A Comparative Study on the Environmental Impact of Cast-in-Situ (Cis) and Industrialized Building System (IBS): A Life Cycle Assessment Approach

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DOI: https://doi.org/10.47772/IJRISS.2025.91200049

Received: 11 December 2025; Accepted: 18 December 2025; Published: 31 December 2025

ABSTRACT

This study aims to investigate the embodied energy (EE) and embodied carbon (EC) of cast-in-situ (CIS) and industrialized building system (IBS) methods in the construction phase of residential buildings within the Malaysian construction industry. The objectives are to determine the EE and EC values for both methods and recommend the most environmentally sustainable option. A Life Cycle Assessment (LCA) was conducted using Staad Pro V8i software to model and analyse the building components. The study found that the IBS method consistently resulted in the lowest EE (GJ/m²) and EC (tCO_2e/m^2) values across all building types, with the 2-storey bungalow achieving the lowest values. It was observed that the total floor area, building materials, and component sizes significantly impact the EE and EC results. The research concludes that these factors are critical in minimizing the environmental footprint of residential buildings, thereby achieving the study's objectives of identifying the most sustainable construction method.

Keywords: Life Cycle Assessment, Industrialized Building System, Cast-In-Situ

INTRODUCTION

According to ISO 14040[1], defining system boundaries and functional units is essential in conducting a life cycle assessment (LCA). This study focuses on evaluating the environmental impacts, specifically EE and greenhouse gas (GHG) emissions, in the manufacturing process of residential buildings using CIS and IBS in Malaysia. Given the limited research on EE in building construction and the pressing need to address GHG emissions, these aspects are the primary objectives of this LCA. The scope of the LCA is crucial for determining which environmental issues are addressed [2].

Various LCA methodologies, such as cradle-to-grave, cradle-to-gate, and cradle-to-cradle, have distinct boundaries and objectives [3, 4]. Cradle-to-grave assesses the entire lifecycle from construction to demolition, while cradle-to-cradle emphasizes material recycling. Cradle-to-gate, selected for this study, focuses on the production and construction phases up to delivery, excluding reuse and disposal processes outside the defined boundaries [2].

The environmental impacts assessed include EE and EC, which are critical metrics for evaluating the sustainability of building materials and methods. EE refers to the total energy consumed throughout a product's lifecycle, while EC measures the carbon emissions from production, use, and disposal [2]. These metrics help identify the environmental footprint of construction methods, guiding decisions to mitigate impacts.

Utilizing LCA as a methodological framework, this study aims to analyze and compare the EE and EC of CIS and IBS methods during the manufacturing phase of residential buildings in Malaysia. It seeks to recommend the most sustainable construction method to optimize environmental performance, supporting global initiatives to reduce environmental impact and enhance resource efficiency in the Malaysian construction industry.

ISSN No. 2454-6186 | DOI: 10.47772/IJRISS | Volume IX Issue XII December 2025

LITERATURE REVIEW

Embodied Energy (EE)

According to Mohd Safaai, Zainon Noor [5], energy consumption in Malaysia increased dramatically between 2000 and 2010 as a result of the country's economic expansion. The entire energy stored in building materials during the stages of manufacture, construction, and final destruction and disposal was referred to as EE [6]. It included the energy required for the extraction of raw materials, transportation, the production of building materials, and the many procedures involved in building and demolishing a structure [7]. EE could be classified into two categories: on-site direct energy consumption and off-site indirect energy use for material manufacture and transportation [8]. Indirect energy was widely used in the production of materials and may be found at all stages of the process, including primary, refurbishment, and deconstruction [7]. The overall energy needed to create a structure, which included the indirect energy needed to manufacture the building's materials and components as well as the direct energy consumed during construction and assembly [7].

Embodied Carbon (EC)

According to Wyckoff and Roop [9], the concept of EC emerged from their analysis of the carbon content in manufactured products involved in international trade. Various case studies have assessed EC in residential buildings. Early studies focused on measuring the amounts and sources of EC and their impact on overall life cycle carbon emissions. The emissions of GHG associated with building construction were measured by EC. This included the emissions from raw material processing, building material and component manufacturing, transportation to the construction site, and building component assembly [10]. In order to quantify the effect of GHG emissions, a global warming potential (GWP) was assigned to each GHG in order to provide a standard comparison known as carbon dioxide equivalent (CO_2e) [11].

Life Cycle Assessment (LCA)

According to Delnavaz, Norouzianpour [2], LCA was a process that involves assessing a product's environmental impact throughout its entire lifespan, aiming to improve resource efficiency and reduce environmental harm. It analysed the environmental burdens associated with processes and products over their entire life cycle, as shown in Figure 2.1. This assessment covered every stage of a product or process, including manufacturing, construction, operation, maintenance, and end-of-life phases[3, 4]. According to ISO14040 [3], LCA consisted four stages, which were goal and scope definition, life cycle inventory (LCI), life cycle impact assessment (LCIA), and interpretation of results [3]

LCA examined the environmental impact of a product from raw material extraction to disposal. It considered ecological impacts, effects on human well-being, and resource use [3]. The LCA process involved defining the study's goals and scope, conducting LCI, performing LCIA, and interpreting the data. It highlighted the environmental benefits of new building methods, encouraging engineers to consider them in design. Additionally, the results could set a standard for future studies [2].

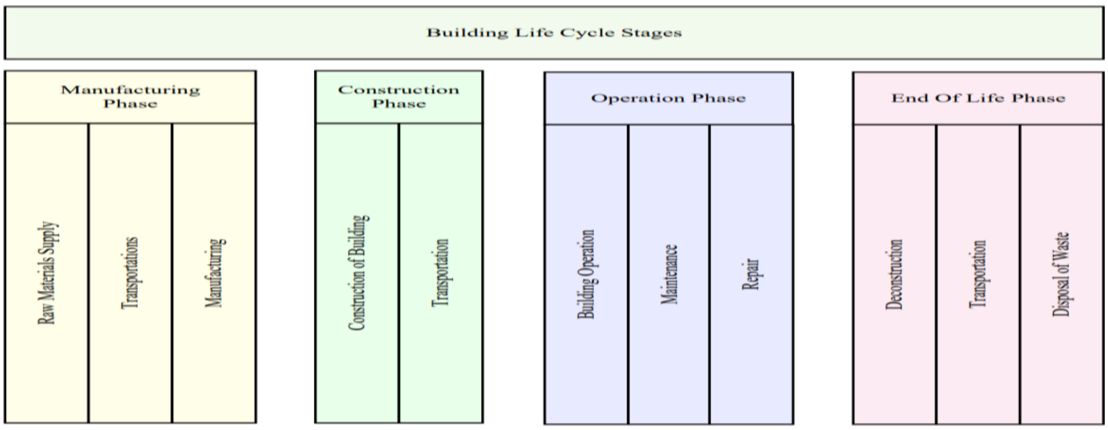

Figure 1: Life cycle stages of buildings

ISSN No. 2454-6186 | DOI: 10.47772/IJRISS | Volume IX Issue XII December 2025

The EE and EC Reduction through LCA

LCA played a crucial role in reducing EE and EC in the construction industry. By systematically evaluating the environmental impacts of building materials and processes from the extraction of raw materials to the end of their life cycle, LCA provided a comprehensive understanding of where and how energy and carbon emissions were generated [7]. This holistic view allows stakeholders to identify and quantify the sources of EE and EC, enabling informed decision-making to minimize these impacts. In essence, LCA served as a vital tool for achieving sustainable construction by pinpointing areas for improvement and guiding the implementation of eco-friendly practices [2, 3].

The existing body of research provided valuable insights into the application of LCA in various contexts. Table 2.1 summarized key studies, highlighting their locations, building types, building phases analysed, and the specific LCA boundaries employed.

Table 1: The phases and methods used by different researchers

Sources	Location	Building Type	Building Phase	LCA Boundary	Method
Lu and Wan Omar [12]	Malaysia	Residential	Manufacturing Phase	Cradle-to-gate	Software
Wan Omar, Doh [13]	Malaysia	Residential	Manufacturing Phase	Cradle-to-gate	Case Study
Abouhamad and Abu-Hamd [14]	Egypt	Residential	End of Life Phase	Cradle-to-grave	Case Study
Zhang, Sun [15]	China	Residential	Manufacturing Stage	Cradle-to-gate	Case Study
Zhao, Xu [16]	China	Residential	Construction Stage	Cradle-to-gate	Software
Basbagill, Flager [17]	USA	Residential	Operational Phase	-	Software & Case Study
Haddad, Sedrez [4]	Brazil	Residential	Construction Phase	Cradle-to-gate	Case Study
Siti Halipah, Zaini [6]	Malaysia	Commercial	Construction Phase	Cradle-to-gate	Case Study
Delnavaz, Norouzianpour [2]	Iran	Residential	Construction Phase	Cradle-to-gate	Software & Case Study
Zaini, Siti Halipah [18]	Malaysia	Commercial	Manufacturing Phase	Cradle-to-gate	Software
Mohebbi, Bahadori-Jahromi [11]	UK	Commercial	Manufacturing Phase	Cradle-to-gate	Software
Helal, Stephan [19]	Australia	Residential	Manufacturing Phase	Cradle-to-gate	Software

ISSN No. 2454-6186 | DOI: 10.47772/IJRISS | Volume IX Issue XII December 2025

Khasreen, Banfill [20]	UK	Commercial	Construction Phase	Cradle-to-gate	Case Study
Zabalza Bribián, Aranda Usón [21]	Spain	Residential	End of Life Phase	Cradle-to-grave	Case Study
Hui and Ma [22]	Hong Kong	Residential	Operational Phase	-	Case Study
Blengini and Di Carlo [23]	Italy	Residential	Operational Stage	-	Case Study
Wan Omar [24]	Malaysia	Residential	Manufacturing Stage	Cradle-to-gate	Case Study
Zhang, Chen [25]	China	Residential	Operational Stage	-	Case Study
Xiang, Mahamadu [26]	China	Commercial	Manufacturing Stage	Cradle-to-gate	Case Study

These studies showcased a diverse range of applications and findings, highlighting the versatility and significance of LCA in various building contexts and phases. Through an examination of these different research efforts, a clearer understanding of global trends and best practices in reducing EE and EC through informed LCA methodologies was gained. This comparison emphasized the necessity of tailoring LCA approaches to specific regional and building type contexts to achieve the most effective outcomes.

METHODOLOGY

Based on Figure 1 below, this study analyses how various building components affect the environment in residential homes by measuring their EE and EC values. Using advanced software like Staad Pro V8i, it models and assesses components such as walls, roofs, bars, and rods. By standardizing material volumes and weights into MJ/m³ for EE and $kgCO_{2e}/m^3$ for EC, the research aims to evaluate sustainable building designs, particularly in Malaysia. Total EE and EC have been normalized by dividing floor area of each model for comparison across studies. These findings offer insights into eco-friendly design options and advocate for sustainable construction practices.

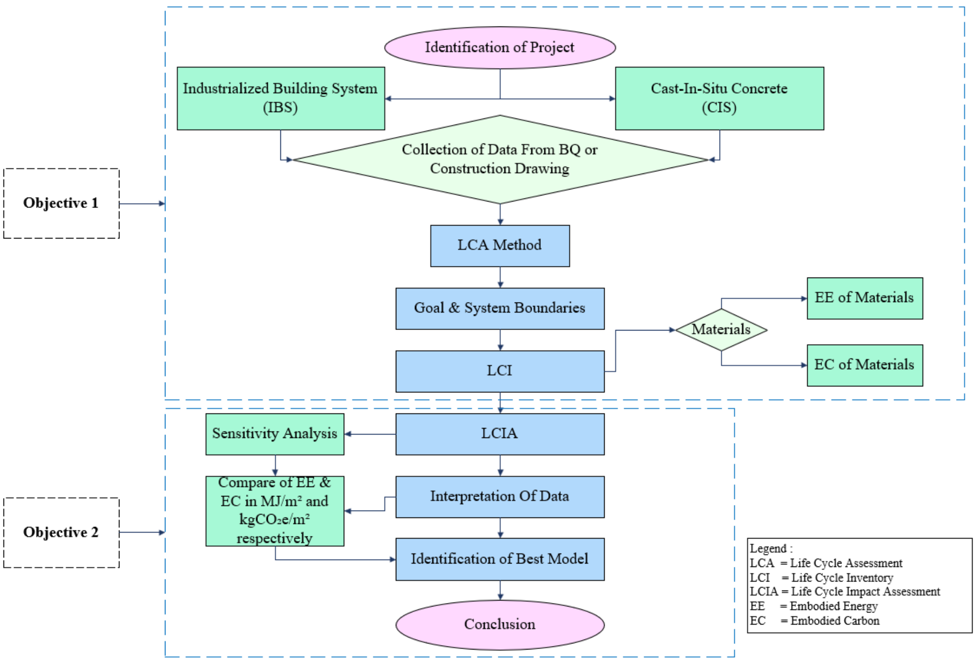

Figure 2: Methodology Flowchart

ISSN No. 2454-6186 | DOI: 10.47772/IJRISS | Volume IX Issue XII December 2025

Development of Models

This study examines the environmental impacts of different construction methods used in Malaysian residential buildings, focusing on 1-storey, 2-storey, and 4-storey bungalows. These structures range in size from 201.69 m² to 1259.75 m², utilizing reinforced concrete columns, beams, slabs, concrete brick walls, and various roof designs. By analysing architectural and structural details, the research aims to highlight the materials, dimensions, and technical specifications crucial for each building type, providing insights to improve industry standards, urban planning regulations, and promote sustainable building practices in Malaysia.

The first type is the 1-storey bungalow, which encompasses a building area of 201.69 square meters. This structure is supported by reinforced concrete (RC) columns, beams, and slabs. The walls are made of concrete bricks, providing robust support and insulation. The roof is a gable design, utilizing size ISA75505 and ISMC75 components. The second type is the 2-storey bungalow, which has a significantly larger building area of 353.01 square meters. Similar to the 1-storey bungalow, it features RC columns, beams, and slabs for its structural framework and concrete brick walls for added stability and durability. The roof is also a gable design with the same size components, ISA75505 and ISMC75, ensuring consistency in the structural design across these two types of bungalows. The third type is the 4-storey bungalow, which includes a basement, shear walls, and a lift, making it the most complex structure among the three. It covers a vast building area of 1259.75 square meters. This bungalow is built with RC columns, beams, and slabs, similar to the other two types, and also features concrete brick walls. However, instead of a gable roof, it has a flat slab roof with L20204 components, accommodating the additional structural requirements of the basement and lift system.

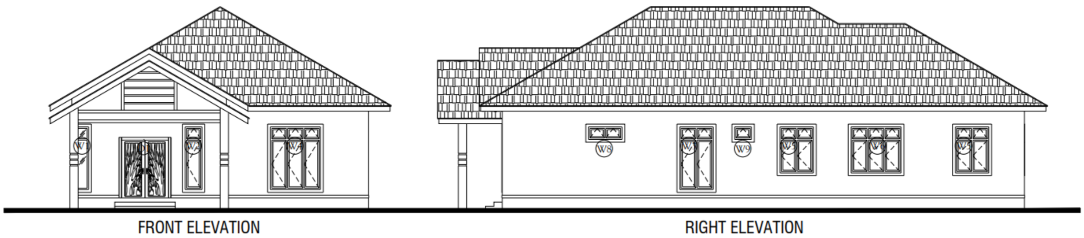

Figure 3**:** 1-Storey Bungalow

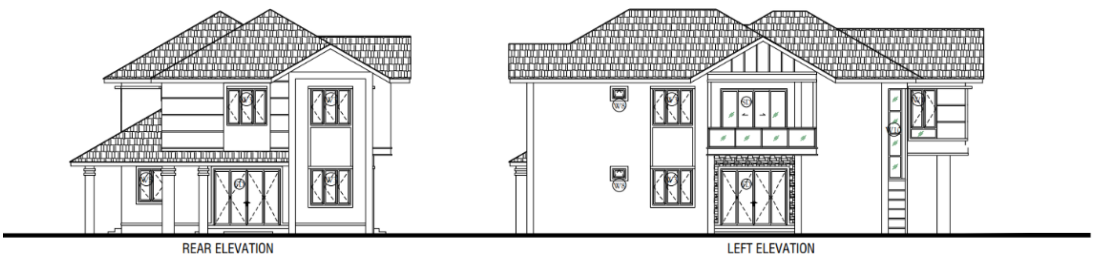

Figure 4: 2-Storey Bungalow

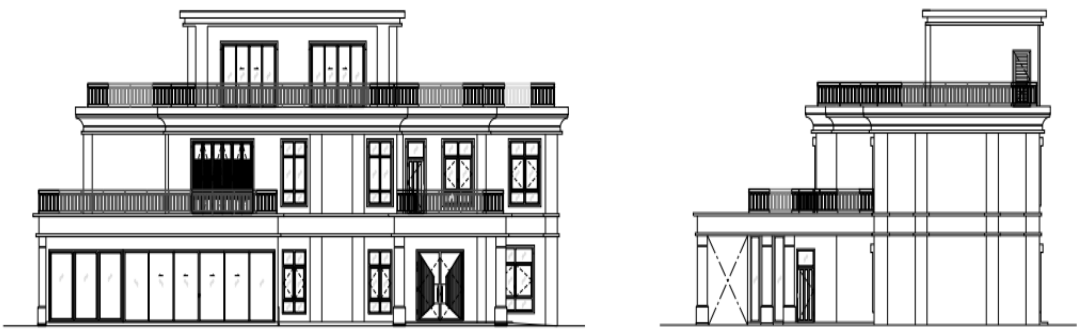

Figure 5: 4-Storey Bungalow

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Using Staad Pro V8i

The methodology for this study involves the use of Staad Pro V8i software to model and analyse the building components of residential structures constructed using CIS and IBS methods. Staad Pro V8i, a powerful structural analysis and design tool, facilitates precise calculations of structural dimensions and material usage. By inputting various building parameters into the software, such as material types, wall thicknesses, roof systems, and structural components, the study effectively assesses the EE and EC for each construction method. This comprehensive analysis enables a detailed comparison of the environmental impacts associated with the CIS and IBS methods during the manufacturing phase of residential buildings in the Malaysian construction industry.

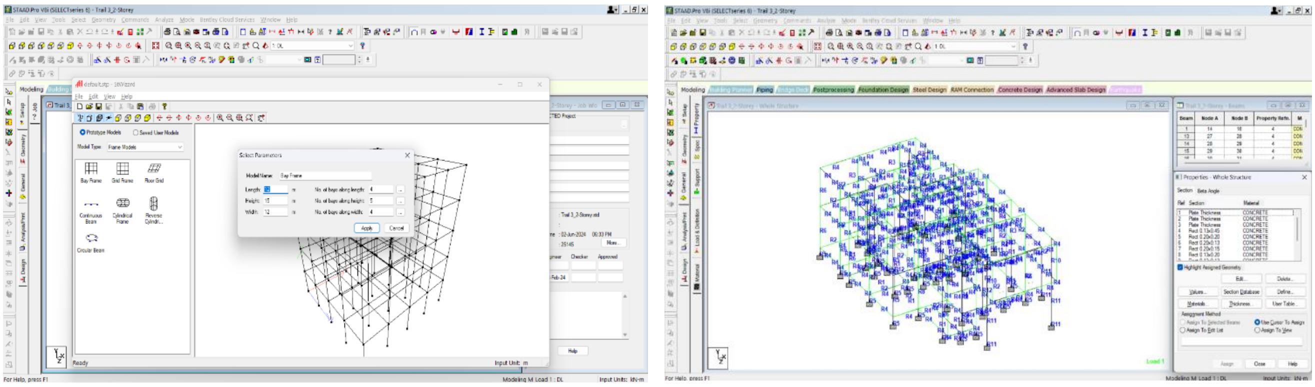

Figure 6: Inputting building dimensions using Staad Pro V8i

Data Collection

To know what materials are needed for a building project, it's essential to carefully study the construction drawings. These drawings show the architectural and structural details of the project. By interpreting symbols and notes on the drawings, this research can understand the materials, dimensions, and technical specifications required for the project. This helps us determine the important aspects of the building project. Once the information from the construction drawings is gathered, it's easier to understand the materials needed for the project. This knowledge is crucial for comparing the environmental impact and effectiveness of different materials in various building projects.

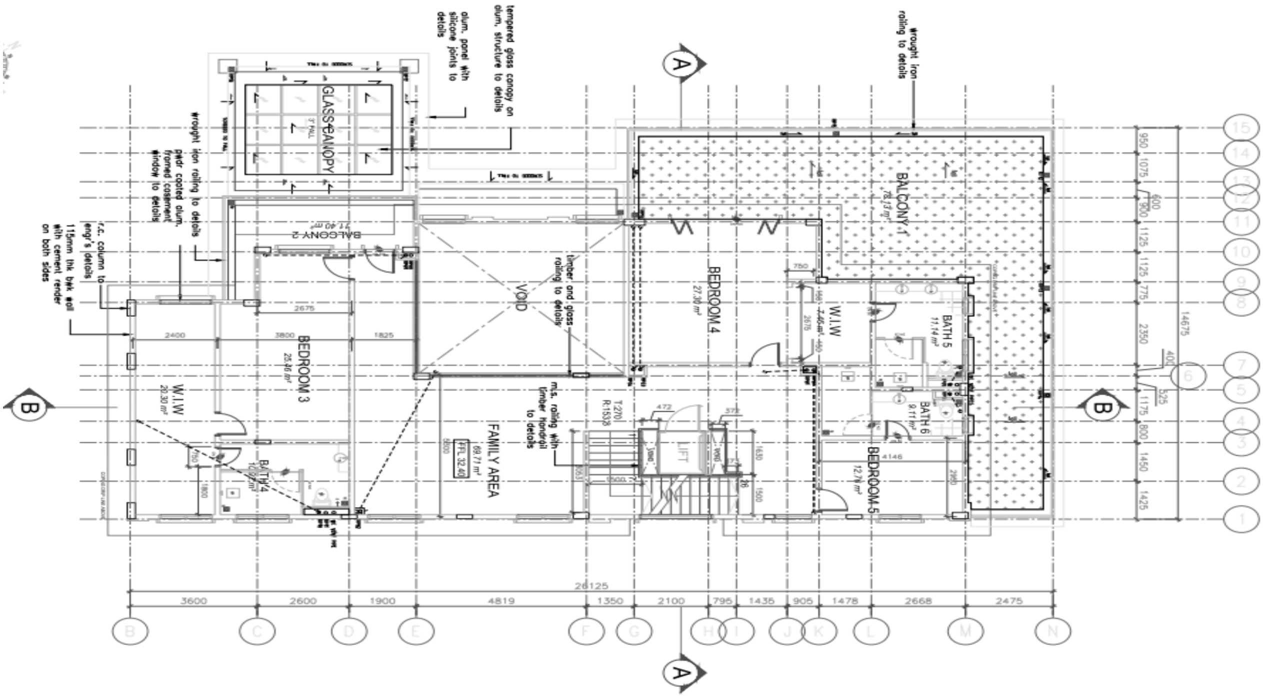

Figure 7: Construction Drawing of 4-Storey Bungalow

Application of Life Cycle Assessment (LCA)

LCA is a comprehensive method used to evaluate how products impact the environment throughout their entire life cycle, from raw material extraction to disposal. It considers ecological impacts, effects on human well-being, and resource use [27]. The process of LCA involves several key steps: defining the study's goals and scope, conducting a LCI to quantify material and energy inputs, performing a LCIA to evaluate environmental effects, and interpreting the data to draw meaningful conclusions [2]. By highlighting the environmental benefits of construction methods, such as CIS and IBS, LCA encourages engineers and designers to consider sustainability in their decision-making processes, setting benchmarks for future studies.

In the context of Malaysian residential construction, LCA plays a crucial role in comparing the environmental impacts of CIS and IBS methods during the manufacturing phase. This research focuses on assessing EE and EC impacts, aiming to provide insights into how these methods influence sustainability within the construction industry [28]. The study employs a functional unit of 1 m² of constructed area to standardize measurements, ensuring a consistent basis for evaluating the environmental performance of different building methods. This approach helps in understanding which construction techniques minimize EE and EC outputs, thereby promoting more environmentally friendly building practices in Malaysia. [2]

Goal and Scope of Boundaries

The first part of the LCA process, called goal and scope definition, sets the purpose and method for including environmental impacts in decision-making [29]. The goal of this study is to compare the EE and EC in the manufacturing phase of residential buildings constructed using CIS and IBS methods within the Malaysian construction industry. By doing so, this study aims to assess how various scenarios impact the reliability of LCA results for both construction methods, providing valuable insights for environmental decision-making in the construction sector.

The effectiveness of the product system's functional outputs was evaluated by a functional unit [3]. In the context of this study, the functional unit is defined as 1 square meter (m²) of constructed area. This unit of measurement is used to standardize the comparison of the environmental impacts of the CIS and IBS methods. According to Delnavaz, Norouzianpour [2], the use of the constructed area of materials to compute construction dimensions provides a consistent and appropriate foundation for the LCA study, ensuring accuracy and comparability in the assessment of environmental impacts. This approach provides a common basis for assessing the environmental effect of the two building methods, facilitating a clear and comparative analysis. The choice of 1m² as the functional unit aligns with previous studies and allows for straightforward comparison and evaluation of the EE and EC associated with each construction method.

The system boundary determines which processes are included in the LCA. This boundary was influenced by the study's purpose, assumptions, cut-off criteria, data and cost limitations, and the target audience [3]. For this project, the system boundary encompasses only the manufacturing phase of residential buildings in Malaysia. This phase is chosen because it produces the most significant amounts of EC and EE, making it the critical focus for assessing environmental impacts.

Life Cycle Inventory (LCI)

During the LCI phase, data on material quantities, energy inputs, and GHG emissions are collected and analysed using methodologies like Process LCI, Input-Output Method (IOM), and Hybrid LCI (HLCI) [12, 30]. These methods quantify the EE and EC by multiplying the volume of construction materials with their respective energy and carbon intensities, expressed in carbon dioxide equivalent ($CO_{2\text{-}e}$) [8]. Advanced software tools such as Staad Pro V8i are utilized to model variations in construction parameters accurately, enabling a comprehensive assessment of how changes in material types, structural dimensions, and design elements affect EE and EC values. According to Lu and Wan Omar [12], the formulas for EE and EC are as follows:

$$\mathrm{EE_m = W_m \times HEI_m} \tag{3.1}$$

$$\mathrm{EC_m = W_m \times HECO_{2-e}I_m} \tag{3.2}$$

Where, EE_m is the total EE used, W_m is the quantity or weight of material, HEI_m is the construction materials' EE intensity, EC_m is the total EC produced, and $HECO_{2-e}I_m$ is EC intensity of the construction materials used.

Sensitivity analysis in this study examines how variations in building materials, sizes, and parameters impact EE and EC during the manufacturing stage of Malaysian buildings [2]. Key parameters such as material types, wall thickness, roof system type, and structural component dimensions were varied using advanced software like Staad Pro V8i. Results indicated that construction material type significantly influences EE and EC values more than wall thickness or roof system type. Standardizing EE and EC by building area revealed insights into the impact of building size on environmental performance. This analysis identified critical factors for material selection and design decisions, reinforcing the study's findings [2, 31].

Life Cycle Impact Assessment (LCI)

Sensitivity analysis in LCI is an important method used in this study to ensure the accuracy of the findings by examining different scenarios [2]. The main goal is to see how various scenarios impact the reliability of LCA results. This study aims to understand the effects of these differences during the manufacturing stage of building in Malaysia by comparing different building materials, sizes, and their environmental impacts.

In this study, sensitivity analysis was conducted to evaluate how changes in various parameters affect the overall results, specifically the EE and EC values of different building components. The primary aim was to understand the validity of the findings and identify the key factors that significantly influence the environmental impact of the buildings. In this research, sensitivity analysis is used to evaluate how different scenarios affect residential building designs that use CIS and IBS construction methods during the manufacturing stage [31]. Considering various building designs is expected to improve the accuracy and reliability of LCA findings [2]. This method helps to reflect the uncertainties and possible variations in the building methods used in Malaysia.

The first step in conducting the sensitivity analysis involved identifying the critical parameters that could vary during the manufacturing phase. These parameters included the type of materials used (such as GEN2 with 30% fly ash versus Ordinary Portland Cement), the thickness of the walls, the type of roof system (gable versus flat), and the dimensions of the structural components like beams, columns, and roof trusses. Each parameter was systematically varied within a reasonable range to observe its impact on the EE and EC values.

Table 2: EE and EC values of various sizes and materials for 4-storey bungalow

Component Size	Design Option	Materials	Concrete Volume (m^3)	Concrete Volume (kg)	Embodied Energy		Embodied Carbon	
					MJ	MJ/m^2	$kgCO_2e$	$kgCO_2e/m^2$
Highest	Option 1	G30	69.8	167,520	325,658.88	1614.65	33,135.456	164.289
	Option 2	GEN 1 (15%)	69.8	167,520	108,888.00	539.88	14,741.760	73.091
	Option 3	RC 20/25	69.8	167,520	135,691.20	672.77	19,097.280	94.686
	Option 4	GEN 2 (0%)	69.8	167,520	127,315.20	631.24	17,757.120	88.042
	Option 5	RC 25/30	69.8	167,520	142,392.00	705.99	20,269.920	100.500
	Option 6	GEN 2 (15%)	69.8	167,520	118,939.20	589.71	16,416.960	81.397
Moderate	Option 13	G30	42.4	101,760	197,821.44	980.82	20,128.128	99.797

	Option 14	GEN 1 (15%)	42.4	101,760	66,144.00	327.95	8,954.880	44.399
	Option 15	GEN 2 (0%)	42.4	101,760	77,337.60	383.45	10,786.560	53.481
	Option 16	GEN 2 (15%)	42.4	101,760	72,249.60	358.22	9,972.480	49.445
	Option 17	RC 20/25	42.4	101,760	82,425.60	408.67	11,600.640	57.517
	Option 18	RC 25/30	42.4	101,760	86,496.00	428.86	12,312.960	61.049
Lowest	Option 19	G30	28.6	68,640	133,436.16	661.59	13,576.992	67.316
	Option 20	GEN 1 (15%)	28.6	68,640	44,616.00	221.21	6,040.320	29.949
	Option 21	GEN 2 (0%)	28.6	68,640	52,166.40	258.65	7,275.840	36.074
	Option 22	GEN 2 (15%)	28.6	68,640	48,734.40	241.63	6,726.720	33.352
	Option 23	RC 20/25	28.6	68,640	55,598.40	275.66	7,824.960	38.797
	Option 24	RC 25/30	28.6	68,640	58,344.00	289.28	8,305.440	41.179

Interpretation of Data

In the interpretation phase, LCA findings are reviewed to ensure accuracy, reliability, and alignment with the study's objectives. Data validation, including comparisons with existing research, enhances the credibility of results by confirming the consistency and robustness of EE and EC assessments per cubic meter of material. This thorough approach not only facilitates a clearer understanding of the environmental impacts of construction methods but also supports informed decision-making towards more sustainable building solutions in Malaysia and beyond.

Evaluation of Best Models

Identifying the best construction model involves evaluating design alternatives to find the most sustainable and efficient use of resources. The goal is to minimize EE and EC while ensuring structural integrity and safety. Using Staad Pro V8i, data on the area and weight of concrete and steel are converted into kilograms to calculate EE and EC values per m², allowing for direct comparisons between building sizes and types. Models are ranked based on their EE and EC values, with the lowest EE and EC model recommended as the most environmentally efficient, promoting sustainable construction practices without compromising safety.

INTERNATIONAL JOURNAL OF RESEARCH AND INNOVATION IN SOCIAL SCIENCE (IJRISS)
ISSN No. 2454-6186 | DOI: 10.47772/IJRISS | Volume IX Issue XII December 2025

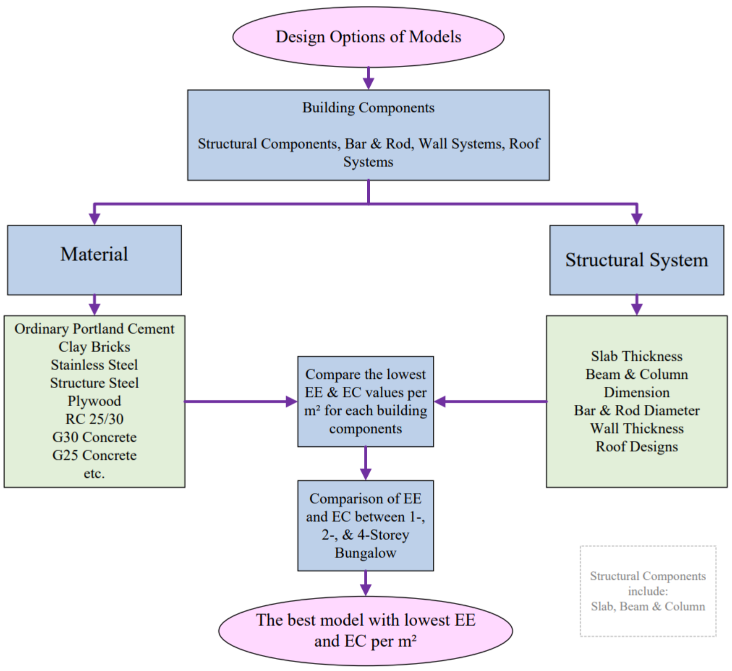

Figure 8: Design Options of Models

RESULTS AND DISCUSSION

Comparison of EE and EC values between two construction methods: CIS and IBS

The comparison of EE and EC values between CIS and IBS methods reveals distinct differences in their environmental impacts. CIS typically involves traditional on-site construction practices, which often result in higher EE and EC values due to the intensive labor, extended construction time, and increased material waste. On the other hand, IBS employs prefabricated components, which are manufactured in controlled factory settings and then assembled on-site. This method tends to lower EE and EC values because of improved efficiency, reduced material waste, and optimized use of resources. By analysing the data in Figures 9, 10, and 11, it becomes evident that IBS generally offers a more sustainable option compared to CIS, as it minimizes energy consumption and carbon emissions during the construction process. This comparison underscores the potential environmental benefits of adopting IBS in residential building projects.

The results of the LCA reveal significant differences in the EE and EC between the CIS and IBS methods across various building types. By referring to Figure 9, the CIS method shows an EE of 1,837.87 GJ/m² and an EC of 156.98 tCO_{2e}/m². In comparison, the IBS method demonstrates lower EE and EC values at 1,425.96 GJ/m² and 154.68 tCO_2e/m², respectively. This indicates that the IBS method is more energy-efficient and produces fewer carbon emissions even at this basic level of residential construction.

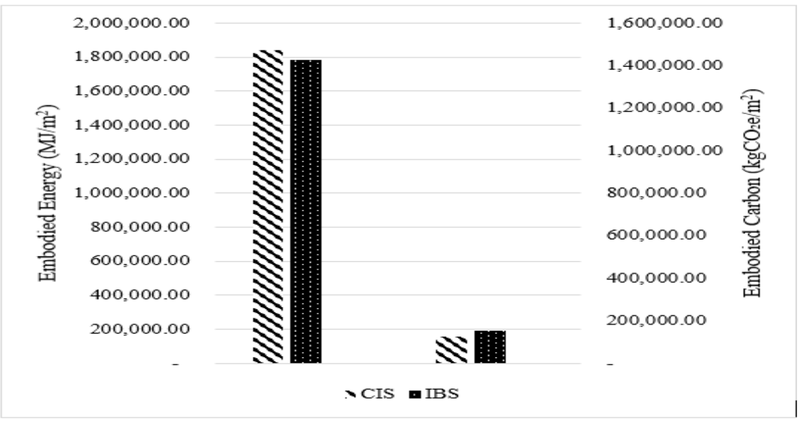

Figure 9: Comparing total EE and EC for both CIS and IBS in 1-storey bungalow

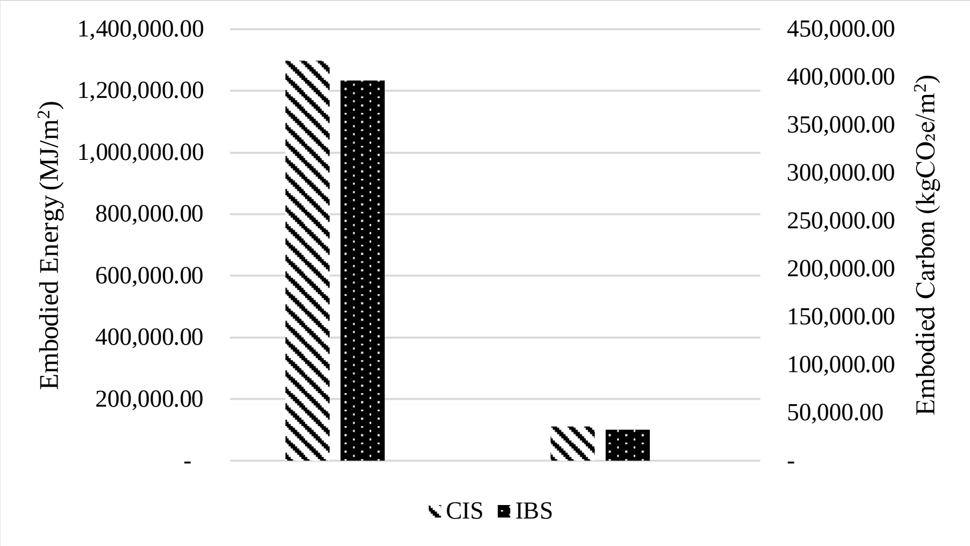

Figure 10: Comparing total EE and EC for both CIS and IBS in 2-storey bungalow

When analysing the results as shown in Figure 10, the advantages of the IBS method become even more pronounced. The CIS method for a 2-storey bungalow results in an EE of 1,298.81 GJ/m² and an EC of 110.99 tCO_2e/m^2, whereas the IBS method achieves substantially lower values of 396.54 GJ/m² for EE and 32.39 tCO_2e/m^2 for EC. This substantial reduction highlights the efficiency of the IBS method in managing both energy use and carbon emissions, particularly as the complexity and size of the building increase.

According to the data as shown Figure 11, the trend of IBS outperforming CIS continues. The EE and EC values for the CIS method are 1,197.75 GJ/m^2 and 102.22 tCO_2e/m^2, respectively. In stark contrast, the IBS method records significantly lower EE and EC values of 371.82 GJ/m^2 and 30.56 tCO_2e/m^2. These results demonstrate the scalability and effectiveness of the IBS method in reducing environmental impacts as the building height and complexity grow.

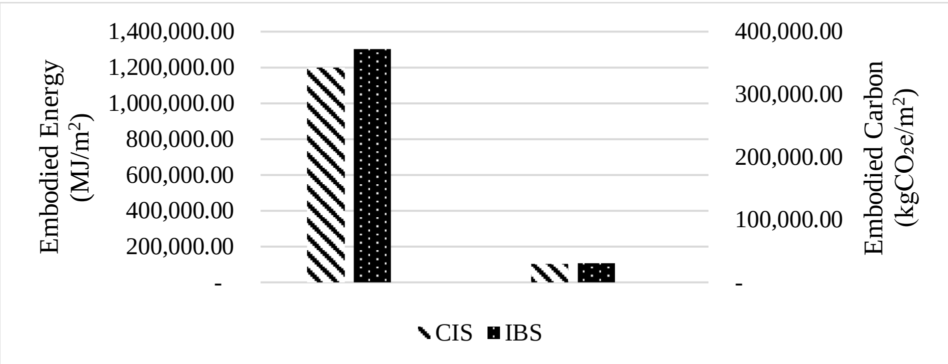

Figure 11: Comparing total EE and EC for both CIS and IBS in 4-storey bungalow

The comparative analysis across different building types underscores the consistent superiority of the IBS method in terms of environmental performance. The reductions in EE and EC achieved by the IBS method can be attributed to its use of prefabricated components, which are manufactured in controlled environments. This leads to increased efficiency, reduced material waste, and lower energy consumption during the construction phase. The CIS method, on the other hand, involves more energy-intensive processes and greater material waste, resulting in higher EE and EC values.

Overall, these findings reinforce the potential of the IBS method as a more sustainable alternative to traditional CIS construction. By adopting IBS, the construction industry in Malaysia can significantly reduce its environmental footprint, contributing to global efforts to mitigate climate change. The study highlights the importance of integrating LCA into the decision-making process for construction projects to identify the most environmentally efficient building methods and promote sustainable practices in the industry.

Comparing Various Design Options between the 3 Building Sizes

Structural Components

The lowest data of EE and EC for 1-storey, 2-storey and 4-storey bungalow were given in Figure 12 below. The results demonstrate that multi-storey bungalows generally have a lower environmental impact per unit area compared to single-storey bungalows. This finding highlights the potential benefits of vertical construction in terms of resource efficiency and environmental sustainability. By distributing structural loads and materials across multiple floors, multi-storey buildings can achieve significant reductions in EE and EC, making them a more sustainable option for residential construction.

The study underscores the importance of considering building design and construction methods in reducing the environmental footprint of residential buildings. Multi-storey designs, particularly those utilizing efficient construction practices and materials, offer a promising pathway towards more sustainable construction. Future research should continue to explore these design efficiencies and extend the analysis to other building types and construction methods to further refine our understanding of the environmental benefits of different construction approaches.

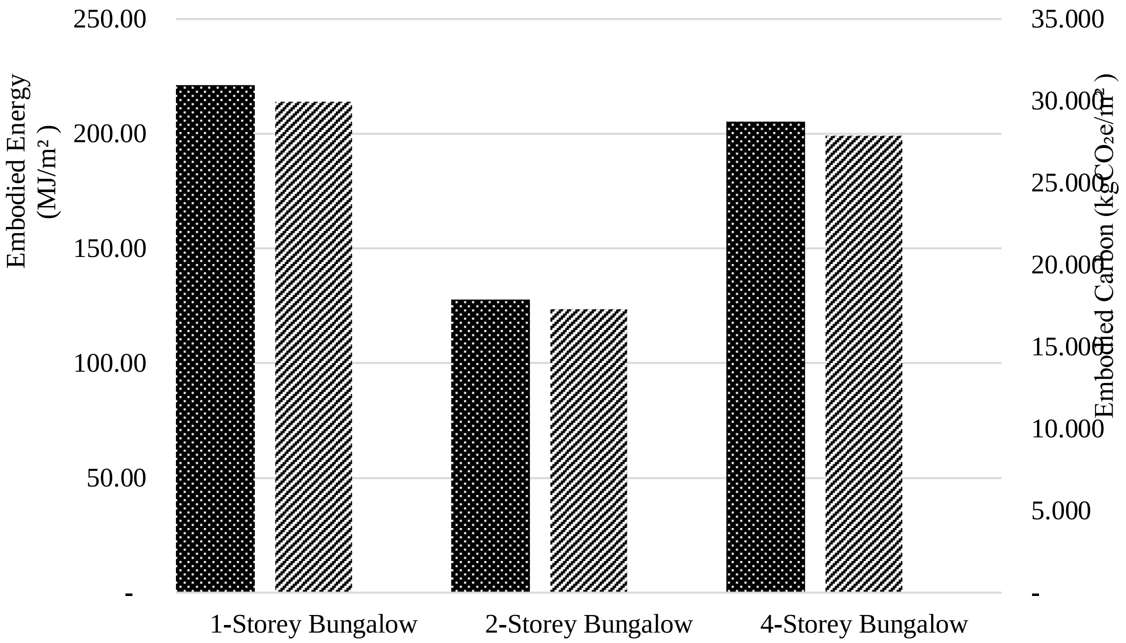

Figure 12: Comparing EE and EC of structural components between 1, 2, and 3-storey bungalow.

Wall Systems

In building construction, wall systems play a crucial role in determining the structural integrity and thermal performance of a building. Various materials can be used for wall systems, each contributing differently to the EE and EC of the building. In this study, several materials for wall systems, including Ordinary Portland Cement (OPC), clay bricks, and different generations of concrete mixes with varying percentages of fly ash: GEN 1 (15%), GEN 2 (15%), GEN 2 (30%), and GEN 3 (15%) were evaluated. The study examined wall thicknesses of 100mm, 150mm, and 200mm. By changing the wall thickness with different material types, the EE and EC values can be compared. This approach allows the study to identify the most sustainable combinations of materials and thicknesses for different building types.

By referring to Figure 13, the analysis reveals that building height significantly influences the environmental performance of wall systems, with multi-storey constructions showing notably lower EE and EC per square meter compared to single-storey buildings. This trend highlights the substantial environmental benefits of advanced construction methods like the IBS. The findings emphasize the importance of innovative construction techniques and materials in reducing the environmental footprint of residential buildings.

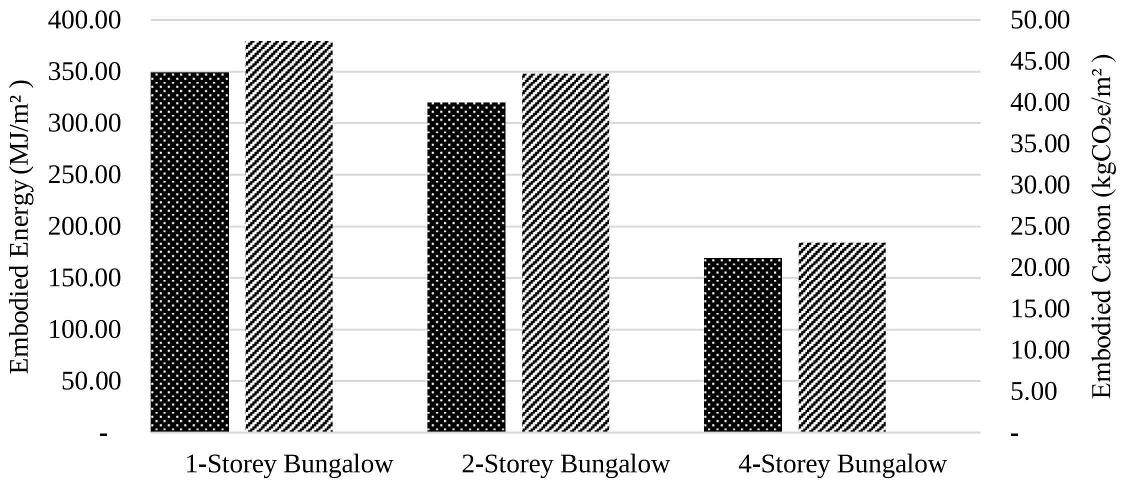

Figure 13: Comparing EE and EC of wall systems between 1, 2, and 3-storey bungalow.

Roof Systems

The roof system of a building plays a crucial role in its overall structural integrity and environmental impact. This study examined various materials and design options to evaluate their EE and EC values. The materials considered included aluminium, stainless steel, section steel – ROW, and plywood. These materials were used in two types of roof designs: gable roof and flat roof. To comprehensively compare the EE and EC values, the roof types with different material types and sizes were analysed. The different roof types with varying materials and sizes were compared to assess their EE and EC values.

Overall, from data given in Figure 14, the results indicate that the EE and EC of roof systems increase with the building's complexity and height, as seen in the significant rise from the 1-storey to the 2-storey bungalow. However, the 4-storey bungalow data suggests that advanced construction techniques can mitigate some environmental impacts, resulting in a less dramatic increase in EE and EC. These findings underscore the need to consider the environmental impacts of different building components when assessing construction methods' sustainability. By understanding these variations, stakeholders can make informed decisions to optimize design and material choices, promoting more sustainable construction practices.

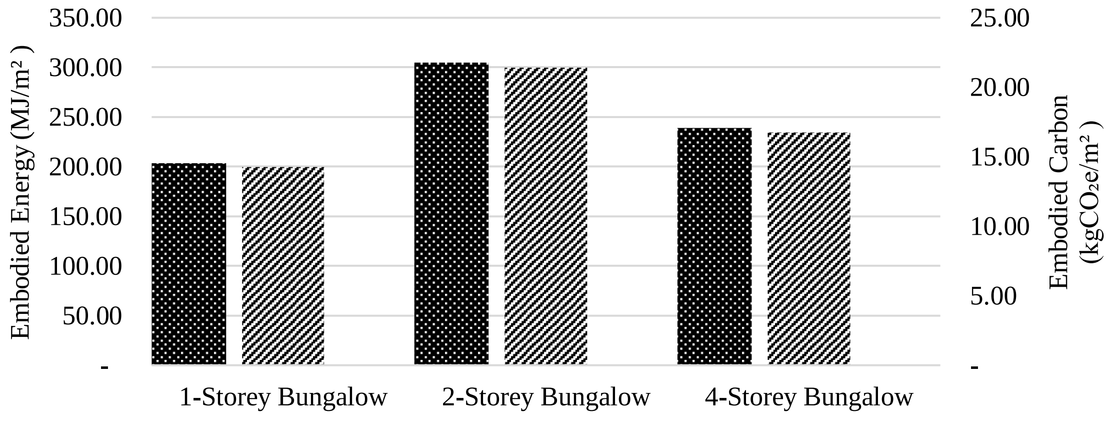

Figure 14: Comparing EE and EC of roof systems between 1, 2, and 3-storey bungalow.

Comparison of Total EE and EC Between 1-storey, 2-storey, and 4-Storey Bungalow

The evaluation of roof systems across different building sizes in terms of EE and EC reveals critical insights into their environmental impacts. Figure 15 presents the total EE and EC values for 1-storey, 2-storey, and 4-storey bungalows, highlighting notable differences across these structures.

For a 1-storey bungalow, the roof system exhibits relatively high energy consumption and carbon emissions. This is likely due to the larger roof surface area relative to the overall size of the building, along with the substantial energy input and emissions generated by the chosen materials and construction techniques. In contrast, the results for a 2-storey bungalow show a notable decrease in both energy consumption and carbon emissions. This reduction is attributed to the increased efficiency inherent in multi-story building designs. The shared structural components and reduced roof surface area per unit of floor space in taller buildings contribute to this lower per-square-meter environmental impact. For the 4-storey bungalow, energy consumption and carbon emissions slightly increase compared to the 2-storey bungalow yet remain lower than those of the 1-storey bungalow. This indicates that while there are initial efficiency gains in the 2-storey structure, the benefits may plateau or regress slightly due to the additional structural complexities and materials required for taller buildings. Nonetheless, the 4-storey bungalow still benefits from shared structural elements and a reduced relative roof surface area.

The comparison of these results underscores the importance of optimizing roof system design and materials to minimize environmental impacts. Multi-story buildings generally perform better in terms of energy and emissions per square meter, largely due to the more efficient use of materials and construction methods that leverage shared structural components. However, the slight increase in energy and emissions for the 4-storey bungalow suggests diminishing returns in savings as building height increases beyond a certain point.

Overall, these findings highlight the need for careful consideration of roof system designs in sustainable building practices. The significant reductions in energy consumption and emissions achieved in multi-story bungalows emphasize the potential for environmental benefits when optimizing building height and design. By leveraging these efficiencies, the construction industry can make more informed decisions that contribute to reducing the overall environmental footprint of residential buildings.

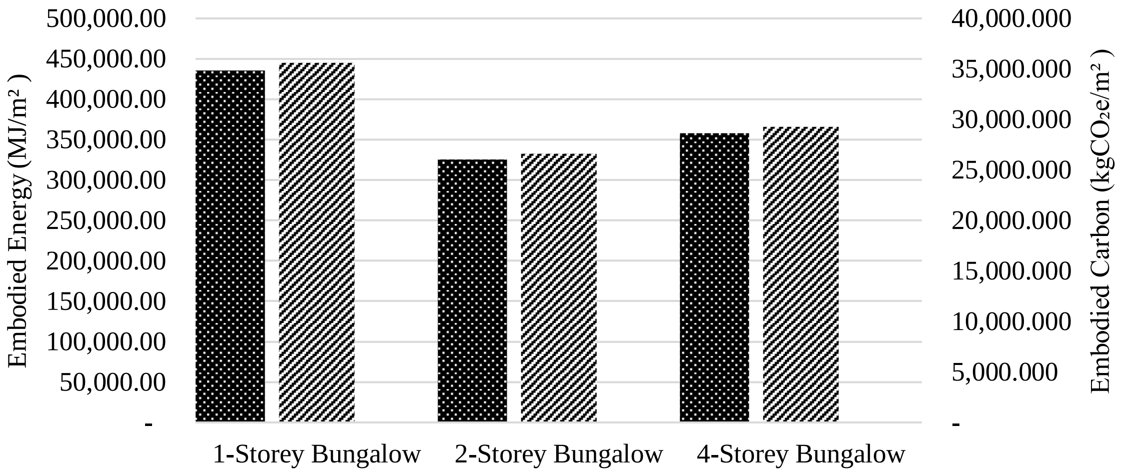

Figure 15: Comparison of total EE and EC values between 1-storey, 2-storey, and 4-storey bungalow

CONCLUSION

In conclusion, this research aimed to investigate the EE and EC values of different building methods and materials within the Malaysian construction industry. The primary focus was on comparing the CIS and IBS methods to identify the most environmentally sustainable options.

The first objective was to examine the EE and EC values during the manufacturing phase of both CIS and IBS methods. The analysis revealed that the IBS method consistently resulted in lower EE and EC values compared to the CIS method across different building sizes. This can be attributed to the use of prefabricated components in the IBS method, which are manufactured in controlled environments, leading to increased efficiency and reduced material waste. These findings suggest that switching to IBS could significantly reduce the environmental impact of residential construction. The second objective was to recommend the best option by evaluating the environmental impact with a focus on minimizing EE and EC. The results indicated that even when considering different building materials and component sizes, the IBS method still performed better in terms of lower EE and EC values. This reinforces the conclusion that the IBS method, due to its prefabrication process, is a more sustainable choice for reducing the environmental footprint of building construction. The results obtained from the two objectives highlight the importance of selecting appropriate building methods and materials. The significant reduction in EE and EC values with the IBS method underscores its potential for contributing to more sustainable construction practices. By adopting IBS, the Malaysian construction industry can move towards more environmentally friendly practices, aligning with global sustainability goals and reducing the overall carbon footprint of residential buildings. This research provides a clear recommendation for the industry to consider the IBS method as a viable alternative to traditional CIS construction, promoting both environmental and economic benefits.

To build upon the findings of this research, several recommendations for future work can be made. Firstly, extending the scope of the study to include a broader range of building types and configurations would provide a more comprehensive understanding of the environmental impacts associated with different construction methods. This could involve analysing high-rise buildings, commercial structures, and industrial facilities to assess whether the observed benefits of the IBS method apply universally across various building categories. Secondly, future studies should consider the long-term performance and durability of materials used in both CIS and IBS methods. Evaluating the lifecycle impacts, including maintenance, repair, and eventual disposal or recycling of materials, would offer a more holistic view of the environmental benefits. This would help in understanding not just the immediate EE and EC values but also the sustainability of the building methods over their entire lifespan.

ACKNOWLEDGEMENT

I would like to express my deepest gratitude to my supervisor, Dr. Wan Mohd Sabki, for his invaluable guidance and support throughout this research. I also extend my heartfelt thanks to my family members for their unwavering encouragement and to my friends for their constant support. Their collective contributions have been instrumental in the successful completion of this study.

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