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QUANTIFICATION OF EMBODIED CARBON (EC) FOR RESIDENTIAL DEVELOPMENT PROJECT

Chao Jien TING[1], Kok Weng TAN[1, *]

[1] Faculty of Engineering and Green Technology, Universiti Tunku Abdul Rahman, 31900 Kampar Perak, Malaysia.
[*] corresponding author: E-mail: tankokweng@utar.edu.my

Abstract

This study aims to provide a comprehensive understanding on the quantitative study on indirect energy-related emissions, so called embodied carbon in housing development projects using Life Cycle Assessment (LCA) approach. The assessment was carried out based on a residential housing development project in Malaysia, with a gross floor area of 92,903 m². The assessment focused on the cradle-to-site phase of the building lifecycle, excluding on-site waste generation. Results revealed that a single residential unit accounted for 68.60 tCO_2e (0.738 tCO_2e/m^2). The primary contributors to embodied carbon from material manufacturing were steel (38.12%), bricks (15.26%), and concrete (14.16%). The findings suggest that embodied carbon can be significantly reduced by sourcing materials locally within a 200 km radius, which alone could reduce material transportation emissions by 11%. The proposed LCA framework offers a practical reference for Malaysian construction companies to initiate early-stage embodied carbon assessments, potentially advancing sustainable residential building practice.

Keywords:

Carbon emission;
Climate action;
Life cycle analysis;
Malaysia.

1 Introduction

Human activities are significant contributors to greenhouse gas (GHGs) emissions, leading to substantial environmental challenges such as climate change and landfill overflows. Among GHGs, carbon dioxide (CO_2) plays a critical role in the greenhouse effect, capturing solar heat and exacerbating global warming [1][2]. These emissions pose severe risks to sustainable development goals and human survival. Addressing this global crisis requires decisive actions, such as the legally binding international “Paris Agreement.” Malaysia ratified the agreement on November 16, 2016, committing to a 45% reduction in carbon intensity relative to the gross domestic product (GDP) by 2030, compared to 2005 levels.

The key economic sectors in Malaysia, contribute to GHG emissions which are energy, industry, transportation, agriculture, and land development. The global CO_2 emissions are attributed to the construction of the built environment [3]. The construction sector, accounting for 39% of direct and indirect emissions [4][5] which plays a crucial role due to its substantial resource consumption and carbon footprint. The emissions from construction sector can be categorized into operational carbon (OC) emitted during a building's usage phase and embodied carbon (EC) arising from the production, transportation, and installation of building materials. Although operational carbon dominates a building’s lifecycle emissions, recent studies emphasize the significant annual impact of embodied carbon due to its release over a shorter time frame [6][7]. This highlights the importance of evaluating and mitigating embodied carbon during the design phase.

Life Cycle Assessment (LCA) represents the predominant methodology for assessing embodied carbon, as it systematically evaluates the environmental impacts associated with all stages of a product's life. The method relies on quantifiable data concerning materials, energy use, and emissions, positioning embodied carbon analysis as a specialized application within the broader LCA framework. Impact categories such as global warming potential, resource depletion, and acidification are frequently used in the evaluation of buildings [7].

While conceptually straightforward, LCA is methodologically intricate, as it involves several assumptions that vary based on materials and other context-specific factors. LCA consists of three primary phases. First, the Life Cycle Inventory (LCI) phase compiles data on inputs (e.g., raw materials, energy) and outputs (e.g., emissions, waste) across all life cycle stages, from raw material extraction to demolition. These flows are typically expressed in CO_2e, which standardizes greenhouse gas emissions into a common metric. The second phase involves impact assessment, determining the environmental consequences of these inputs and outputs. The final phase involves interpretation which synthesizes findings to support environmentally responsible decisions. LCA can be carried out using input-output models, detailed process analysis, or hybrid methods [8].

Globally, countries, including Malaysia, have pledged to quantify embodied carbon emissions from construction materials using LCA approach. However, this task remains challenging due to extensive data requirements spanning raw material extraction, transportation, construction, and material end-of-life stages. According to the analysis done by [8], An average of 76.5 million tonnes of CO_2-equivalent was emitted by the construction sector during the 2016–2019 period, accounting for 24% of Malaysia's total greenhouse gas (GHG) emissions. The EC in construction material accounted for 90% of total GHG emissions, with construction site GHG emissions contributing 7%, and transportation of construction materials making up the remaining 3%. At the construction site, the fuel consumption, power consumption, and waste management (including transportation and treatment) contributed 90%, 6%, and 4%, respectively to total average breakdown of 7%. Based on the fuel consumption analysis, it revealed that bitumen was the primary contributor at 42%, followed by diesel fuel (35%), lubricant (12%), and liquefied petroleum gas (11%).

Malaysian Government has introduced the Malaysian Carbon Reduction and Environmental Sustainability Tool (MyCREST) as a mandatory assessment for all construction projects. Additionally, publicly listed companies are required by Bursa Malaysia to disclose their carbon footprints and reduction initiatives. Despite these measures, the Malaysian construction sector has largely focused on operational carbon, neglecting embodied carbon due to enforcement gaps, resource constraints, and low awareness. Eventually, only a small number of construction companies conduct embodied carbon assessments, while the majority prioritize operational carbon evaluations. This challenge limits the widespread adoption of embodied carbon practices, even as awareness of their significance continues to grow [9]. Establishing a baseline by quantifying embodied carbon in the early design stages allows it to serve as a key design driver, ultimately leading to more effective carbon reductions [10][11][12]. Therefore, this paper presents a quantification approach of embodied carbon throughout the lifecycle of a residential building within a housing development project in Malaysia. The findings will contribute to developing strategies for carbon reduction in the construction sector.

2 Methodology

2.1 Assessment approach

Embodied carbon is the carbon footprint of a product, building, or infrastructure project throughout the project's life cycle. Hence, the quantitative assessment of embodied carbon was conducted based on the life cycle assessment (LCA) approach in accordance with ISO 14040 and ISO 14044:2006. Before quantifying the embodied carbon in a building project, embodied carbon emissions boundary was defined. The operational phase will be excluded, and "cradle-to-site" boundary was chosen in this study. Fig. 1 indicates the life cycle stages in terms of A, B, C, and D stages which are based on the BSI EN 15978:2011 [23]. It can be measured and quantified in terms of all greenhouse gas emissions generated within the boundaries of "cradle-to-site" or "cradle-to-gate" [13]. With the aid of this systematic evaluation process, precise and numerical data was developed for further mitigation of carbon emissions.

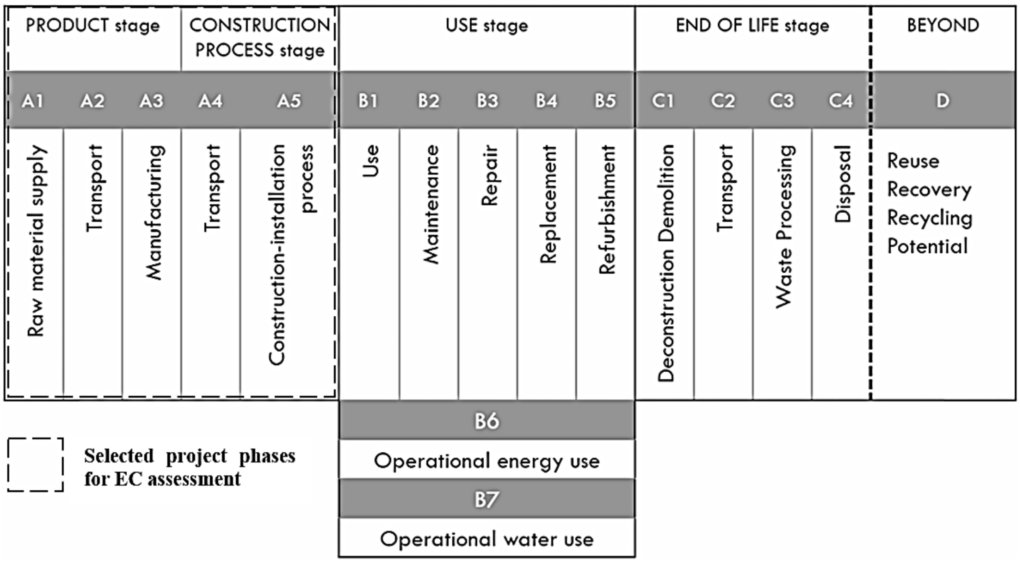

Fig. 1: Embodied carbon life cycle stages [23,14].

As mentioned earlier, the process based LCA method was used in this study. This method entailed defining a product system and its boundaries and then documenting all the inputs and outputs that happen between that system and the environment. Materials and energy are both considered flows, and once the inventory was created, each item's environmental impact was assessed. The corresponding research was then established, which involves introducing the project, determining carbon emission inventories, and collecting data on building material consumption and transportation. The gathering of data on system inputs and outputs from primary or secondary sources is necessary for embodied carbon assessment.

Collecting primary data requires accessing suitable sources, which can be resource intensive. Hence, this study used the secondary data provided by the project developer. The secondary data is more accessible but may not be fully representative of the process or material being assessed. Carbon factors are reported in units of carbon dioxide equivalent, CO_2e. For example, carbon factors for materials are generally reported in terms of mass or volume, with units of $kgCO_2e$ per kg (or tone) or per cubic meter (or other appropriate unit) of material; whereas, for energy can be reported per megajoule or kWh of electricity, or per unit of fuel consumed (e.g. liters). The material amounts were multiplied by their respective embodied carbon coefficients, as stated in the data inventories chosen.

By adding the EC values of all materials in each element, the elemental embodied carbon was calculated. The elemental EC values were then used to calculate the embodied carbon of the building skeleton. For the construction, installation, and transportation activities, embodied carbon emissions were calculated by multiplying economic activities by their corresponding emission factor. Total carbon emissions for the economic activity process were determined by summing up the emissions of each segment or stage.

2.2 The background of housing development project

The selected project for this study involved the development of a residential building. Total 347 units of low-cost single-story terrace houses were built in the Manjung District located in Perak State, Malaysia. Table 1 highlights basic information of the project. The selected residential housing development was divided into three categories into (i) end unit, (ii) intermediate unit, and (iii) corner unit. There are differences in material usage and the construction area in each category, which is taken into consideration in the assessment. The gross floor area (GFA) of the building was 92.903m^2.

2.3 Data collection

The physical quantities of materials and energy at each life cycle stage (input and output) were collected from the developer. Based on physical quantities of materials and energy, the carbon factors corresponding were determined based on the standard provided by Malaysia Construction Industry Development Board (CIDB).

Table 1: The basic information of the case building.

Project details	Description
Objective	Determine the embodied carbon per unit
Building type	Residential
Location	Kampung Serdang, Manjung, Perak
Size –(m^2)	92.903 (268 m^2 per unit)
Total unit	347
Assessment boundary	A1-A5 stages
Data sources	Material quantities – Bill of quantity Carbon data – Construction Industry Development Board (CIDB) database

Ideally, data from the Malaysian construction industry, including material properties and prices, was preferred. National average data has been utilized by certain researchers instead of overseas data to enhance the reliability of the results. However, lack of comprehensive life cycle inventory analysis was conducted using data specific to Malaysia. Therefore, this research study utilized both local and international data, including ICEv3.0 and United Kingdom (UK) Government data (https://www.carbonfootprint.com/international_electricity_factors.html), for the compensation of a scarcity of local data.

This study focused on embodied carbon emissions during construction phases. This study did not encompass the recurrent carbon emissions involved in use and the end-of-life stage (B, C and D stage). The reason was due to the numerous assumptions needed to encompass the complete lifespan of a structure and the project may subject to change locally.

Furthermore, stage A5 can be classified into 2 types: A5w (material wastage on site) and A5a (site activities). The Malaysian construction industry does not commonly practice reuse, recovery, and recycling, resulting in insufficient data for calculating the embodied carbon assessment in stage A5w and stage D. Thus, the selected project phases for EC assessment were A1: Raw material supply, A2: Transportation of raw material, A3: Manufacturing of construction material, A4 Transportation of construction to site, A5 Construction installation process.

The inventory of building materials, products, and components is required to quantify the embodied carbon footprint during A1 to A3 stages. Material quantities were acquired from quantity survey data, and a standard bill of quantities (BoQ) in several units. These units included kilograms (kg), tone (t), meter (m), square meter (m^2), and cubic meter (m^3). To ensure the reliability and accuracy of the results, the carbon emission factors of the selected construction materials were extracted from the inventory developed by Construction Industry Development Board (CIDB) Malaysia. However, there are only 500 embodied carbon data information available in this local inventory, thus, Inventory of Carbon and Energy (ICE) ver. 3.0 database (https://circularecology.com/embodied-carbon-footprint-database.html) was chosen as the backup database to use for addressing the unavailable embodied carbon data.

There were assumptions made in transportation stage which are A2 and A4 as the actual transport distance, type of vehicles, and mode of transport might be different in some situations. While the amount of fuel consumption was excluded due to the unavailable record of the fuel. In Malaysian context, all average mode of transportation used is indicated in terms of heavy goods vehicles, tonnage, etc. The calculation of embodied carbon for transportation within the cradle-to-gate boundary should be based on the mode of transport, emission factors of transport per kg km, and the transportation of 1 kg of materials such as gCO_2/kg/km. Information on body type, distance travelled for material transportation from factories to construction site (in km), and mode of transport will be collected. However, local data is still not available, therefore international transport emissions factors as shown in CIDB inventory will be applied in this research. Also, some transport emissions factors from other literatures will be considered as well. Table 2 is the transport emissions factors for different transport modes.

The site activities are indicated in terms of on-site electricity consumption and fuel consumption. Fuel consumption of construction equipment will not be considered in this study as Malaysian construction companies have no practice in recording the fuel consumed either in terms of cost or volume.

Table 2: Transport emissions factors for different transport mode [15,17].

Transport mode	Transport emission factors [kgCO_2e/kg/km]
Road transport emissions	0.10650×10^{-3}
Sea transport emissions	0.16140×10^{-4}
Freight flight emissions	0.59943×10^{-3}
Rail transport emissions	0.25560×10^{-4}

The amount of electricity consumed during the construction activities is extracted from the electricity bill in unit of kWh. Likewise, the type of electricity used needs to be determined to multiply with the corresponding carbon emission factors. In Malaysia, coal type fuel is the major generator for grid electricity, but renewable energy is also available in higher cost. Due to the absence of local data, the electricity emissions factors are adopted from [17].

The electricity emission factor was calculated by assuming the fuel source used is 38 % of coal, 48 % of natural gas, 36 % from oil, and 40 % from bioenergy. Based on fuel data by Malaysia on 2022, 41.8 % of coal, 38.1 % of gas, 17.0 % of hydropower, 1.1 % of oil, and 1.1 % of solar energy were utilized as fuel mix used to generate grid electricity. Therefore, the calculated emission factor is acceptable to be used in embodied carbon assessment. Table 3 shows the electricity emission factors for generation and transmission & distribution and the total electricity production. The construction activities also involved water usage for cleaning and cooling down the machinery, thus the carbon emission from water usage might be considered although it is expected to be insignificant in the overall embodied carbon emissions of a construction building. The emission factor for water consumption in Malaysia is 0.344 kgCO_2e/m^3 as reported by [16]. The various sources of data used for this study, the main sources were identified and summarized in Table 4.

Table 3: Electricity emission factor [17].

Generation [kgCO_2e/kWh]	Transmission & distribution [kgCO_2e/kWh]	Total production [kgCO_2e/kWh]
0.45295	0.08539	0.53834

Table 4: The sources for the input of data.

Data sources	Input data
Government data – carbon factors provided by Construction Industry Development Board (CIDB) Malaysia	Inventory data for construction materials & building elements [16]
	Transport emissions factors [16,17]
Government data – provided by Malaysian Green Technology Corporation	Electricity conversion factors [17]
Government data - Department for Energy Security & Net Zero (DESNZ) Greenhouse gas reporting: conversion factors 2023 by UK government	
Factors derived from literature review	Transport emissions factors [17]
The Inventory of Carbon and Energy (ICE) database	Inventory data for construction materials & building elements
Bill of Quantity (BoQ)	Quantity of materials used
Industry data – information provided by industry body	Transport mode, transport distance
	Project details

2.4 Embodies carbon calculations

The fundamental principle of embodied carbon (EC) calculation is multiplying the quantity of a material or product with the embodied carbon factor. The total carbon emissions within the lifecycle of the building project can be calculated from the sum of the carbon emissions of all products used at each stage of the lifecycle. Thus, the equation was shown as:

$$Embodied\ carbon\ (kgCO_2e) = \sum_{each\ stage}(Quantity\ (kg) \times carbon\ factor\ (kgCO_2e/kg)) \quad (1)$$

There is an exception for A5a stage which was not calculated based on material quantities as it is the construction site activities emissions.

A1 to A3 emissions for production of the construction material was calculated by multiplying the material quantities obtained from BoQ with the corresponding embodied carbon emission factors (ECF). The equation is:

$$EC_{A1-A3}\ (kgCO_2e) = \sum Quantity\ (kg\ or\ t\ or\ m^3) \times ECF_{A1-A3}(kgCO_2e/kg) \quad (2)$$

where:
EC = Embodied Carbon,
ECF = Embodied Carbon Factors.

After getting the information on the transportation mode and delivery distance, the ECF for transportation was calculated by multiplying the transport distance (in km) with the respective transport mode emission factor, TEF ($kgCO_2$/kg/km). The formula can be defined as:

$$ECF_{A4}\ (kgCO_2e/kg) = \sum Transport\ Distance\ (km) \times TEF\ (\ kgCO_2e/kg/km) \quad (3)$$

where:
TEF = Transport Mode Emission Factors.

Accordingly, A4 emissions for delivering a quantity of materials and elements from the factory gate to the construction site can be estimated by using the equation:

$$EC_{A4}\ (kgCO_2e) = \sum Quantity\ (kg\ or\ t\ or\ m^3) \times ECF_{A4}(kgCO_2e/kg) \quad (4)$$

In short, embodied carbon emissions from A1 to A4 can be summarized as the equation:

$$EC_{A1-A4}\ (kgCO_2e) = \sum_{i=1}^{n}[Quantity \times \left(ECF_{A1-A3,i} + ECF_{A4,i}\right)] \quad (4)$$

where:
I = Number of phases or type of construction materials.

A5a emissions for the electricity consumption of on-site equipment which denotes the electric use was calculated by multiplying the consumption quantity of resource (kWh) by the emission factor of respective fuel source ($kgCO_2e$/kWh). The equation follows:

$$EC_{A5a(e)}\ (kgCO_2e) = \sum Consumption\ amount\ (kWh) \times ECF_{A5a}\ (kgCO_2e/kWh) \quad (5)$$

While for the water consumption was calculated by multiplying the consumption quantity (m^3) with the emission factor ($kgCO_2e/m^3$). The equation is:

$$EC_{A5a(w)}\ (kgCO_2e) = \sum Consumption\ amount\ (m^3) \times ECF_{A5a}\ (kgCO_2e/m^3) \quad (6)$$

The total of A5a emissions for the construction activities was computed by total up the results from equation 6 and equation 7. The equation follows:

$$EC_{A5a}\ (kgCO_2e) = EC_{A5a(e)} + EC_{A5a(w)} \quad (7)$$

After that, the total embodied carbon of a building is estimated using the equation:

$$EC_{total}\ (kgCO_2e) = \ EC_{A1-A4} + EC_{A5a} \quad (8)$$

Finally, the result is then normalized to ensure the consistency of the study. The total embodied carbon is then divided by the gross floor area, GFA (m^2). The equation:

$$EC_{total}\ (kgCO_2e) \Big/ GFA\ (m^2) = kgCO_2e/m^2\ \ GFA \qquad (9)$$

where:
GFA = Gross Floor Area.

To make comparison with the past study, the kg unit in every equation will be divided by 1000 to convert it into t, tonne.

3 Results

3.1 Embodied carbon from material production stage (A1 to A3 stages)

The Table 5 shows the production stage embodied carbon (measured in terms of tCO_2e,) for each building element across the residential building. The EC of this stage was 65.09 tCO_2e, which accounted for 94.89 % of overall EC of the cradle to site for this case building. The embodied carbon emission of the residential building has been classified into 4 major building elements which are substructure, superstructure, finishes, and other services. The superstructure in the residential building accounted for more than 50 % of EC which was found to be 38.00 tCO_2e. Moreover, the substructure contributed 18.49 tCO_2e (28.40 % of cradle to grave EC), followed by the finishes with 8.39 tCO_2e emissions (12.88 % of cradle to grave EC), and the services with an EC of 0.22 tCO_2e (0.34 % of cradle to grave EC). This emission is due to the quantities of materials required for the building elements. The larger the quantities, the greater the EC emissions. The materials input for the superstructure was found to be the highest among 4 building elements.

Table 5: The breakdown of embodied carbon based on different building elements.

Element Cluster	Total material used quantity [kg]	Total Embodied Carbon [tCO_2e]	Percentage contribution to total
1.0 Superstructure	**82,651.62**	**38.00**	**58.3%**
1.1 Doors	545.17	0.77	1.2
1.2 External Walls	22,617	8.60	13.2
1.3 Frame	29,286.10	4.52	6.9
1.4 Internal walls & partitions	22,297.39	5.35	8.2
1.5 Roof	7,897.98	12.74	19.6
1.6 Windows	7.98	6.02	9.2
2.0 Substructure	**60,709.35**	**18.49**	**28.4%**
3.0 Finishes	**13,649.51**	**8.39**	**12.9%**
3.1 External ceiling finishes	124.2	0.054	0.1
3.2 External floor finishes	3,105	0.43	0.7
3.3 External wall finishes	1,004.7	0.25	0.4
3.4 Internal ceiling finishes	256.21	0.57	0.9
3.5 Internal floor finishes	1,417.5	1.11	1.7
3.6 Internal wall finishes	7,741.9	5.97	9.2
4.0 Other Services	**134.70**	**0.22**	**0.4%**
4.1 Sanitary Appliances	134.7	0.22	0.4
Total		**65.1**	**100 %**

The superstructure in the case building contributed 58.3 % of the total EC intensity at the production stage. This significant contribution is due to the large amount of concrete and reinforcing steel used in this building element. The superstructure was consisted of external walls, frame, internal walls, roof, windows, and doors. These building components were produced with various types of materials associated with high EC intensity. These results are also corresponded with case study done by [17] [18]. Comes to the material level, the amount of concrete is the highest among the five building materials, but not the highest proportion of embodied carbon. Steel, on the other hand, is the greatest embodied carbon contributor, although it has a smaller amount of material. This is because steel has a higher embodied carbon factor value than brick, concrete, and cement without comparing it to the window. This result is consistent with the findings of previous study by [19] and supports that steel is the main contributor to the embodied carbon at the material level. Therefore, recycling or reuse of steel products should be more effective to reduce embodied carbon.

For the construction material level, Table 6 shows the embodied carbon emissions of the case building at the material level. Their total contribution to the entire building was presented in the ranking. Based on the ranking, the top five building materials account for 86.14 % of the estimated total EC of the building. These products included steel (38.12 %), brick (15.26 %), concrete (14.16 %), cement (9.36 %) and windows (9.24 %). Glass also contributed to a large proportion of the carbon embodied in the materials (5.26 %), followed by tiles (3.25 %), PVC (1.43 %), timber (1.10 %), other materials (1.06 %), gypsum (0.98 %), and paints (0.79 %).

Table 6: Major construction material consumption and embodied carbon contribution.

Materials	**Material quantity**	**Unit**	**Total embodied carbon [tCO_2e]**	**Percentage contribution to the total**
Steel	13,728.44	kg	24.82	38.12%
Brick	41,376.60	kg	9.93	15.26%
Concrete	76,800.00	kg	9.22	14.16%
Cement	11,494.24	kg	6.09	9.36%
Windows	7.98	m^2	6.02	9.24%
Glass	2,101.11	kg	3.42	5.26%
Tiles	5,193.50	kg	2.11	3.25%
PVC	288.08	kg	0.93	1.43%
Timber	1,996.04	kg	0.71	1.10%
Other	2,459.70	kg	0.69	1.06%
Ceiling	1,490.00	kg	0.64	0.98%
Paints	209.58	kg	0.51	0.79%
Total	**-**	**-**	**65.1**	**100.00%**

3.2 Embodied carbon from material transportation stage (A4 stage)

Since the mode of transportation is the same for all materials, namely road transport, the EC emissions depend on the transport distance and the total weight of the transported material. Based on the data on the total distance from the suppliers to the construction site and the total weight of the transported materials, the EC emissions for the transportation of the materials are calculated and listed in Table 7. The total EC emissions of the A4 phase amounted to 3.438 tCO_2e, which is 4.72 % of the total EC emissions from cradle to site for this case building. It should be noted that the weight of the transported materials may differ from the amount of material used for construction, as some of the materials were recycled from previous construction projects and no data is available for this recycling. The transportation distance of steel material was the highest compared to other materials. Obviously, the transportation of concrete was the highest EC contributor with 48.04% of total EC of A4 stage. The amount of concrete used for construction is the highest, so the EC value is greatest during transportation to the construction site. This depends on the amount of material transported. The larger the amount of material, the higher the EC emissions. This also proved that the emissions of the A4 stage depend mainly on the weight of the transported material, but not on the transport distance.

Emissions associated with material transportation to the construction site are primarily attributed to the fuel consumption of heavy-duty vehicles. Several strategies may be employed to reduce the embodied carbon (EC) emissions during this phase. As indicated in Table 7, steel and tiles have the longest transportation distances (> 200km) among all materials.

Table 7: The proportion of embodied carbon associated with the transportation of each material.

Material category	Description	Distance – return and delivery [km] from the sources	Embodied carbon emissions [tCO_2e]	Percentage contribution to total
Concrete	From Chemor, Perak to the construction site	190.2	1.556	48.04%
Brick	From Bidor, Perak to the construction site	183.6	0.809	24.98%
Steel	From Petaling Jaya, Selangor to the construction site From Sungai Petani, Kedah to the construction site From Nibong Tebal, Penang to the construction site	402.0 428.0 296.0	0.454	14.01%
Cement	From Ipoh, Perak to the construction site	156.4	0.191	5.91%
Tiles	From Seremban, Negeri Sembilan to the construction site From George Town, Penang to the construction site	324.0 392.0	0.191	5.89%
Metals	From Ipoh, Perak to the construction site From Lumut, Perak to the construction site	141.2 11.2	0.029	0.89%
Timber	From Lumut, Perak to the construction site From Ipoh, Perak to the construction site	20.0 162.8	0.007	0.21%
Aggregate	From Lumut, Perak to the construction site	11.2	0.002	0.06%
Total			**3.238**	100.00%

Therefore, prioritizing local and regional sourcing can significantly reduce both transportation distances and the corresponding carbon emissions.

Notably, there is a substantial number of suppliers for steel and tiles located in the Ipoh City, Perak region. Procuring materials from these local sources could reduce the transportation distance to approximately 137–185 km. This adjustment is projected to lower EC from 3.238 tCO_2e to 2.87 tCO_2e—an estimated reduction of about 11%. Transporting materials within a 200 km range typically results in lower emissions. Furthermore, the company may collaborate with suppliers to adopt low-emission transport methods. For instance, suppliers could use fuel-efficient vehicles or alternative fuels such as biodiesel. Additionally, maintaining optimal tire pressure can enhance fuel efficiency and further mitigate emissions.

3.3 Embodied carbon from construction activities (A5 stage)

The EC of this phase amounted to 0.266 tCO_2e, which only accounted for 0.39 % of the cradle-to-site of construction embodied carbon. The total electricity and water consumption were calculated based on the total bill received as shown in Table 8. The EC generated from the electricity consumption of on-site equipment contributed to 0.244 tCO_2e in this stage which stands for 91.61 % of EC from the construction activities. Electricity in the study location of the case building is generated using coal fire power plant; hence the carbon emissions could be much higher than the water consumption. The EC contribution of water consumption is relatively insignificant as only 0.022 tCO_2e with only 8.39 % of EC is emitted during construction.

Table 8: The embodied carbon resulting from energy consumption (including electricity and water usage) during construction activities.

Category	Total consumption	Embodied carbon emissions (tCO_2e)
Electricity	452.76 kWh	0.244
Water	64.93 m^3	0.022
Total		**0.266**

3.4 The total embodied carbon throughout the cradle-to-site phase of the housing development

The embodied carbon (EC) emissions of the residential building were calculated using the corresponding data and reported using LCA methods across cradle to site which are production stage (A1 to A3) and construction stage (A4 to A5) which has been shown in **Table 9**. The total embodied carbon per unit of building was calculated at 68.60 tCO_2e. The cradle-to-gate emissions for the construction elements (A1-3) have the greatest impact, accounting for just over 90 % of total emissions. The next largest contribution comes from transportation (A4) – 4.72 % and followed by construction activities (A5) – 0.39 %. As lack of data for the maintenance or repair of various building components (B1-4), this phase of the life cycle was excluded from the assessment. The embodied carbon reduction strategies dealing with carbon-intensive materials and construction were further investigated to determine the carbon reduction potential in Malaysia.

Table 9: The total embodied carbon across the A1 to A5 stages for a single unit of the building.

Assessment Boundary	**Total Embodied Carbon [tCO_2e]**	**Percentage contribution to total**
A1 to 3 – Building products	65.09	94.89 %
A4 – Transportation	3.24	4.72 %
A5 – Construction activities	0.27	0.39%
Total	**68.60**	**100.00 %**

4 Discussion

Compared to the study of embodied carbon (EC) using LCA approach for a 6,800 m² building construction project in China [20]. The measurement of actual emissions data during the design stage is complex and inconsistent due to construction-stage variables. The building's frame structure primarily consists of concrete and steel. Construction materials are transported approximately 200–500 km from manufacturers to the site. During material production, a total of 13,502.84 tCO_2 was emitted, with an additional 1,330.19 tCO_2 attributed to transportation. Consequently, the building's total embodied carbon amounted to 14,833.03 tCO_2 (2.18 tCO_2e/m^2). A similar trend was observed, with steel, sand, and gravel identified as major contributors to EC. However, the EC per unit of building construction in Malaysia (0.256 tCO_2e/m^2) is significantly lower than that in China (2.18 tCO_2e/m^2). Variations in carbon emission factor databases for construction materials in China and other countries often lead to errors of up to 30% in embodied carbon calculations. Using more localized emission factors can enhance accuracy and reliability.

Embodied carbon emissions in the A5 construction phase primarily result from the operation of on-site machinery. Therefore, limiting machinery usage and improving operational efficiency can serve as effective strategies for mitigating the associated carbon footprint [21]. Reducing machine idle time and optimizing equipment utilization not only enhances productivity but also lowers emissions and operational costs. This ensures that machinery operates only when necessary, avoiding unnecessary energy consumption during idle periods. Site managers can further support emission reduction by conducting audits to identify inefficient equipment, which should be replaced with more energy-efficient models. This practice not only reduces fuel and electricity consumption but also leads to significant cost savings. Additionally, regular maintenance is essential to sustain optimal equipment performance and energy efficiency.

Lastly, the workflow coordination can be more effective in reducing emissions than merely improving machine efficiency. The better scheduling of equipment usage such as preventing simultaneous operation of multiple machines, although this alone may not significantly improve emissions control [22]. Thus, adopting enhanced management strategies such as task scheduling, operational planning, and activity sequencing can lead to more substantial reductions in on-site emissions. Furthermore, construction companies can reduce energy expenditures by integrating smart technologies such as automated lighting systems and motion sensors. These devices optimize energy use by automating processes such as switching off lights when areas are unoccupied, thereby improving both environmental performance and budget efficiency.

5 Conclusion

This paper presented an evaluation of embodied carbon in a housing development project using the Life Cycle Assessment (LCA) framework. The analysis encompassed emissions from the cradle-to-site stages, excluding on-site waste generation, and included material production, transportation to the site, and construction activities. The study aimed to establish general standards for embodied carbon in residential buildings. However, challenges in Malaysia, such as limited data availability (e.g., Environmental Product Declarations, EPDs), inadequate record-keeping for construction activities and material carbon factors, low awareness among construction stakeholders, weak regulatory enforcement, and constrained budgets and resources, contribute to potential inaccuracies and inconsistencies in assessment outcomes. The embodied carbon footprint of the case study building was 68.60 tCO2e, with an average of 65.10 tCO2e (0.701 tCO2/m²) primarily generated by material consumption. Material production contributed significantly to embodied carbon, with steel (38.12%), bricks (15.26%), and concrete (14.16%) as the main contributors. Among the four major building elements, the superstructure accounted for over 50% of embodied carbon emissions, totalling 38.00 tCO2e. Additionally, material transportation to the site contributed an average of 3.24 tCO2e (0.035 tCO2/m²), while construction activities emitted 0.27 tCO2e (0.0029 tCO2/m²). Based on the results, the paper concluded that the standardized embodied carbon assessment can be conducted by adopting a systematic approach such as life cycle assessment to compute and report the embodied carbon of buildings. The current assessment did not account for on-site waste generation or fuel consumption, highlighting the importance of collaboration with companies performing carbon reporting to reduce uncertainties and build a comprehensive database. Future studies are recommended to address uncertainties in the embodied carbon assessment process and extend the LCA stages for a more holistic evaluation.

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