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The Review of Embodied Carbon Quantitative Assessment in the Construction Sector

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Abstract

The construction sector is a major contributor to greenhouse gas emissions, yet the role of embodied carbon (EC) emissions associated with materials and construction processes remains under-addressed, particularly in Malaysia. This paper reviews current practices, challenges, and methodologies for assessing EC in the Malaysian construction industry. It highlights the dominance of operational carbon in regulatory reporting and the limited industry-wide adoption of embodied carbon evaluation, largely due to data gaps, lack of awareness, and implementation barriers. Drawing on local and international studies, the paper explores assessment methods such as Life Cycle Assessment (LCA), Input-Output LCA, and hybrid approaches. It evaluates the implications of building design systems, especially the role of Industrialized Building Systems (IBS), in reducing EC. The findings stress the need for standardized EC data, stronger policy enforcement, and industry collaboration to support Malaysia's transition toward sustainable, low-carbon construction.

Keywords: Embodied carbon, Construction sector, Housing development

1. Introduction

Since the 1800s, the onset of global emissions has marked the beginning of the first Industrial Revolution, recognized as a pivotal event in human history (Steffen et al., 2007). It has exerted a profound influence on people's daily lives, encompassing both economic and quality-of-life dimensions, but the environmental impacts of the Industrial Revolution cannot be overlooked. This revolution is said to be a driver of climate change due to excessive greenhouse gas emissions. Climate change refers to long-term alterations in weather conditions and temperature patterns, leading to diverse impacts, including rising sea levels, more severe extreme weather events, such as heatwaves and droughts, and disruptions in precipitation patterns.

Human activity is the primary contributor to significant greenhouse gases (GHGs) emissions and excessive waste in landfills. Carbon dioxide (CO_2), a major greenhouse gas (GHG), traps heat from the sun, contributing to the greenhouse effect (Yue and Gao, 2018). The accumulated GHG emissions amplify the effects of climate change, resulting in global warming. This phenomenon poses significant threats to the achievement of sustainable development goals and human survival. The 21st United Nations Climate Change Conference (COP21), held in 2015, marked a significant milestone with the establishment of the Paris Agreement. This global pact aims to set long-term goals for reducing greenhouse gas (GHG) emissions. Malaysia ratified the Paris Agreement on November 16, 2016, and subsequently enhanced its mitigation commitments, targeting a 45% reduction in carbon intensity relative to GDP by 2030 compared to 2005 levels (UNFCCC, 2022).

Wang et al. (2018) report that buildings account for one-third of all global energy-related carbon emissions, contributing to 39% of direct and indirect emissions. The carbon emissions during a building's life cycle are categorized into operational carbon (OC) and embodied carbon (EC), which occur at different times. Liu and Qin (2016) claimed that the operational stage accounts for up to 85.4% of total carbon emissions, while 12.6% arise from activities such as material production, transportation of building materials, construction installation, and waste generation. The carbon dioxide emitted from these activities is termed embodied carbon, whereas operational carbon refers to emissions from energy consumption during the operational phase. Despite the dominance of OC over a building's lifespan, recent research suggests that EC can have significant annual impacts owing to its release within a short time frame. Embodied carbon assessment is crucial during design to evaluate the emissions associated with construction materials.

Countries worldwide, including Malaysia, have committed to determine both direct and indirect GHG emissions associated with construction materials and their production. However, assessing indirect carbon emissions can be a challenging task, as it involves a wide range of factors, including the extraction of raw materials, transportation to facilities or sites, construction activities, and the end-of-life of materials. Despite the Malaysian government's introduction of the Malaysian Carbon Reduction & Environmental Sustainability Tool (MyCREST) as a mandatory building rating system for all construction projects, the implementation of this tool may pose constraints for construction companies (Kamal et al., 2018. Moreover, the Bursa Malaysia has mandated that all publicly listed companies disclose their carbon footprint and their initiatives in carbon reduction (Bursa Malaysia, 2024; Aman and Jaafar, 2020). However, the construction industry in Malaysia has largely neglected the quantification of indirect emissions (embodied carbon) associated with buildings, and the embodied carbon assessment process is time-consuming. As a result, only a limited number of construction companies are initiating the early stages of embodied carbon assessments, while the majority focus solely on direct emissions (operational carbon) as required by the stock exchange regulator- The Bursa Malaysia. The main problems in this regard are a lack of enforcement mechanisms, resource constraints, and low industry-wide awareness about embodied carbon. This paper aims to provide some possible approaches for the Malaysia's construction sector to conduct an embodied carbon assessment.

2. The Importance of Embodied Carbon Assessment in Malaysia's Construction Sector

The attainment of Net Zero Carbon Emissions by 2050 represents a group-wide objective that applies to the operations of all publicly listed construction and property firms in the local area, as per the public listing guideline of Bursa Malaysia. According to public listing guideline, the reporting of scope 1 and 2 emissions is mandatory, while the reporting of scope 3 emissions is optional. Scope 1 emissions are mandatory to measure as they represent the direct emissions resulting from the direct use of fossil fuels and other activities that are controlled by the reporting organization. Scope 2 emissions, on the other hand, refer to the indirect emissions caused by the usage of purchased electricity or heat. Lastly, scope 3 emissions are indirect emissions that are related to all other greenhouse gas emissions throughout the company's operations, including the use of sold products, business travel, employee commuting, extraction, production, and transportation of purchased materials and fuels that are not under the company's control. The determination of scope 3 emissions is a highly challenging and time-consuming task for disclosure.

The assessment of embodied carbon (EC) is currently a novel concept in Malaysia. The construction sector in Malaysia is a significant contributor to greenhouse gas (GHG) emissions, primarily carbon dioxide emissions. Buildings in Malaysia account for 39% of the total direct and indirect global energy-related carbon emissions, which is one-third of the overall total (Wang et al., 2018). Klufallah et al. (2014) also stated that more than 33.3 percent of the total energy use and greenhouse gases (GHGs) emissions can be attributed to buildings construction in developing countries like Malaysia. The Malaysian construction sector is responsible for 24% of the total carbon dioxide emissions (Hannah and Max, 2020). In Malaysia, GHGs are converted into carbon dioxide equivalent (CO_2-eq) for evaluation and analysis purposes, as stipulated by the Paris agreement. Carbon dioxide is the most significant GHG in contributing to global warming and climate change. The carbon emissions from a building's entire life cycle can be divided into embodied carbon (EC), which includes all GHG emissions from the materials' life cycle, such as extraction, manufacturing, construction, maintenance, and disposal, and operational carbon (OC), which refers to the total GHG emissions that occur during the building's operational phase. The main source of GHG emissions is energy consumption in different aspects. The GHG emissions based on cradle-to-site approach consists of three categories, as shown in Table 1.

Table 1. The three types of GHGs emission aspects

Greenhouse Gases Emission Criteria	Greenhouse gases Emission Sources
1) **Embodied Carbon in the Material** Construction material consumption, e.g., concrete, reinforcement, cement, steel, etc.	"Cradle-to-gate" embodied carbon is generated from the material extraction and manufacturing which release GHG after consumed energy.
2) **Material Transportation** Delivery of construction materials to the site e.g truck, lorry and other transportation methods.	The fuel consumption like diesel can be found during the material transportation and this can emit GHGs including those released from fuel processing and distribution
3) **Construction Site Emission** Utilization of machinery and equipment in the construction activities including maintenance and renovation, and the waste generation at the site.	Electricity and/or fossil fuel consumed by the machinery and equipment during the construction stage. The GHG from the fuel consumption can be sourced from combustion, production, processing, and distribution of fuel. Disposal of waste can also release the GHG.

(Source: Butler *et al.,* 2010)

The three aspects of energy consumption in relation with buildings and construction materials are operational energy, embodied energy, and inherent energy. Operational energy is defined as the energy required for heating, cooling, lighting, and powering appliances, while inherent energy is the energy embedded in building materials, that is, the energy content of the raw material. Henceforth, energy is released during the disposal of a building through combustion or chemical processing. For example, incineration of construction waste, such as debris, is inherently energy intensive. For embodied energy, it can be classified into initial and recurring embodied energy. The initial embodied energy (EE) in the construction activities is recognised as the total energy consumed across various stages, including raw material extraction and processing, construction material manufacturing, and transportation from the manufacturing site to the construction site. Moreover, recurring embodied energy refers to the energy needed in maintenance and refurbishment of a building. In accordance with (Zaid et al., 2015), residential buildings in Malaysia account for around 65 % of the global total sectoral emissions, while commercial buildings represent for the balance of 35 %. In details, the bulk of construction sector's greenhouse gases emissions are mostly produced during the operational phase with 80-90 % from energy consumption for lighting, ventilation and appliances, heating, and cooling, whereas the activities like pre-production, deconstruction, transportation of building materials, and demolition produced 10-20 % of its GHG emissions (CIDB, 2020; CIDB, 2021). A broadly similar point has also been made by Liu and Qin (2016), who found that in China construction sector, operational stage gave 85.4 % of the total carbon emissions, and approximately 12.6 % of the overall carbon emissions can be resulted from activities such as materials production, transportation of building materials and products, waste generation, and construction installation.

According to the analysis done by CIDB (2020), 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. Based on the Table 2. 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%) (CIDB, 2020).

Table 2. The breakdown of GHG emissions in construction sector

Year	GHG Emission (million $tCO_2eq.$)				% compared to National GHG Emissions 2014
	Construction Material	Transportation	Construction Site	Total	
2016	45.6	1.2	4.9	51.8	16 %
2017	67.9	2.1	5.2	75.3	24 %
2018	71.8	2.3	5.5	79.6	25 %
2019	66.8	2.3	5.6	74.6	23 %
Average (2016 – 2019)	68.8	2.2	5.5	76.5	24 %
Average Distribution (2016 – 2019)	90 %	3 %	7 %	-	-

(Source: CIDB, 2020)

According to Urge-Vorsatz et al. (2005), the energy use in the building construction sector is expected to increase from 60% to 90% and GHG emissions are projected to rise between 2005 and 2050. This projection is supported by a study conducted by CIDB for the period 2020 to 2050. CIDB used an econometric approach to estimate projections of material consumption, fuel consumption, electricity consumption, and waste up to the year 2050. The CIDB utilized the GDP as the economic indicator, referring to the Department of Statistic Malaysia (DOSM), Economic Planning Unit (EPU), and the World Bank. The historical correlation between consumption of construction materials and energy demand, as well as activity indicators, were derived with the aid of GDP. If no mitigation actions are adopted, the total GHG emissions are projected to be 147 million tCo2eq by the year 2050, representing a 92% increase compared to 2020.

2.1 Building Design System in Malaysia

Building activities and material production in the construction sector contribute significantly in GHG emissions. It is crucial to not only select appropriate strategies and technologies, but also the right materials, in order to reduce the sector's contribution to climate change. Numerous studies have indicated that timber, a naturally insulating material, is a better choice than other materials such as brick or concrete. This is because timber has low carbon dioxide emissions and is more environmentally friendly. Cole and Kernan (1996) conducted a study on an office building built using various structural frame materials which manufacturing and producing concrete frames required extra 6% energy compared to steel frames and 14% to wood frames.

Petersen and Solberg (2002) found that wood produces lower greenhouse gas (GHG) emissions compared to non-wood building components in Norway. Ortiz et al. (2010) sought to assess the environmental impacts of exterior and interior wall scenarios involving typical blocks during the construction phase. Using CML life cycle impact assessment (LCIA) method, the researchers have able to assess the global warming potential (GWP). In terms of environmental impact of GWP in a construction project, Different portions of energy were used for material fabrication, construction activities, transportation, and waste management, accounting for 8%, 6%, and 1%, respectively. Peuportier (2001) conducted a life cycle assessment study for houses which made by wood and concrete building material. The result proved that highly insulated wood house had just about half of the negative impacts as compared to concrete house. Although the use of wood in Malaysia's building components is more preferrable in reducing GHG emissions, timber structures might face short lifespan problem in terms of material strength and defective. Che-Ani *et al.* (2008) concluded that timber houses are not being constructed at the present time in Malaysia because the humid weather can lead to structural problems. Defects of timber structures can be attributed to fungal infestations, insect, weathering, and mechanical failure. Therefore, Malaysian construction and development companies prefer using timber as an alternative material for homes in the situation of the land is plentiful in the types of biomass renewable energy resource (Bin Marsono & Balasbaneh, 2015). The conventional building system, and industrialized building system (IBS) (Figure 1**)**. are identified as design system widely applied in Malaysia.

Conventional building systems can be divided into 2 primary components. The 1st component is the structural system what a column-beam-slab frame system with timber and plywood as formwork (Badir et al., 2002). This system undergoes four stages (i) formwork and scaffolding fabrication, (ii) reinforcement bar and installation, (iii) concrete placement and (iv) subsequently disassembly of formwork and scaffolding. The 2nd component is the wall system, composed of infill materials and non-load-bearing bricks.

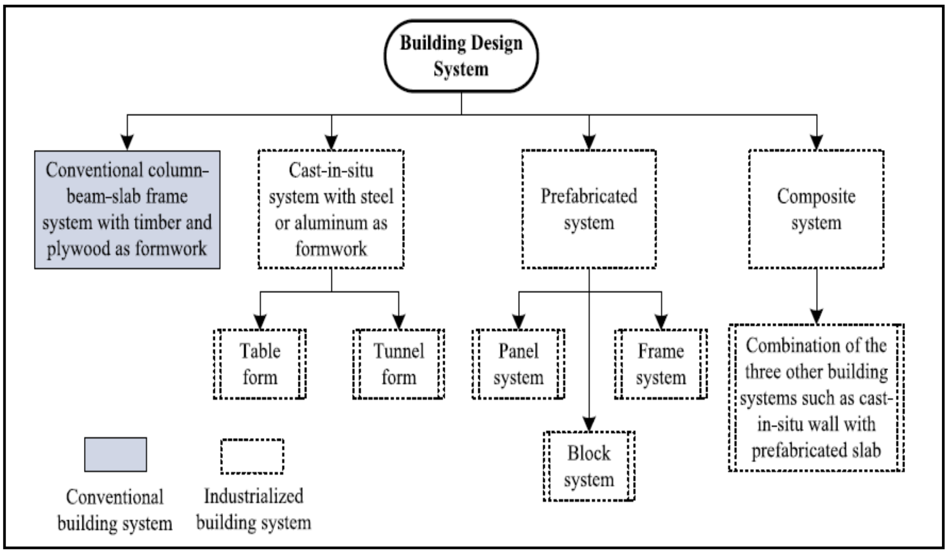

Figure 1. Types of building systems in Malaysia (Al-Awag et al., 2023)

The Industrialized Building System (IBS) is an engineering technology that utilizes in-situ cast formworks, prefabricated components, and composite systems (Al-Awag et al., 2023). The in-situ cast formworks specifically utilises prefabricated formwork made from lightweight materials such as fiberglass or aluminum. The prefabricated component involves casting structural elements before their installation at the construction site. It can be done either on-site or off-site. The composite construction method integrates factory-cast elements with those cast on-site. In essence, the Industrialized Building System (IBS) is a holistic approach that covers the entire process of building component production, including design, fabrication, transportation, and on-site assembly (Richard, 2017).

Al-Awag et al. (2023) reviews the intensities of embodied carbon (EC) and embodied energy (EE) across ten case studies in Malaysia featuring different building design systems. The studies analyzed include conventional, prefabricated, and composite systems, with some cases incorporating the in-situ cast wall paired combined with prefabricated slab. It employed an input-output life cycle assessment (I-O LCA) method, aligning with the product categories defined by the Malaysian Standard Industrial Classification (MSIC). The embodied energy (EE) intensities were primarily attributed to sectors such as natural gas, coal, petroleum refining, electricity, and gas supply (Department of Statistics, 2000). The findings revealed that industrialized building systems (IBS), particularly in residential development project, exhibited higher intensities of embodied energy and embodied carbon compared to conventional systems used in commercial and office development project. This increase is mainly due to the significant use of concrete and reinforcement steel in IBS panel systems. Similarly, Chau et al. (2017) stated that EC intensities could be increased by approximately 5% (approximately 6.3-15 kg CO_2/m^2) of total carbon emissions if there were 80% to 50% of concrete and façade elements constructed using off-site prefabricated materials. Moreover, high EE and EC values were associated with roof structures using steel-fabrication and sheeting, this is due to the high energy demands of the steel manufacturing process, which emits significant amounts of carbon dioxide.

Conversely, in conventional building designs, the most significant contributions to EE and EC intensities were observed in the upper floor elements, which typically feature a conventional column-beam-slab frame system. Because of the substantial amounts of concrete and reinforcement steel used, these materials contributed 30.47% and 30.75% to the total embodied energy and embodied carbon intensities of the building, respectively (Al-Awag et al., 2023). Thus, the choice of building design systems significantly impacts EE and EC intensities, either increasing or decreasing them. In the Malaysian context, where concrete and reinforcement steel are extensively used, IBS emerges as the most advantageous option for building construction. It not only minimizes resource wastage but also accelerates construction, thereby potentially reducing overall GHGs emissions. The GHGs emissions in construction sector is crucial to be considered in Malaysia due to current rapid economy growth. In fact, a lot of public-listed construction companies acted on their carbon footprint reduction initiatives. For instance, use of solar energy as alternate energy source, monitoring of diesel and electricity consumption, motion sensors lighting, diverting waste from landfill, and promoting and using local supply chain. Nonetheless, currently there are no construction companies working on embodied carbon evaluation and involvement of IBS technology in construction is not normalized among the Malaysian contractors but applicable only for public-listed companies in the stock market. In terms of cost factors and high availability of resources, the construction sector in Malaysia is less emphasising on carbon reduction, especially embodied carbon.

2.2 Current State of Embodied Carbon (EC) Assessment in Malaysia

The assessment of embodied carbon in construction materials and their production is becoming a trend in Malaysian construction industry. Earlier studies indicate that indirect emissions may surpass direct emissions for energy-intensive materials like cement and steel reinforcements. Moreover, small-medium companies' contractors in Malaysia opt for conventional building systems instead of Industrialized Building systems (IBS) due to buyers' traditional mindset. This may be due to the cost factors which unable to motivate developers, especially small and medium companies in shifting the building system from conventional to IBS. This situation is not only causing obstacles in embodied carbon reduction, but also local contractors struggle to compete with foreign counterparts who implement IBS. Currently, reducing the embodied carbon footprint is one of the major concerns in the Malaysian construction industry. However, the Malaysian construction sector is still in the early stages of developing awareness and knowledge regarding embodied carbon. To address this, the Construction Industry Development Board (CIDB) Malaysia has developed an embodied carbon inventory tailored to the needs of the country's construction sector. This initial assessment of embodied carbon focuses on various life cycle stages, including the production stage (encompassing raw material extraction, processing, manufacturing, and transportation to the factory gate), transportation to the site, construction and installation processes, as well as material waste (CIDB, 2021).

Embodied energy is defined as the total primary on-site and off-site energy consumption within the boundaries of cradle-to-gate. The activities included production and manufacturing of building materials (upstream and downstream processes), prefabrication, transportation, construction, and administration. Obviously, embodied carbon is strongly related to embodied energy. Embodied carbon refers as the sum of fuel related (embodied energy) carbon emissions and process related (chemical processes) carbon emissions throughout whole life cycle (Finnegan, 2018). It can be measured from cradle-to-gate, cradle-to-site, cradle-to-grave, or even cradle-to-cradle. In the past few years, much emphasis has been placed on improving operational carbon. Basic tactics, such as enhancing building insulation and using LED lighting and automatic controls, have been applied for a long time to increase energy efficiency. However, these mitigations still contribute to the embodied carbon of the site through the addition of new products and materials, and the removal and disposal of old ones. While both embodied carbon (EC) and operational carbon (OC) indicate a building's overall carbon footprint, they have different implications for sustainability. It is crucial to prioritise EC as it constitutes a significant portion of overall carbon footprint of a building, especially for materials with high embodied carbon like steel, cement, and aluminium. Referring to Sturgis (2019), the built environment utilizes most of the three materials, which account for 23 % of total global emissions. According to Jin *et al.* (2022), the built environment generates 39 % of the global CO_2 emissions each year, and 13 % of it is due to embodied carbon from building, and infrastructure materials and construction. Malaysian contractors and developers must address embodied carbon appropriately to meet global and national net-zero targets, whether in anticipation of future regulations or in line with public sustainability agendas.

Although there are a lot of journals proposing the embodied carbon assessment, the embodied carbon computation is still on hold in Malaysian construction industry. This is because measuring and tracking embodied carbon is complex, in contrast to operational carbon that can be extrapolated from energy bills. Furthermore, sustainability reporting methods have only required scope 1 and 2 emissions accounting and disclosures, leading public-listed Malaysian construction companies to prioritize reducing OC emissions. In terms of building design systems, IBS can be one of the best options for Malaysian construction industry in embodied carbon reduction (Othuman Mydin *et al.,* 2014). With the aid of IBS technology, only minimal installation work is required, and equipment at the construction sites can be reduced. Also, the extra or unused components can be stored for future construction projects that have the similar designs, in other words, enhancing material usage. As a result, low embodied energy consumed lead to low embodied carbon emissions.

The Industrialised Building Systems (IBS) concept has been introduced in Malaysia since nearly four decades ago, however, its applications are still at low levels. This is because contractors today are not willing to take the risk to implement pre-cast and prefabricated construction as a lot of buyers prefer houses built with brick and mortar and think the pre-cast or prefabricated building elements are always with lower quality (Kamar *et al.,* 2012). Apart from that, higher costs may result from the lack of experience and technical knowledge of contractors in IBS as they unable to manage the costs effectively. Furthermore, conventional building systems have been the norm for many contractors for years and the is an abundance of cheap foreign labour.

The IBS implementation in Malaysia has increased to 84 % in 2021, whereas, in private projects, it has increased to 60% in 2021. The Construction Industry Transformation Programme (CITP) 2016-2020, the National Construction Policy 2021-2025, and Construction 4.0 Strategic Plan 2021-2025 boosted the growth of IBS in Malaysia steadily over last 15 years (CIDB 2020). Also, the construction industry would widely adopt CIDB's sustainability measures – Malaysian Carbon Reduction and Environmental Sustainability Tool (MyCREST) and Sustainable Infrastructure Rating Tool (INFRASTAR) as a means of evaluating sustainability. The IBS implementation has been increased among Malaysian construction companies, the evaluation of embodied carbon in a building is still not gaining much attention in Malaysia. The main root-causes are due to the lack of completed information management system and active stakeholder participation in the assessment. To determine the embodied carbon of building materials, it required the co-operation of every party and partner. Manufacturers, suppliers, subcontractors, and consultants are essential to be transparent about their processes and conduct self-assessments. However, it is impossible to know from the finished product alone, and they may not reveal their emissions accurately. Other than that, a local comprehensive life-cycle inventory database is still not available for

Malaysian construction companies to conduct carbon emission assessment. Therefore, an inventory data with 500 embodied carbon data for various construction materials and building elements was provided by CIDB.

Although accounting for embodied carbon has been a low-priority action item for firms due to the challenges associated with it, proactive construction and property firms will realize that it is now necessary because of some changes in regulatory policies and sustainability trends in Malaysia. As an example, the Sunway Construction Group Berhad has started to work on embodied carbon calculation for readily disclosure in their sustainability report. Embodied carbon can be emitted from waste; thus, waste disposal and recycling data is reported in their annual report, and this waste data disclosure is always not available in other construction companies. This data can help to compute the approximate embodied carbon footprint from the waste. Since embodied carbon requires a strong methodological foundation and a lot of input database, this consumes a lot of time and manpower to complete an embodied carbon assessment. Additionally, there are no generalized embodied carbon assessment in Malaysia buildings, but only for few buildings like residential buildings and office buildings. Yet, it is still a long journey to quantify the embodied carbon in Malaysia, especially construction sector.

3. Discussion

The process of embodied carbon (EC) quantitative assessment involves evaluating and measuring all the greenhouse gas emissions, including carbon dioxide in every stage of a product's life cycle (LC) i.e from its extraction and production to its recycling or disposal. There are number of standards developed for Life Cycle Assessment (LCA). The four-stage framework in the ISO 14040 Standard has been a significant milestone for EC assessment. The critical requirements for these assessments were further specified in 2008 by PAS 2050 (Specification, P.A., 2008). The 'Carbon management in infrastructure' was launched in 2016 as a complimentary British publicly available specification named PAS 2080. Reporting, benchmarking, and target setting are all included in its guidance. The associated documents provide an abundance of worked examples and practical tips in the England. The European Committee for Standardization Technical Committee 350 (TC 350) established European standards in March 2011 that specify the stages that need to be incorporated. The EN 15978, one of the TC 350 standards, proposes that buildings' environmental performance assessments should combine the human activity scope with an emission factor coefficient (National Standards Authority of Ireland, 2011).

The assessment considers emissions generated throughout the entire life of a product or system for a holistic understanding of its environmental impact. Different methodologies can be applied for embodied carbon assessment. The most popular used approach in quantifying embodied carbon is Life Cycle Assessment (LCA). This method requires the assessment of quantitative data on material, energy, and waste flows related to a product's entire life cycle to determine its environmental impact. Therefore, embodied carbon assessment can be viewed as a subset of a wider LCA methodology. Different impact categories can be employed in the impact assessment methodology to present the outcomes of an LCA study on buildings.

The process of a Life Cycle Assessment (LCA) includes three key stages. The first stage of the Life Cycle Assessment (LCA) process involves creating a comprehensive inventory of environmental discharges, energy and material inputs, and resource flows for a specific system. In this context, solid wastes or emissions to air or water are typically classified as releases. This inventory is referred to as the Life Cycle Inventory (LCI). The LCI encompasses various types of data, including material and transportation data, construction data, operational data, maintenance data, and demolition data. The standard unit for measuring embodied carbon is kilograms of CO_2 equivalent (CO_2eq) per kilogram of product or material. The second stage of the LCA process involves assessing the potential impacts associated with these inputs and discharges. For example, this stage evaluates the effects of CO_2 and other greenhouse gas emissions on global warming. The third stage focuses on interpreting the results to facilitate informed decision-making.

The process analysis has been the traditional method for compiling LCIs. Bullard et. al. (1978) propose that the process life cycle assessment (LCA) is the optimal approach for industrial chains, products, or processes where the physical movement of goods and services can be readily identified and traced. The process of product manufacturing is time and labour-intensive due to the need to identify numerous, sometimes elusive energy inputs (Lenzen and Treloar, 2002). The analysis involves assessment of resource consumption and environmental discharges from on-site production, the essential inputs contributed by suppliers. Heijungs (1994) pioneered the matrix inversion technique and the flow diagram approach, which is widely used, are the two common approaches to process analysis (Suh and Huppes, 2005). The interdependence among industry sectors in contemporary economies is inescapable, and it extends upstream throughout the entire life cycle of every good, resembling a vast network of tree branches (Rowley et al., 2009). According to Nässén et al. (2007), the incomplete definition of system boundary causes systematic truncation errors in process LCA. Since the bottom-up approach can cause the truncation error, the top-down analysis led to around 90% of the specific energy consumption.

Nässén et al. (2007) noted that the energy consumed by services and transportation in production stage was underestimated by bottom-up approach in comparison to the use phase. The ease of estimating the use phase through direct energy consumption is the primary reason. Expanding the boundaries of system in a process flow schematic can also lead to a truncation error of up to 50 %, as reported in certain industrial sectors (Lenzen, 2000). To tackle the issue of data shortage in the building sector, Hong et al., (2016) suggested an uncertainty analysis framework could be developed by integrating data quality indicators with a probabilistic technique. The feasibility could be evaluated through different uncertainty studies focused on process-based assessments of a building's embodied carbon. The truncation issue in the matrix inversion technique for process analysis lies in its inability to account for further upstream inputs, even though it may consider infinite orders of interactions within the upstream boundary (Rowley et al., 2009).

However, Liu and Leng (2022) advocates for slightly modified Life Cycle Assessment (LCA) methodologies, specifically the Input-Output (I-O) analysis approach. The input-output (I-O) method has found broad usage in economic and environmental research. The financial transaction in industrial framework is described using a top-down linear macroeconomic approach (Lenzen et al., 2003). Moreover, the optimal solution is to accurately gauge the direct influence of carbon emissions and enhance the evaluation methodology within an LCA framework (Williams et al., 2009). The utilization of I-O data in LCA, as shown in Crawford (2008), enhances dependability by enhancing the comprehensiveness and reliability elements for the life cycle inventories, which couldn't be find in traditional inventory analysis. Crawford (2008) discovered that capital inputs accounted for 22 % of the overall input to the I-O table for specific components. An I-O table can be used to show the flow of services and commodities in different sectors within an economic system (Treloar, 1997). Alcorn & Baird (1996) suggested that the tracking the energy flow throughout an economic system can be carried out by analysing the monetary flows in the energy sectors, then physical energy value can be determined by conversion factors. The use of I-O LCA ensures identification and capture of all energy transactions within national economic structures. Using these, the inputs and outputs of energy can be assessed. Although I-O LCA captures comprehensive energy transactions, it has limitations and cannot fully replace process-based LCA for accuracy.

According to Acquaye (2010), the Input-Output (I-O) methodology is subject to potential errors, including issues with proportionality and homogeneity functions, handling of imports, conversion of economic data to physical data, total error, double counting in energy supply sectors, and product aggregation within sectors. Pure I-O LCAs face a downward bias because assessments do not consider emissions from usage to decommissioning (Khan et al., 2022). There has been a continuous improvement in the model's assumptions, and the progress in compiling input-output tables has been significant. The analysis and measurement of embodied carbon in trade was initially conducted by researchers using single-region input-output models in the trade field (Huang and Zhao, 2018). The model considers all external countries/regions as a unit and measures the carbon emission embodies in the trading between the home country and the external regions (Wang et al., 2019). In combination, the I-O LCA framework enables a comprehensive mapping of material flows and energy use within an economic system, providing a macro-level understanding of the primary energy requirements for goods and services.

The completeness and input-output assessment (IOA) specificity processes' strength have been primarily directed toward hybrid approach execution (Suh et al., 2005.). Hybrid life cycle assessment (HLCA) aims to merge the benefits of the precise LCA method and a broad system scope of I-O LCA as mentioned by (Mattila et al., 2010). It balances system boundaries, model applicability identification, and time and cost efficiency. The HLCA allows for the extension of both upstream and downstream manufacturing processes which includes the direct and indirect GHG emissions. By applying this assessment approach, the curtail errors in terms of time and location in operational analysis can be reduced while still maintaining detailed product information to compare similar products or systems (Heijungs and Suh, 2002). Meta-hybrid analysis, input-output-based hybrid analysis, and hybrid analysis at multiple levels are the three types of tests consistently employed during the literature review process (Khan et al., 2022). The mining and release phases, along with multiple upstream processes, utilize process-based data in a multi-level combined analysis. The two datasets are combined in this analysis, along with other modelled upstream processes using input-output analysis (Suh and Huppes, 2005). The process analysis strategy involves conventional detailing, along with input-output assessment (IOA) to address the process gaps. The I-O LCA framework can minimize aggregation uncertainty by utilizing a more detailed process of LCA data, which provides solutions. Furthermore, HLCA can aid in approximating the degree of immediate unpredictability. Typically, within every 5years, an in-depth I-O LCA will be issued. Quick scoping analysis of temporal variability can be done by gathering prices from a particular time frame. According to Williams et al. (2009), The assessment and handling of geographic uncertainty can be enhanced by HLCA. The requirements of HLCA are known to be data- and time-intensive, in spite of its advantages.

Wan Omar (2018) conducted a HLCA of embodied carbon emissions in precast concrete wall panels using the conventional building systems and industrialised building systems (IBS), then the detailed out the system boundaries. A clearly defined system boundary is necessary to guarantee reliable and consistent results. The establishment of the boundaries of building materials and goods using HLCA is required at the early stage. Then, the relationships between supply chains across industries can be identified based on the boundaries. Figure 2 displays the completed system boundary for precast concrete products production. The construction material such as concrete and steel reinforcement are commonly used in the manufacturing of precast concrete wall panels, which is used the direct and indirect energy (Wan Omar, 2018). All of these can be traced accordingly then converting it into GHG emission. Of the total carbon emissions in upstream processes, 46 % and 31 % are attributed to domestic and imported emissions, respectively (Nässén et al., 2007).

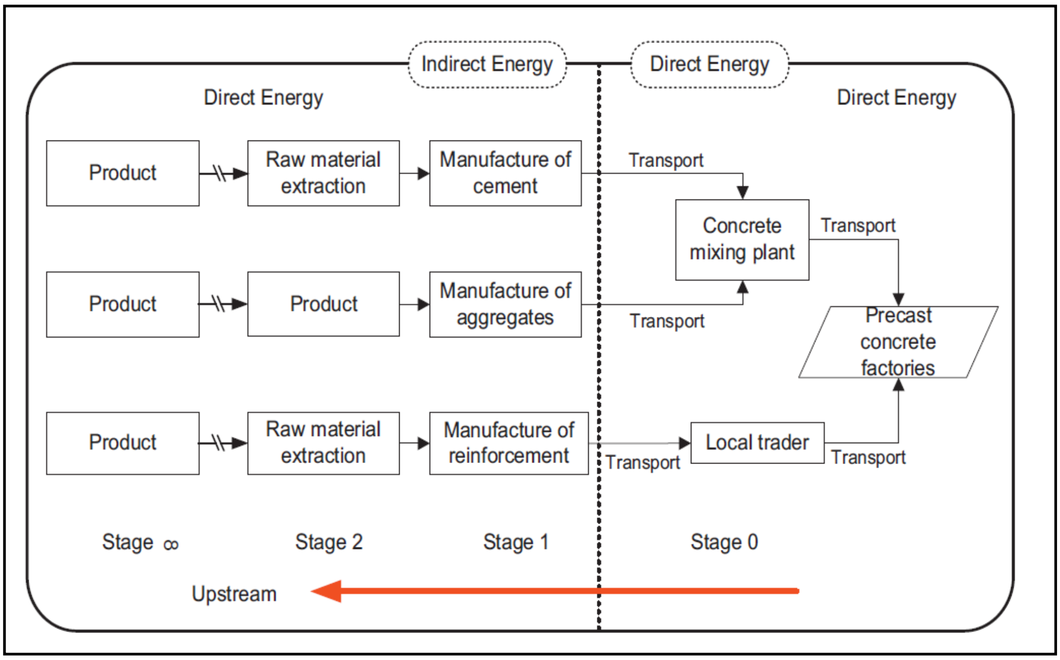

Figure 2. Complete system boundary for precast concrete products production (Nässén et al., 2007)

The HLCA approach provides a more comprehensive analysis of environmental impacts but faces notable challenges in embodied carbon assessment. These include data inconsistencies between process-based and economic input-output (EIO) models, risks of double-counting emissions, and limited resolution due to the aggregated, often outdated nature of EIO data. HLCA's complexity reduces transparency and usability, especially for local assessments or evolving industries. Moreover, integrating incompatible data and tools complicates practical application, increasing error risk and reducing accessibility for non-experts. Therefore, HLCA results require cautious interpretation in carbon evaluations.

4. Conclusion

The construction sector in Malaysia plays a critical role in contributing to national greenhouse gas emissions, with embodied carbon representing a significant, yet often overlooked, portion of the total environmental impact. This review highlights the urgent need for broader adoption and integration of embodied carbon (EC) assessment methodologies in the Malaysian construction industry, especially as the country moves toward achieving its net-zero carbon goals. While operational carbon has received considerable attention due to regulatory mandates, EC remains underreported due to data limitations, methodological complexities, and insufficient stakeholder awareness. Moreover, the Industrialized Building Systems (IBS) offer a promising pathway to reducing embodied carbon through material efficiency and minimized on-site emissions. However, barriers such as cost, limited technical expertise, and cultural preferences for conventional building methods hinder widespread adoption. Current initiatives, including CIDB's embodied carbon inventory and sustainability tools like MyCREST, provide foundational support, but further industry engagement and regulatory enforcement are necessary to drive systemic change. Future research should prioritize the development of a comprehensive, localized life cycle inventory database, foster collaborative industry partnerships, and refine hybrid life cycle assessment (HLCA) methodologies to include full cradle-to-cradle scopes. By addressing current limitations in data transparency and methodological standardization, Malaysia's construction sector can make meaningful progress in embodied carbon mitigation, supporting national and global climate objectives.

Competing interests

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.

Informed consent

Obtained.

Ethics approval

The Publication Ethics Committee of the Macrothink Institute.

The journal's policies adhere to the Core Practices established by the Committee on Publication Ethics (COPE).

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The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

Data sharing statement

No additional data are available.

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