq. (4).

$$V_{ij}=X_{ij}{}^{*}W_{j} \tag{4}$$

In the next step, the negative ideal solution (A^{-})isdetermined as well as the positive ideal solution (A^{+}) using Eq. (5).

$$A^{+}=\left\{\left(maxv_{ij}|j\in J\right)|i=1,\cdots,m\right\}=\left\{v_{1}^{+},\cdots,v_{n}^{+}\right\} \tag{5}$$

$$A^{-} = \left\{ \left(min v_{ij} | j \in J \right) | i = 1, \cdots, m \right\} = \{ v_1^{-}, \cdots, v_n^{-} \}$$

Next, the distance between alternative and positive and negative ideal solutions is computed using Eqs. (6) and (7). The separation measures are based on Euclidean distance,S_i^{+} and S_i^{-} of each alternative from the negative-ideal and positive-ideal solutions, respectively.

$$S_i^{+} = \left[\sum_{j=1}^{m} \left(V_{ij} - V_j^{+} \right)^2 \right]^{0.5} \tag{6}$$

$$S_i^{-} = \left[\sum_{j=1}^{m} \left(V_{ij} - V_j^{-} \right)^2 \right]^{0.5} \tag{7}$$

P_i Calculate the relative closeness of each alternative using Eq. (7).

$$P_i = \frac{S_i^{-}}{S_i^{+} + S_i^{-}} \tag{8}$$

The larger the relative closeness value, the better the performance of the alternative. The ranking order of P_i for different mass timbers will be between 0 and 1, and the option closest to one will be determined as the best choice.

3. Results

This research evaluated different alternative materials used as formwork for a concrete wall. Firstly, it analysed a single cycle of formwork for constructing the wall. Secondly, it compared the results with an optimum number of uses for 50 instances of building the same dimension wall. The result highlights whether or not the most suitable option is different with a higher number of cycles. The LCA, LCC and energy demand for alternative types of formwork was compared to provide a holistic view of the optimum selection.

3.1. Environmental

A wide range of criteria was chosen for LCA analysis (stage 1). Figs. 3 and 4 shows the results of this analysis related to one cycle and 50 cycles of formwork, respectively. The first environmental impact is GWP. The result shows that timber formwork contributes to the lowest CO$_2$eq emissions compared to other types of formwork. The total emissions for production and construction of the formwork ($3 \times 3.6 = 10.8$ m^2) was calculated as 594 kg-CO$_{2eq}$ for first-time use. Thus, constructing one square metre of timber formwork releases 55 kg-CO$_2$eq into the atmosphere.

The second-lowest emissions relate to plywood formwork with 819 kg-CO$_{2eq}$ for production and construction. The emissions of one square metre of plywood formwork are 76 kg-CO$_{2eq}$ which is 27 % higher than for timber. The third option is for plastic formwork. When used once, it releases 2100 kg-CO$_{2eq}$ emissions. The emissions for one square metre of plastic formwork are equal to 194 kg-CO$_{2eq}$. This is 72 % and 61 % higher than timber and plywood, respectively, for a single use. The highest emissions are for steel formwork for the production and manufacturing stage, being 2840 kg-CO$_{2eq}$. The emissions for one square metre of steel formwork are 262.9 kg-CO$_{2eq,}$ being the highest for one usage. The steel formwork has higher emissions of 79 %, 71 %, and 27 % than timber, plywood, and plastic formwork respectively. These results show that steel formwork has higher CO$_2$ emissions than plastic formwork. The higher emissions for steel relate to a larger quantity of steel (almost three times). Otherwise, the emissions for 1 kg of plastic are higher than for 1 kg of steel. Based on the results generated by SimaPro, plastic has a carbon emission factor of 2.04 kg-CO$_2$e/kg versus 1.5 kg-CO$_2$e/kg for steel. This indicates that renewable materials such as timber emit 4.8 times less carbon than non-renewable materials such as steel. However, not all materials used in timber formwork are wood-based.

Timber formwork needs ancillary materials such as steel fixings and tie wire. Carbon offsets may be factored in for all formwork through different scenarios such as reuse or recycling. Transportation has the lowest carbon emissions among other stages of 72.5 kg-CO$_{2eq}$. The net energy saving for steel is -811 kg-CO$_{2eq,}$ followed by -568 kg-CO$_{2eq}$, and -228 kg-CO$_{2eq}$, for plastic and timber for a single use, respectively. Finally, the total GWP are 1605 kg-CO$_{2eq}$, 2101 kg-CO$_{2eq}$, 664 kg-CO$_{2eq}$, and 506 kg-CO$_{2eq}$ for plastic, steel, plywood, and timber formwork, respectively.

However, the result changes profoundly when 50 cycles of formwork are considered, as shown in Fig. 4. Plywood and timber formwork production and manufacturing emissions rise to 5733 kg-CO$_{2eq}$ and 4158 kg-CO$_{2eq,}$ respectively. That is because each of those materials can only be used seven times.

Transportation needs to be included six times more for transferring the formwork to site (a total of 7 times). This is because plywood has 2.7 and 2 times more emissions than plastic and steel formwork for the production stage. This shows that increasing the number of formwork uses influences sustainability. Thus, considering materials for only one cycle makes it difficult to make comparisons. Finally, total emissions from cradle to cradle for alternative formwork options are 1453 kg-CO$_{2eq}$, 2101 kg-CO$_{2eq}$, 4648 kg-CO$_{2eq}$, and 3511 kg-CO$_{2eq}$ for plastic, steel, plywood and timber for 50 cycles of usage. Therefore, the GWP result indicates that plastic formwork is the best choice.

The next environmental impact is terrestrial acidification potential (TAP). This is different to GWP. Plastic formwork has the highest impact in this category with 2, 4, and 7 times higher emissions than steel, plywood and timber formwork respectively. The total emission is 11.7Kg SO$_{2eq}$, 5.5Kg SO$_{2eq}$, 2.7Kg SO$_{2eq}$, and 1.7 Kg SO$_{2eq}$ for FW1, FW2, FW3, and FW4, respectively. However, the result completely changes when 50-cycles are considered. Plastic formwork then becomes the second-best option after steel (Fig. 4). For 50 cycles, plywood becomes the worst formwork option as it can only be used seven times, and transportation emissions increased. Despite the large quantities of timber and plywood having end-of-life applications, the emissions of these materials are not alleviated. The total emissions are 11.86 Kg SO$_{2eq}$, 5.52 Kg SO$_{2eq}$, 18.75 Kg SO$_{2eq}$, and 12.23 Kg SO$_{2eq}$ for plastic, steel, plywood and timber formwork, respectively. This shows that the best option evolves from timber formwork to steel for 50 uses.

The next environmental impact considered was human non-carcinogenic toxicity (HCT). The production and manufacturing phases are responsible for 18.50 Kg 1,4-DCB, 12.20 Kg 1,4-DCB, 2.78 Kg 1,4-DCB, and 7.63 Kg 1,4-DCB for plastic, steel, plywood and timber formwork, respectively. Plastic had the highest emissions, being 1.5 times more than steel formwork. The main result for a single formwork use shows that plywood contributes the least emissions, 2.97 Kg 1,4DCB versus 14.65 Kg 1,4-DCB, 9.97 Kg 1,4-DCB, and 6.57 Kg 1,4-DCB, for plastic, steel and timber formwork respectively. Timber, previously ranked third, releases the most emissions after 50 uses. The total emissions for 50 uses are 14.65 Kg 1,4-DCB, 9.97 Kg 1,4-DCB, 20.76 Kg 1,4-DCB, and 46 Kg 1,4-DCB for plastic, steel, plywood and timber formwork, respectively. This ranks timber as the worst option in this HCT category being 3.1, 4.6 and 2.2 times more than plastic, steel, and plywood formwork.

Ozone formation, human health (OFHH) was also considered in this study. For a single formwork use, plastic emitted the most for the production stage by 7.4 Kg NOxeq versus 4.1 Kg NOxeq, 2.9 Kg NOxeq, and 1.2 Kg NOxeq for steel, plywood and timber formwork respectively. Once the emissions related to transportation and the end-of-life impact were taken into account, the total emissions for plastic decreased to 5.9 NOxeq due to recycling. A single use of plastic formwork had 1.7, 2.2, and 4.5 times more emissions than steel, plywood and timber formwork. The total emissions for 50 uses show that plywood contributed the most, followed by timber. Thus, despite plastic and steel not being appropriate options for a single formwork use, for 50 uses, these materials are considered better choices. The results for fossil resource scarcity (FRS) align with the last three environmental impacts (TAP, HCT, and OFHH). Although plastic formwork appears to have the highest emissions after

Fig. 3. Life cycle assessment for one cycle of formwork, Plastic (FW1), steel (FW2), Plywood (FW3), timber (FW4).

Fig. 4. Life cycle assessment for 50 cycle reuses of formwork, Plastic (FW1), steel (FW2), Plywood (FW3), timber (FW4).

50 uses, steel is the best formwork option.

The overall result for one use shows that timber formwork has the lowest environmental impact compared to plastic. Plastic generates the most emissions and impacts in all environmental categories except GWP (Table 2). Surprisingly, after evaluating 50 uses of timber and plywood formwork, the result changed from plastic (with the highest emissions) to plywood formwork. Plywood contributes three times more emissions than plastic formwork in the GWP category. This trend was similar for other environmental impacts. Plywood has a 2.4, 1.7, 4-, and 2.5-times more impact than plastic formwork (second-highest rank) for terrestrial acidification, human non-carcinogenic toxicity, ozone formation for human health, and fossil resource depletion. Steel formwork is then ranked as the second-lowest option for 50 uses in the all-environmental category, except GWP. Thus, there are no definitive conclusions about which formwork performs best in relation to environmental impacts.

3.2. Cumulative energy demand

Cumulative energy demand measures indirect and direct energy used during the life cycle of materials (stage 2). It thus includes the energy used during production, manufacturing, and end-of-life processes for raw materials. For example, the primary energy demand for plastic is higher than for timber and steel. The embodied energy for one kg of plastic is 70 Kg/MJ versus 35 Kg/MJ for steel. However, almost three times more steel formwork is required than plastic formwork, which is the main reason why steel formwork has higher embodied energy than plastic (Fig. 5).

The embodied energy for the production and transportation of plastic formwork are 34800 MJ and 222 MJ. However, the net energy saving for recycling equals −12000 MJ which needs to be deducted from the overall embodied energy. Steel has the highest embodied energy among the alternatives, with 51300 MJ and 222 MJ for manufacturing and production, and transportation, which is 1.5 times higher than the embodied energy of plastic formwork. Therefore, the net reduction for recycling steel formwork is −22000, which is deducted from the total energy to calculate the total embodied energy for steel. The embodied energy of plywood is 9960 MJ, 222 MJ, −1750 MJ for manufacturing and production, transportation and end of life benefits, respectively. Timber formwork has the lowest embodied energy of 6050 MJ, 222 MJ, and −1010 MJ for manufacturing and production, transportation and end-of-life for one use. Finally, the total embodied energy of steel formwork is 1.3, 3.5, and 5.6 times higher than plastic, plywood, and timber formwork.

Fig. 6 shows the embodied energy of four alternative formwork configurations after 50 uses. The result changes profoundly when 50 uses are considered. Plywood has the highest embodied energy (69720 MJ for production and manufacturing stage versus 34800 MJ, 51300 MJ, and 42350 MJ for plastic, steel and timber formwork, respectively.) Plywood thus has 2, 1.3 and 1.6 times more embodied energy than plastic, steel and timber formwork. This shows that using renewable materials such as plywood is not the ideal choice because they have a shorter life span. Transportation energy for plywood increases from 222 MJ to 1554 MJ because materials need to be transported to site seven times.

The end-of-life avoided production is a net energy saving equal to −12000 MJ, −22000 MJ, −1750 MJ and-1010 MJ for plastic, steel, plywood and timber formwork as shown in Fig. 6. Steel has the highest net energy saving among all the alternatives. The energy recovered from recycling steel formwork is 1.8 times higher than the net energy reduction for plastic. Finally, the total embodied energy is 23022 MJ, 29522 MJ, 59024 MJ, and 36834 MJ for plastic, steel, plywood and timber formwork. This shows that plywood has 2.5, 2, and 1.6 times more embodied energy than plastic, steel and timber formwork. Thus, the best materials from the perspective of embodied energy are plastic as they require less energy for 50 uses.

3.3. Economic analysis

The LCC of purchasing, transporting formwork to site, workers' wages, and the income from selling at the end of the life cycle were evaluated over one and 50 uses for all four options (stage 3). Table 4 shows the cost of setting up a single use wall formwork, excluding the end-of-life impact. The steel formwork is 23 % more expensive ($3194) than plastic formwork ($2460). On the other hand, the plywood formwork costs 9 % more than timber plywood at $1645 versus $1495.

The proportion of materials and processes for plastic formwork is slightly different for steel for one use. The contribution of the plastic panels is 51 %, 3 %, 5 %, 10 %, 7 %, 1 %, 3 % and 20 % for the plastic panels, tie rod, anchor nut, pull–push prop, alignment bar, locking handle, wages, and transportation, respectively. Thus, the highest

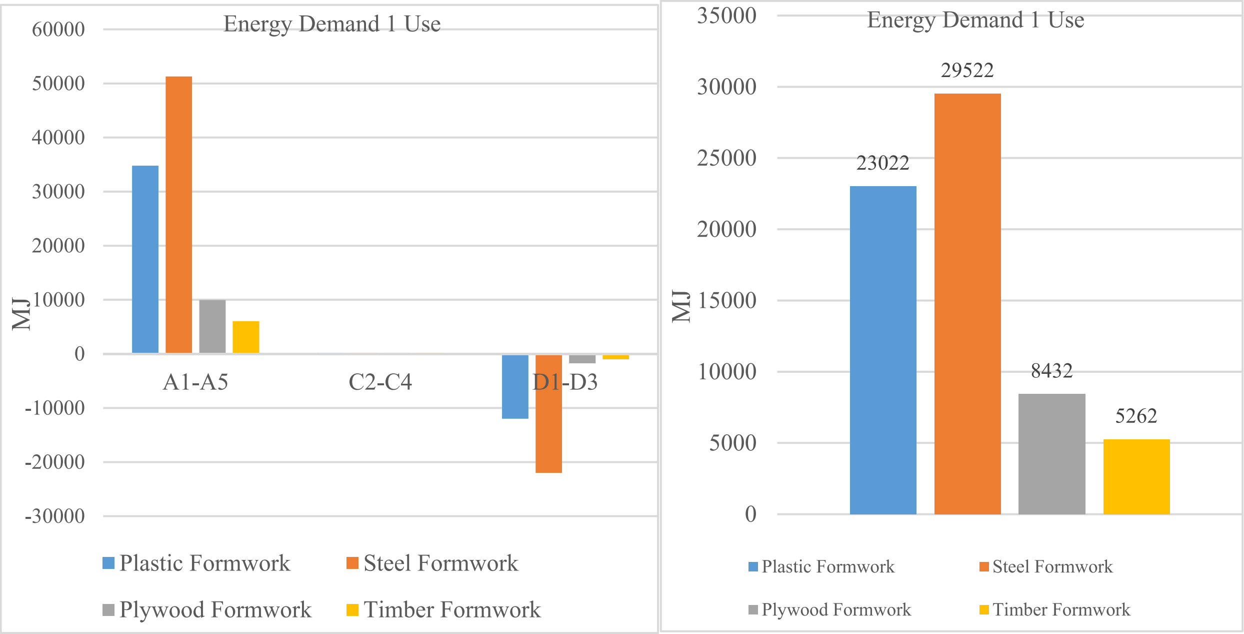

Fig. 5. Cumulative energy demand for one use.

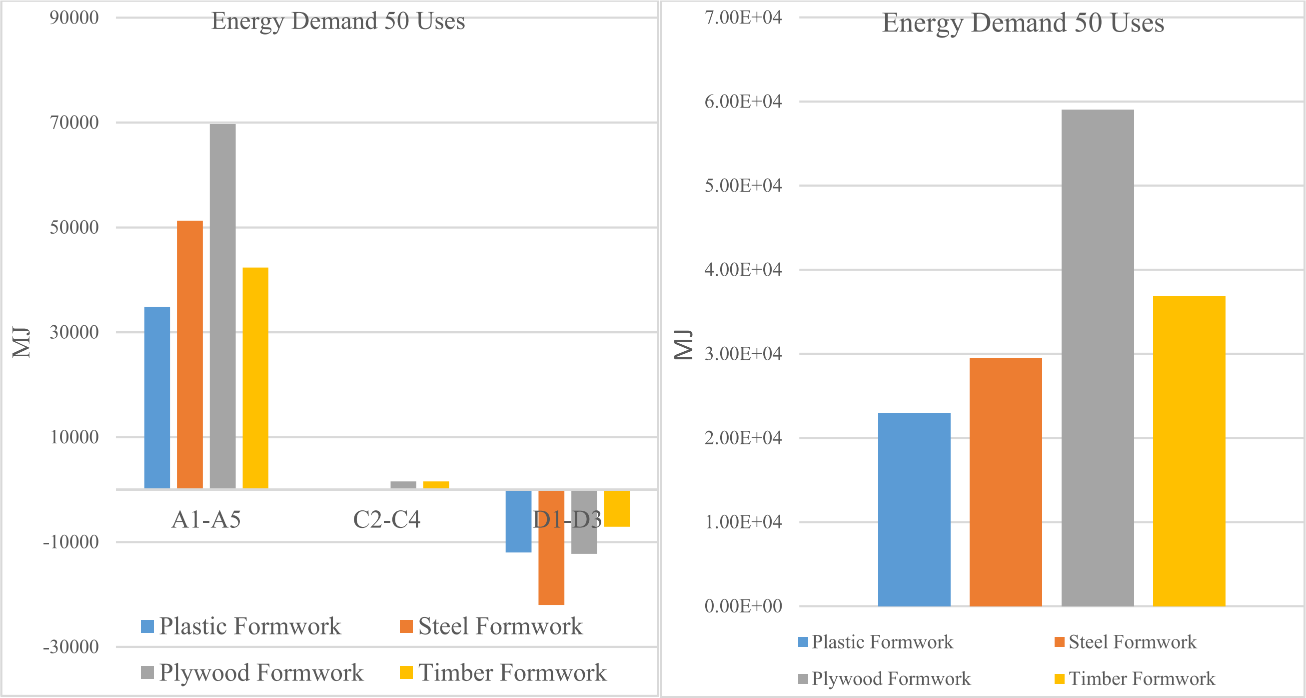

Fig. 6. Cumulative energy demand for 50 uses.

Table 4
Life cycle cost for one cycle.

Items- Case studies		*Materials*	*Cost-$*	*Wages*	*Transportation*
Plastic Formwork	*FW1*	Plastic panel	1,254	70	497
		Tie rod	77		
		Anchor nut	127		
		Pull-push Prop	239		
		Alignment Bar (Waler)	167		
		locking Handle	29		
Steel Formwork	*FW2*	Metal panel	1672	70	497
		Bolt and nut	61		
		Alignment Bar (Waler)	461		
		Tie rod	76		
		Pull-push Prop	230		
		Plate nut	127		
Plywood Formwork	*FW3*	Plywood sheathing panel	780	80	200
		Stud & wale (wooden)	140		
		Tie wire	85		
		Stringbacks	110		
		Pull-push Prop	250		
Timber Formwork	FW4	Wood sheathing panel	650	80	200
		Stud & wale (wooden)	120		
		Tie wire	85		
		Stringbacks	110		
		Pull-push Prop	250		

contribution to cost relates to plastic panels and transportation. The contribution of steel formwork cost is similar to plastic. Transportation is responsible for 52 % and 16 % of the cost. The whalers contribute 15 % of the total cost for one use. Other components and process costs are bolts, tie rods, plate nuts, and wages of 2 %, 2 %, 7 %, 4 %, and 2 %, respectively. The highest cost for plywood (FW3) relates to the plywood sheathing panel as the main part of formwork contributing 47 % of the cost and pull–push props that align the sheathing in place during the casting of concrete accounting for 15 % of cost. The timber (FW4) formwork's highest costs relate to the wood sheathing panel (44 %), Wood sheathing panel (17 %), and transportation (13 %).

Overall the main formwork panel, pull–push prop, and transportation are the three main cost components of constructing the formwork. The resale of formwork has a net income, and steel shows the best performance. The net cost savings are −378, −525, −136, and −121 for plastic, steel, plywood, and timber formwork. Finally, the steel formwork has the highest economic cost of $2,670, versus $2,081, $1,509 and $1,374 for plastic, plywood, and timber formwork, respectively (Fig. 7, A). Thus, the LCC result of one formwork use shows that timber is the ideal choice.

Finally, after 50 uses, the plywood formwork has the highest cost of $14,000 followed by timber formwork at $13,055. This shows that renewable materials are not suitable because their life span is shorter when used as formwork. Alternative materials such as steel and plastic have cost advantages. The LCC of plastic is $5,556, which is lower than steel by $6,144. Therefore, it can be concluded that in the LCC category, plastic formwork is the best option.

3.4. *Multi-Criteria Decision-Making*

MCDM was used to rank the formwork options by balancing their environmental, embodied energy, and economic impacts (stage 4). To begin, construction estimators, project engineers and academics evaluated the importance of each criterion. They assigned weightings based on the importance of each of the seven criteria. The results are shown in Table 5. CRa less than 0.1 indicates that the comparison matrix is consistent. The first group of respondents was of construction estimators whose priority was cost. The project engineer believed strongly that cost should be prioritised when choosing formwork. Literature[42]indicated that formwork accounts for up to 25 % or more of the cost of the structure of a building. The project engineer considered GWP impact as secondary and embodied energy as third. Of note is that the second and third ranks are close to each other (0.23 versus 0.22).

Moreover, the construction estimator believed that HCT should be the fourth priority, followed by OFHH and TAP. Project engineers had

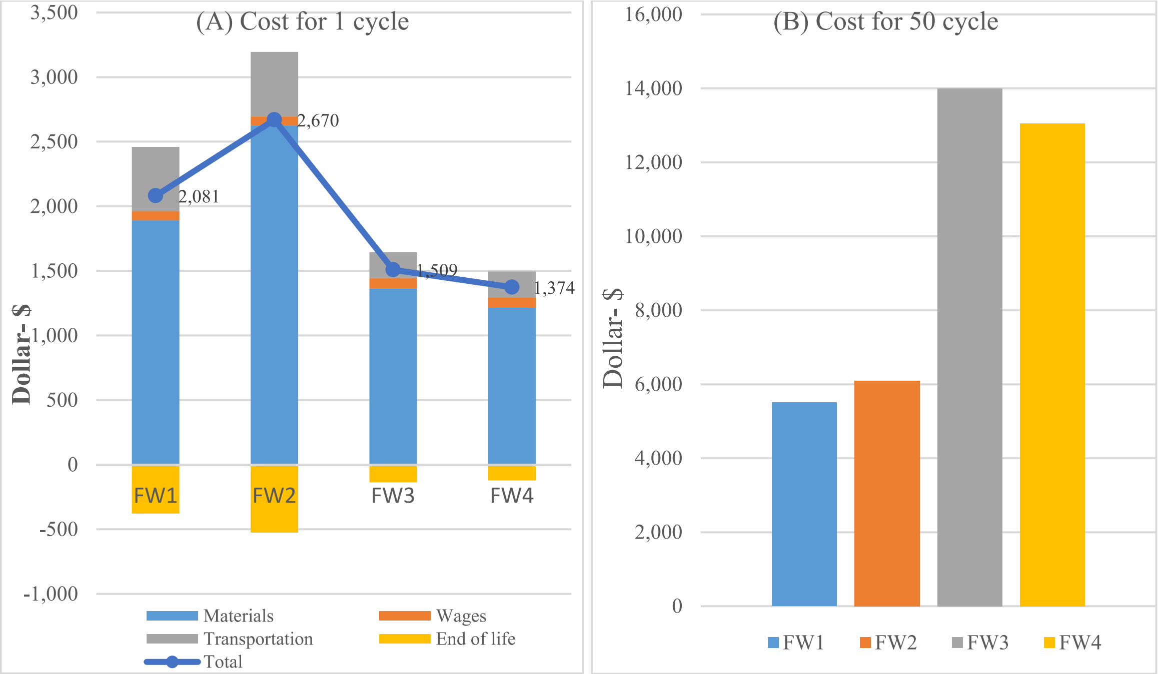

Fig. 7. A) LCC of one cycle, B) LCC of 50 cycles.

Table 5
Generalised survey results.

Criteria	*Construction Estimator*		*Project Engineer*		*Academic*		*Total*	
	Weighting	Priority	Weighting	Priority	Weighting	Priority	Weighting	Priority
GWP	0.23	2	0.2	2	0.19	1	0.207	2
TAP	0.05	6	0.035	7	0.11	6	0.065	7
HCT	0.11	4	0.12	5	0.11	6	0.113	5
OFHH	0.077	5	0.12	5	0.12	5	0.106	6
FRS	0.046	7	0.155	4	0.14	4	0.114	4
Embodied energy	0.22	3	0.16	3	0.17	2	0.183	3
Cost	0.267	1	0.21	1	0.16	3	0.212	1
CR_a	$0.045 < 0.1$		$0.066 < 0.1$		$0.043 < 0.1$		$=1$	

Legend: Global Warming Potential (GWP), Terrestrial acidification potential (TAP), Human non-carcinogenic toxicity (HCT), Ozone formation, human health (OFHH), fossil resource scarcity (FRS).

the same priorities as construction estimators. They prioritized cost over other choices. Interestingly, their second and third choices were the same as for construction estimators. After that, they selected GWP and embodied energy. Their fourth to seventh priorities were FRS, OFHH, HCT and TAP. Unlike the two previous groups, the academics strongly believed that GWP should be considered the highest priority. They considered embodied energy and cost as second and third, respectively. The FRS, OFHH, HCT, and TAP were their fourth to seventh priorities. Finally, the accumulation and average of the three groups of respondents revealed that cost was considered most important, followed by GWP, embodied energy, FRS, HCT, OFHH, and TAP.

The initial decision-making matrix for the different formwork configurations is presented in Table 6 (drawn from Figs. 4, 6, and 7). To analyse the alternative criteria it is necessary to define the non-beneficial criteria and the beneficial ones. The non-beneficial criteria were identified as those with the maximum value or amount. For example, comparing the cost of four formwork cases (Table 6), timber formwork has the highest cost at $14,000. Thus, all the criteria considered their minimum amount as the beneficial value.

Table 7 shows how MCDM was used to rank the different types of formwork using the TOPSIS method. This approach uses the best data for the four formwork options based on seven criteria and based on their weighing from Table 5. Firstly, the matrix was normalised using Eq. (3). (The results are provided in appendix 1.) Secondly, the weighed normalised matrix value was calculated using Eq. (4), with the results shown in Table 7. For example, the weighted normalized matrix of GWP is 0.05, 0.07, 0.15 and 0.11 for FW1, FW2, FW3, and FW4, respectively. In the next step, the ideal best value was assessed. Since all the criteria

Table 6
Initial decision-making matrix.

Formwork	GWP	TAP	HCT	OFHH	FRS	Embodied energy	Life cycle Cost
FW1	1453	7.88	12	4.63	509	23,022	5,511
FW2	2101	5.52	10	3.53	434	29,522	6,099
FW3	4648	18.75	21	18.66	1298	59,024	14,000
FW4	3511	12.23	46	9.20	803	36,834	13,055

Table 7
MCDM using TOPSIS results.

Formwork	GWP	TAP	HCT	OFHH	FRS	Embodied energy	LCC	S_i^+	S_i^-	P_i	Rank
FW1	0.0519	0.0294	0.0310	0.0289	0.0344	0.0534	0.0562	0.01	0.20	0.95	1
FW2	0.0679	0.0171	0.0211	0.0170	0.0335	0.0685	0.0622	0.03	0.18	0.87	2
FW3	0.1502	0.0464	0.0440	0.0899	0.0876	0.1370	0.1427	0.19	0.05	0.22	4
FW4	0.1134	0.0303	0.0975	0.0443	0.0542	0.0855	0.1331	0.14	0.09	0.39	3

are non-beneficial such as cost, the minimum value considered as ideal and the maximum value will be the ideal worst using Eq. (5). Thus, the positive ideal solution (A^+) is 0.0519, 0.0171, 0.0211, 0.017, 0.0335, 0.0534, and 0.0562, versus the negative ideal solution (A^-) as 0.1502, 0.0464, 0.0975, 0.0899, 0.0876, 0.137, and 0.1427. In the next stage, the Euclidean distance S_i^+ was calculated from the ideal best using Eq. (6) and the distance between the alternative negative ideal solutions S_i^- was calculated using Eq. (7) to determine the ideal worst solution. In the final stage, the performance score P_i was calculated using Eq. (8). The highest P_i identified the priority choice of formwork, evaluating all criteria. This indicated that plastic was the best material for constructing concrete formwork.

Sensitivity analysis was considered by altering the weightings of different criteria. To avoid human subjectivity in interpreting the results, the weighing considered were the same for all criteria and equal to 0.142 (one divided to seven). Therefore, all the above analysis was recalculated. The best alternative changed from plastic to steel formwork as shown in Appendix 2. Industry and human opinion can thus alter assessments of the ideal alternative because some criteria such as cost, GWP, and embodied energy outweigh terrestrial acidification potential or human non-carcinogenic toxicity.

The next sensitivity analysis was to change the life span of timber and plywood formwork. It became apparent that decreasing the number of uses from seven does not change the result and plastic formwork is still the preferable choice. However, some studies have reduced to five the number of times renewable materials such as wood can be used. This would not change the result from plastic as the best framework option. By decreasing the number of times of wood can be reused, the cost and environmental emissions increased.

Additionally, it can also be assumed that wood and plywood formwork can be reused 10 times. By increasing the life span of plywood for timber from seven to ten times, these materials need to be replaced multiple times for fifty cycles. In this regard, the priority remains unchanged. For example, the GWP are 1604 kg-CO_{2eq}, 2101 kg-CO_{2eq}, 3320 kg-CO_{2eq}, and 2530 kg-CO_{2eq} for plastic, steel, plywood, and timber formwork, respectively. Previous research Bin Marsono and Balasbaneh [8,27,52]only focuses on GWP emissions in LCA analysis. However, in the study reported here GWP is the only criterion that identifies plastic is an ideal formwork material (Fig. 3) and the results of other criteria and against these choices. Thus, evaluating one environmental impact does not provide a holistic comparison of different materials, and might lead to misinterpreting results. We reevaluated the MCDM by considering three criteria (GWP, embodied energy and cost) and excluded the other four environmental criteria (TAP, HCT, OHH, and FRS). This resulted in plastic formwork dominating the other alternatives by P_i of 1.0 versus 0.851, and 0.401 for steel and timber formwork, which were ranked as second and third priorities.

The question also arises whether renewable materials such as timber and plywood can be considered as sustainable formwork choices. Referring to the results for 50 uses, in none of the above problem-solving MCDM could timber or plywood formwork be considered as the idea choice. The reusability and life span of materials such as plastic and steel can profoundly impact the sustainability of these materials. Besides, the number of environmental impacts and human subjectivity involved in the AHP method can alter the final results.

4. Discussion

Concrete formwork usually incorporates wood and plywood in its manufacture. The main disadvantage of such conventional formwork is that it requires assembly by skilled workers. This is time-consuming and costly. Furthermore, timber formwork is generally vulnerable to swelling, twisting, and cracking. Steel and plastic formwork, on the other hand, are easy to install, leakproof and easy to dismantle, but are more expensive. As shown in Fig. 3, for a single cycle, plastic formwork has the highest emissions and impacts in all categories except Global Warming Potential (GWP). However, after 50 cycles, the results change. Fig. 4 shows that steel formwork is the best choice in terms of environmental impact, making it the optimal formwork choice. This controversial result revealed that timber materials may not always be sustainable. While they may be appropriate when used as general building materials, they are the best option when used for formwork. Interestingly, plastic formwork turns out to be an ideal choice after 50 cycles from an embodied energy and economic cost perspective. Thus the main differences between steel and plastic formwork remain those of environmental impact, embodied energy and economic cost. MCDM showed that plastic is the best formwork material.

There are few studies that evaluate the LCA of formwork. This makes it difficult to explore the nuances between different approaches in a paper like this. One such study by, Kazi.,Kazi and F, p, [20]evaluated alternative formwork materials such as timber, plastic and steel, showing that plastic was the cheapest option. This result is compatible with the current study. Future research could evaluate the quality of finished concrete after the formwork is removed. This could be achieved by measuring the profile of the concrete surface as well as of any imperfections. Similarly, the assembly and dismantling of formwork could be evaluated as well as the safety procedures inherent in this work.

5. Conclusion

In concrete construction, formwork refers to the temporary moulds that contain concrete when it is a workable state. The cost of construction components such as formwork is very high. It involves expenditure of up to 25 % of the cost of a structure or, based on other research, up to 60 % of the cost. This shows the importance of evaluating different formwork materials based on their costs and a holistic view of sustainability. This is despite wood and wooden materials being recognised as sustainable choices compared to steel or plastic. However, the challenge of choosing appropriate formwork materials based on their reusability is different, which profoundly impacts decision making about which material to select. To date there is little published research that compares different formwork materials. The life cycle assessment conducted in this study was chosen to evaluate environmental impacts and embodied energy along with the life cycle cost of alternatives. The research comprised two main categories.

Firstly, formwork was evaluated based on one use. This identified timber as the ideal choice in all environmental categories, followed by plywood. Plastic generated lower emissions than steel in all categories except GWP. The embodied energy and cost results also showed that timber was the best choice. Secondly, formwork materials were evaluated based on 50 uses to disclose if the best option based on any criteria changed. The results showed that the ranking of materials had changed for all criteria. Timber formwork became the third best choice after steel and plastic formwork for all environmental categories. Plastic formwork was the best choice with respect to embodied energy, GWP, and cost analysis. Steel then became the second choice based on these criteria. However, steel formwork has a lower impact on terrestrial acidification potential, human non-carcinogenic toxicity, ozone formation, human health, and fossil resource scarcity criteria. Based on common knowledge, renewable materials such as wood are considered the best environmentally sustainable choices. However, an analysis of 50 uses of those materials revealed different results. Since there was no single material that achieved the best value based on all criteria, multi-criteria decision-making problem solving was used to provide an outcome. MCDM showed that plastic was the ideal choice for formwork systems in the construction concrete industry, followed by steel.

Moves by the construction industry and stakeholders towards sustainable construction should benefit from these results. It is recommended that investigations of formwork materials be augmented to include consideration of aspects such as accessibility to work, maintenance, labor efficiency, and the impact of building shape. Meanwhile, the present study had some shortcomings, including the fact that it focused only on reusing formwork materials for concrete walls, while other criteria such as the quality of the finished concrete wall, storage of formwork, quality of surface finish after removing the formwork, accessibility to work, and safety were not considered.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix 1. . Normilized matrix

Formwork	GWP	TAP	HCT	OHH	FRS	EE	Cost
FW1	0.251	0.452	0.274	0.274	0.303	0.291	0.265
FW2	0.328	0.263	0.186	0.161	0.295	0.374	0.293
FW3	0.727	0.714	0.388	0.850	0.771	0.747	0.672
FW4	0.549	0.466	0.860	0.419	0.477	0.466	0.627

Appendix 2. . Same weighting

Formwork	GWP	TAP	HCT	OFHH	FRS	Embodied energy	Life cycle Cost	Si+	Si-	Pi	Rank
FW1	0.036	0.065	0.039	0.039	0.043	0.042	0.038	0.034	0.179	0.841	2
FW2	0.047	0.038	0.027	0.023	0.042	0.053	0.042	0.017	0.192	0.920	1
FW3	0.104	0.102	0.055	0.121	0.110	0.107	0.096	0.178	0.067	0.275	4
FW4	0.078	0.067	0.123	0.060	0.068	0.067	0.090	0.131	0.095	0.421	3

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I obtained my Ph.D. in civil engineering, specializing in construction management at the Universiti Teknologi Malaysia (UTM) in October 2014. UTM is one of the top public universities in the world and is ranked 191 in the QS Global World Rankings in 2022. I have published 42 papers (in journal papers, conferences, and book chapters). I am the primary author (corresponding author) of 17 ISI journal papers (*cumulative of impact factor*= 113.4). Twelve of these have been published since September 2020. My co-authors attest to my ability to work as a team member. They also confirm my capability to co-operate with high-quality scientists from different fields to address specific scientific problems (Scopus citation: h-index=12, Google Scholar citation: h-index=12, i10-index=14; ORCID id=ID 0000-0002-7823-0477). Please note that, as most of my publications are new, they have not yet been heavily cited. Therefore, I anticipate my h-index has the potential to reach 20 in upcoming years.

I have registered five intellectual property (copyright) applications related to composite material innovations for the building industry. These target different objectives such as sustainability, lightweight structures, and extending the lifespan of buildings. I have filed one intellectual property (patent) related to incorporating engineered wood as a hybrid component for building slabs in collaboration with industry commercialization. These innovations propose cleaner products and environmentally considerate building structures aligned to the circular economy. I have received and led two grants related to saving energy during the operation of buildings. These grants evaluate different insulation and phase-change materials in buildings. I have also actively collaborated on six other research grants since 2019.

I started my career as a lecturer in 2016, and am involved in teaching about 200 students each semester. I am currently working as a senior lecturer in the public Universiti Tun Hussein Onn Malaysia (UTHM) university in Malaysia. Since my major is construction management, I have lectured on many relevant topics in master's and bachelor's degrees. The subjects I have taught include Construction Engineering, Project Management, Sustainable Construction Engineering, and Civil Engineering Software. I supervise students in their final projects, on average 10 undergraduate (Bachelor) and one MSc and one PhD student every year, showing my contribution to knowledge transfer. I serve and contribute to the research community as a member of the editorial board of two journals, Journal of Architectural Environment & Structural Engineering Research and Journal of Building Material Science. I have collaborated as an organizing committee member for two conferences (IConCEES and GCoMSE) in 2021. I have also collaborated in other community services regarding school renovation in Malaysia and many workshops.