EASR

Engineering and Applied Science Research

https://www.tci-thaijo.org/index.php/easr/index

Published by the Faculty of Engineering, Khon Kaen University, Thailand

Reinforced concrete and embodied carbon in construction: Challenges and pathways to reduction in Thailand

Surapong Liwthaisong[1)], Tanayut Chaithongrat[2)] and Preenithi Aksorn*[3)]

[1)]Department of Civil Engineering, Faculty of Engineering, Khon Kaen University, Khon Kean 40002, Thailand
[2)]Construction and Project Management Center, Department of Civil Engineering, Faculty of Engineering, Mahasarakham University, Maha Sarakham 44150, Thailand
[3)]Sustainable Infrastructure Research and Development Center (SIRDC), Department of Civil Engineering, Faculty of Engineering, Khon Kaen University, Khon Kaen 40002, Thailand

Received 2 October 2024
Revised 15 January 2025
Accepted 27 January 2025

Abstract

The increasing demand for construction in Thailand, driven by urbanization and infrastructure development, has heightened the urgency of addressing embodied carbon emissions in reinforced concrete projects. This study evaluates the life cycle carbon emissions of a six-story outpatient department building, focusing on the manufacturing, transportation, and construction stages. Data were collected through stakeholder interviews and analysis of project-specific documents, such as bills of quantities and construction plans. Results reveal that the manufacturing stage contributes 92.75% of total emissions, with concrete and steel as the primary sources, accounting for 6.506 kt CO_2eq. Transportation and construction contribute 6.41% and 0.84%, respectively. The study identifies practical strategies for reducing embodied carbon, including material substitution with supplementary cementitious materials, optimizing logistics, and improving energy efficiency in construction practices. These strategies not only mitigate environmental impacts but also address economic and quality considerations, ensuring feasibility in the local context. The findings provide actionable insights for policymakers and construction professionals to integrate low-carbon practices, contributing to the national and global goals of sustainable development. This research offers a comprehensive framework for reducing embodied carbon emissions while maintaining economic viability and construction quality, positioning Thailand as a leader in sustainable construction.

Keywords: Embodied carbon emissions, Emission reduction strategies, Life cycle assessment, Sustainable construction, Reinforced concrete structure

1. Introduction

Reinforced concrete has long been the foundation of modern construction, offering durability and structural flexibility. However, the environmental cost of its widespread use is increasingly a topic of concern. The construction industry, fueled by materials like cement and steel, contributes approximately 36% of global energy use and 40% of energy-related carbon emissions [1-3]. While efforts to mitigate operational emissions, such as energy used in buildings during their lifecycle, have progressed, embodied carbon, which refers to emissions generated during materials' production, transportation, and construction stages, remains a significant and often overlooked challenge [4, 5].

Embodied carbon emissions from reinforced concrete arise primarily from cement production, which accounts for 8% of global carbon emissions. Steel reinforcement, a critical component of reinforced concrete, also significantly reduces the carbon footprint due to the high energy requirements during production. Combined, these materials represent a substantial share of embodied emissions in construction, necessitating targeted mitigation efforts [4-6].

Lifecycle assessment (LCA) has emerged as a widely adopted tool for measuring embodied emissions. It provides a framework for quantifying environmental impacts across all construction materials' life cycle stages. By applying LCA, researchers and policymakers can identify key stages where emissions are most concentrated and develop targeted interventions [4, 7, 8]. However, significant data gaps and methodological inconsistencies hinder its effectiveness in developing economies like Thailand [9-11].

Globally, the construction sector is at the forefront of sustainability discussions. Initiatives such as the United Nations' Sustainable Development Goals (SDGs) and the Paris Agreement emphasize reducing carbon emissions across all economic sectors [12, 13]. Recent reports from the United Nations Environment Programme (UNEP) highlight the urgency of addressing embodied emissions alongside operational emissions, particularly in developing nations [2, 6, 14]. In Thailand, the construction industry is not only a vital driver of economic growth but also a significant source of greenhouse gas emissions, accounting for over 25% of national GHG output [9-10]. Cement production and reinforced concrete construction are integral to the nation's infrastructure projects, including highways, residential buildings, and urban expansion. However, the sector faces unique challenges, including a reliance on imported construction technologies and limited integration of low-carbon materials [6, 15]. The Nationally Determined Contribution (NDC) Roadmap

*Corresponding author.
Email address: preenithi@kku.ac.th
doi: 10.14456/easr.2025.11

outlines Thailand’s commitment to reducing its carbon footprint, yet actionable strategies for the construction sector remain underdeveloped [9, 10].

Reinforced concrete construction poses unique challenges due to its reliance on high-impact materials. Despite advances in operational carbon reduction, embodied emissions are less studied, particularly in regional contexts like Thailand, where urbanization and infrastructure development are accelerating [4, 5]. Recent studies underscore the potential of using supplementary cementitious materials (SCMs) to replace a portion of Portland cement, potentially reducing embodied carbon by up to 50% [4, 5, 16, 17]. Additionally, generative approaches leveraging data from construction projects have shown promise in optimizing material use and reducing environmental impact [17, 18]. However, the adoption of such materials is limited by cost constraints, supply chain inefficiencies, and a lack of technical expertise [8, 15].

This study aims to bridge the gap in understanding and mitigating embodied carbon emissions in reinforced concrete construction within Thailand. Unlike prior research that predominantly focuses on operational emissions, this work highlights embodied emissions and their critical role in the lifecycle of construction projects. Adopting an LCA framework tailored to Thailand’s context, the research identifies key sources of emissions, evaluates potential reduction strategies, and aligns these with Thailand’s national climate goals and global sustainability targets [2, 7, 9, 12]. The findings of this study contribute to the growing body of literature by offering insights into the environmental impacts of reinforced concrete construction in a developing country. The study also provides practical pathways for reducing embodied carbon, integrating global best practices with local realities, and supporting policymakers in crafting effective mitigation strategies for the construction sector.

2. Materials and methods

The lifecycle assessment (LCA) methodology is a globally recognized framework for evaluating environmental impacts associated with all product life cycle stages. It provides a systematic approach to quantify the inputs, outputs, and potential environmental consequences of products or systems, including construction processes. The LCA is particularly valuable for analyzing embodied carbon emissions and greenhouse gas (GHG) emissions from material extraction, manufacturing, transportation, and construction activities. These emissions are distinct from operational emissions, which arise during a building's usage phase.

The concept of Whole Life Carbon Assessment (WLCA) extends beyond the boundaries of traditional LCA by incorporating all lifecycle stages of a building, from cradle to grave [19, 20], as illustrated in Figure 1. The WLCA framework, as delineated by the Royal Institution of Chartered Surveyors (RICS), consists of five major stages (shown in Figure 1):

- Product Stage (A1–A3): Includes raw material extraction, material transportation, and manufacturing processes.
- Construction Process Stage (A4–A5): This stage covers the transportation of materials to the site and on-site construction activities.
- Use Stage (B1–B7): Encompasses operational energy consumption, maintenance, repair, and replacement.
- End-of-Life Stage (C1–C4): Includes demolition, deconstruction, transportation, and materials disposal.
- Beyond the Building Lifecycle (D1-D4): Accounts for the benefits and loads related to material reuse, recycling, and energy recovery.

This study's analysis focuses on embodied carbon up to practical completion (PC-CO_2e), which includes stages A1–A5 (cradle to site) of the WLCA framework. These stages capture the environmental impacts of material production, transportation, and construction activities [20-23], making them critical for understanding and mitigating embodied carbon emissions in reinforced concrete construction.

The relationship between Embodied Carbon (A1–A5) and WLCA is pivotal in sustainable construction practices. Embodied carbon emissions typically represent a significant proportion of a building's total lifecycle carbon footprint, particularly in the initial stages of construction. Therefore, addressing embodied carbon is essential for achieving meaningful carbon reductions in the construction industry.

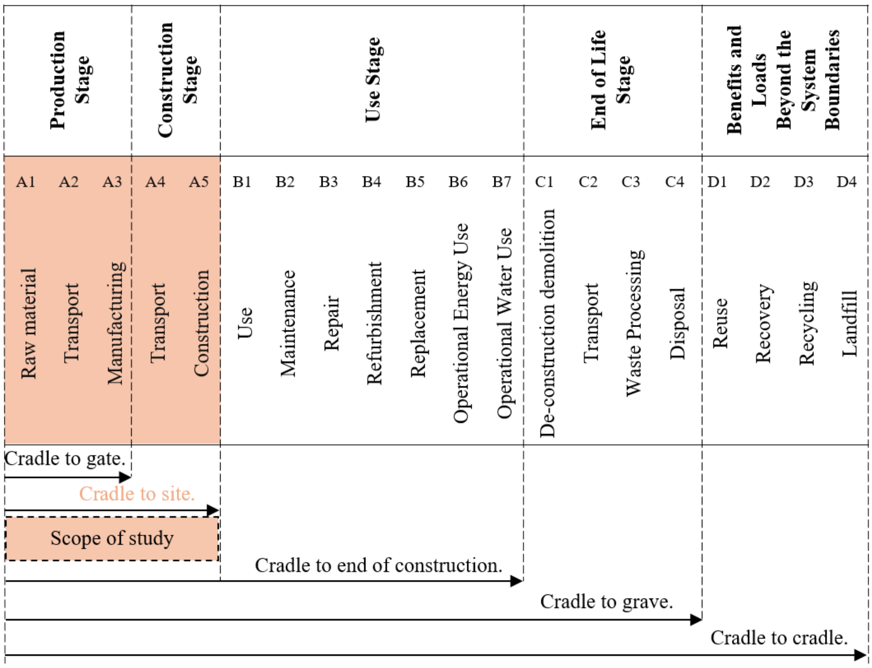

Figure 1 Framework for Assessing Embodied Carbon in Construction: Stages A1–A5

Table 1 summarizes key studies on embodied carbon emissions within the Whole Life Carbon Assessment (WLCA) framework, focusing on stages A1 (Raw Materials) to A5 (Construction Process). The table identifies the stages covered and significant findings. It highlights major contributors to lifecycle emissions, including raw materials (A1 – A3) and construction processes (A4 – A5), emphasizing the need for better data and innovative solutions.

Table 1 Summary of Life Cycle Assessment (LCA) Studies: Cradle to Site Focus in Construction

Author	Stages Covered	Key Finding
Kwok et al. [24]	A1-A3 Cradle to gate	Identified gaps in data for raw materials and stressed the importance of integrating lifecycle stages.
Helal et al. [25]	A4-A5 Construction	Found that structural systems, particularly reinforced concrete, are major contributors to embodied emissions.
Liu et al. [26]	A1-A5 Cradle to site	Highlighted manufacturing and construction stages as key contributors and proposed carbon reduction strategies.
Althoey et al. [27]	A1-A3 Cradle to gate	Showed that using alternative binders like fly ash and slag can reduce embodied carbon by up to 50%.
Xu et al. [28]	A1-A3 Cradle to gate	Identified that A1–A3 contribute the most emissions and proposed improvements in material efficiency.
Gursel et al. [29]	A1-A3 Cradle to gate	Highlighted that reinforced concrete structures are 50% more GHG intensive compared to steel alternatives.
Lai et al. [30]	A1-A5 Cradle to site	Identified key hotspots in A1–A5, with material production and transport contributing the highest emissions.
Xu et al. [31]	A1-A5 Cradle to site	Found that prefabrication reduces emissions by optimizing material use and reducing waste during construction.
Zhao et al. [32]	A1-A3 Cradle to gate	Proposed emergy accounting to better quantify emissions in the product stage.

This table connects prior research to this study's framework, reinforcing the importance of addressing high-impact stages and exploring innovative practices for sustainable construction. By leveraging insights from existing literature, this research aims to develop actionable strategies for reducing the carbon footprint of reinforced concrete projects.

2.1 Project characteristics

The object of this study is the construction of a six-story Outpatient Department (OPD) building (Figure 2). This reinforced concrete structure fulfills the strict requirements set by the Ministry of Health of Thailand for hospital construction. The construction area of the building is 13,208 square meters, and the construction cost is about 10,017,916 USD (exchange rate: 1 USD = 32.93 THB), as shown in Table 2.

This project represents a significant advancement in healthcare infrastructure and serves as a critical benchmark for assessing the environmental impact, particularly carbon emissions, associated with healthcare facility construction. A nuanced understanding of these impacts is paramount for developing efficacious strategies to mitigate the carbon footprint of analogous future endeavors.

Table 2 Project Characteristics of the Reinforced Concrete Project.

Type of construction project	Reinforced concrete
Usable area (m^2)	13,208
Budget	10,017,916 USD
Duration	600 days
Floors (Above ground)	6
Floor area (m^2, above ground)	13,208

Figure 2 The Reinforced Concrete Building Analyzed in This Study.

2.2 Data collection and sources

The study combined quantitative data collection with stakeholder engagement to ensure the robustness and accuracy of the analysis. Figure 3 illustrates the conceptual framework for calculating embodied carbon emissions associated with the construction of reinforced concrete buildings. The process encompasses three major stages: manufacturing, transportation, and construction, which occur throughout the project's lifecycle. Inputs, emission factors, and outputs are integrated to quantify total carbon emissions.

The framework begins with the inputs, which consist of essential data such as construction drawings, material specifications, and the bill of quantities (BOQ). These documents outline the types and quantities of materials required for the project. Procurement planning includes logistics information, such as purchase orders, transportation routes, and delivery bills, while construction planning focuses on scheduling, machine utilization, and equipment requirements.

To quantify carbon emissions accurately, the model primarily relies on emission factors from the Thailand Greenhouse Gas Management Organization (TGO), ensuring alignment with Thailand's specific environmental and industrial context. For emission factors unavailable in the TGO database, supplementary data were sourced from other reliable databases, including the IPCC database for global emission standards, the Inventory of Carbon and Energy (ICE) for embodied carbon values of materials, and relevant literature for additional data. This approach ensures that the calculations are both regionally appropriate and methodologically robust across all lifecycle stages.

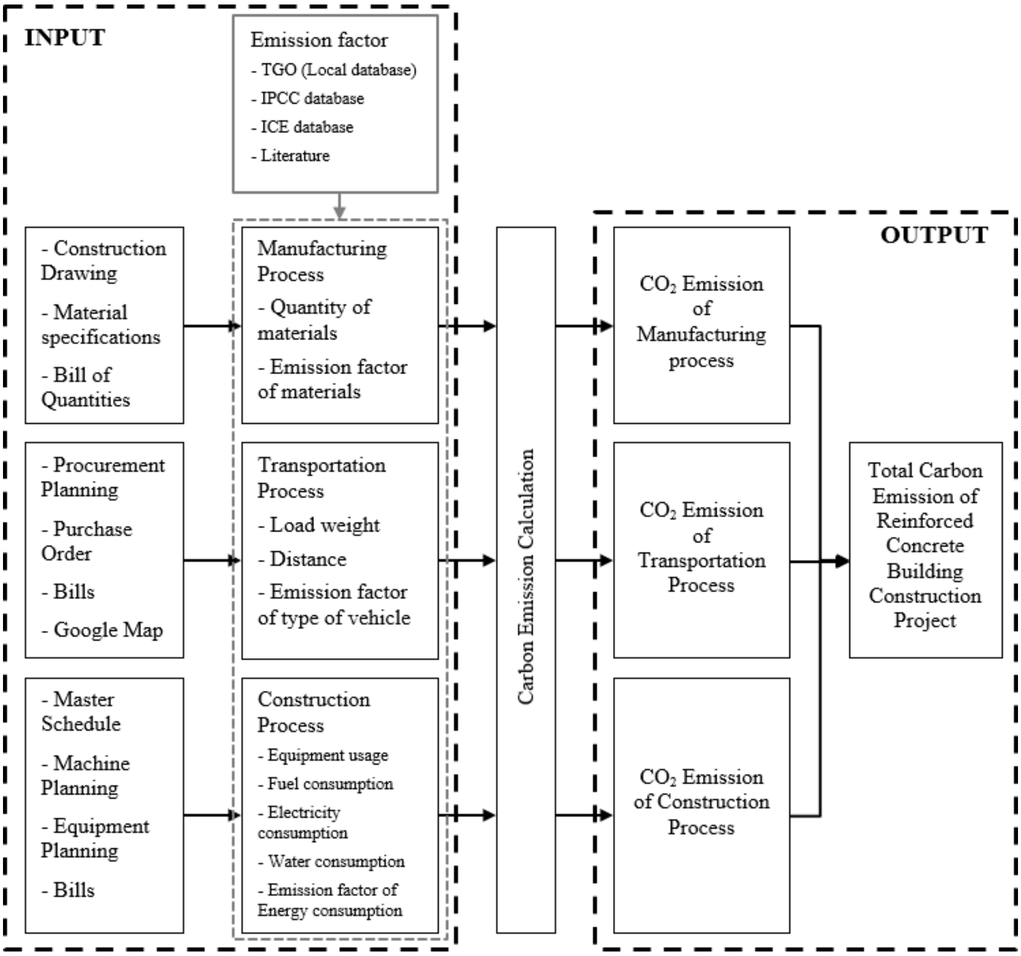

Figure 3 Conceptual Framework for Calculating Embodied Carbon Emissions.

2.3 Emission calculations

Carbon emissions for each stage of the construction lifecycle were calculated using established formulas adapted to the study context. These calculations accounted for material-specific emission factors, transportation distances, and energy usage during construction.

2.3.1 Manufacturing stage

The carbon emissions during material production can be dissected into three distinct phases: These include 1) procurement of raw materials, 2) movement of raw materials to the manufacturing sites, and 3) the actual material manufacturing process [20, 21]. This research focuses on the carbon emissions during the manufacturing phase of materials, as previous studies indicate that this phase is responsible for up to 90% of carbon emissions, while the acquisition and transportation of raw materials are only responsible for 10% [27, 33]. The calculation of carbon emissions during this phase is done by the product of the amount of material used and the carbon emission factor as represented in equation 1 [34, 35].

To ensure the utmost accuracy and relevance to the Thai context, carbon emission factor data from the Thailand Greenhouse Gas Management Organization (TGO) database were primarily sourced [36]. In instances where TGO data were unavailable, we judiciously utilized internationally recognized repositories such as the IPCC Emissions Factor Database [37] and the Inventory of Carbon and Energy (ICE) database [38].

$$CE_m = AD_m \times EF_m \quad (1)$$

Where CE_m denotes the quantity of carbon emissions during the manufacturing stage (kgCO2eq), AD_m represents the quantity of materials used in construction, and EF_m signifies the emission factor of materials.

It is important to acknowledge the potential discrepancy between the amount of material purchased and the material ultimately utilized in construction. This deviation often arises from material waste or losses occurring during the construction process. Factors such as over-ordering, material damage, or inefficiencies in handling can contribute to this discrepancy. The environmental implications of such waste are significant, as the production and disposal of surplus or unused materials generate additional carbon emissions without contributing to the functional outcome of the construction project.

From a sustainability perspective, addressing material waste is critical. Strategies to minimize waste, such as adopting more precise procurement methods, enhancing material handling practices, and incorporating waste reduction technologies, can significantly reduce unnecessary emissions. Moreover, emphasizing material efficiency not only aligns with environmental goals but also supports economic benefits by reducing costs associated with excess material production and disposal. Such measures underscore the importance of aligning industry practices with broader sustainability concerns, fostering a more responsible approach to resource management and carbon footprint reduction in construction.

2.3.2 Transport stage

The material transportation phase is subdivided into outbound and return transportation modes. Carbon emissions for this phase are therefore determined by the product of the material load weight, the transportation distance, and the carbon emission factor of the vehicle. The formula for these scenarios is explained in Equations 2 and 3 [34, 39]. Carbon emission factors were primarily sourced for different types of vehicles and their maximum allowable loads from the TGO database [36] to make the data as close to the Thai construction environment as possible.

1) Assessment of carbon emissions from outbound transportation:

$$CE_o = VL \times D \times EF_o \quad (2)$$

Where CE_o represents the quantity of carbon emissions during outbound material transportation ($kgCO_2eq$), VL denotes the load weight of materials, D signifies the transportation distance, and EF_o represents the emission factor for the specific vehicle type and its maximum load capacity.

2) Assessment of carbon emissions from return transportation:

$$CE_r = VLR \times D \times EF_r \quad (3)$$

Where CE_r represents the quantity of carbon emissions during return transportation ($kgCO_2eq$), VLR denotes the ratio of material load weight to the vehicle's maximum load capacity, D signifies the transportation distance, and EF_r represents the emission factor for the specific vehicle type and its maximum load capacity.

2.3.3 Construction stage

The construction phase encompasses three primary scenarios: fuel oil consumption by the machinery, electricity usage, and water consumption. The carbon emission assessment for each scenario is elucidated as follows:

1) Carbon emissions from fuel oil consumption by machinery are calculated by the product of the fuel quantity and the carbon emission factor [34, 39] as shown in Equation 4:

$$CE_f = AD_f \times EF_f \quad (4)$$

Where CE_f represents the quantity of carbon emissions from machinery fuel consumption ($kgCO_2eq$), AD_f denotes the amount of fuel used, and EF_f signifies the emission factor of the fuel.

2) The carbon emissions resulting from electricity consumption are obtained by multiplying the electricity consumption by the carbon emission factor as indicated in the following equation 5.

$$CE_e = AD_e \times EF_e \quad (5)$$

Where CE_e represents the quantity of carbon emissions from electricity usage ($kgCO_2eq$), AD_e denotes the amount of electricity consumed, and EF_e signifies the emission factor of electricity.

3) Carbon emissions from water usage are determined by multiplying the water consumption by its carbon emission factor [34], as expressed in Equation 6:

$$CE_w = AD_w \times EF_w \quad (6)$$

Where CE_w represents the quantity of carbon emissions from water usage ($kgCO_2eq$), AD_w denotes the amount of water consumed, and EF_w signifies the emission factor of water.

To ensure the highest degree of accuracy and contextual relevance, we have assiduously compiled carbon emission factors for fuels, electricity, and water from the TGO database [36], thereby grounding our analysis firmly within the Thai construction landscape.

3. Results and discussion

3.1 Manufacturing stage

The research has systematically divided the material production process into various work sectors, including structural work, architectural components, electrical and communication systems, sanitary facilities, fire protection systems, air conditioning and ventilation systems, medical gas systems, and interior design. The quantification of carbon emissions for each category yields the following insights.

As highlighted in Table 3 below, the structural works category is the largest contributor to carbon dioxide emissions, contributing to 3,649,496 $kgCO_2eq$, which is 56.09% of total emissions. In this regard, concrete is the most guilty, with a contribution of 58.06 % (2,118,913 $kgCO_2eq$) of emissions. Reinforced and structural steel follow suit, and both combined contribute to 39.78% (1,452,102 $kgCO_2eq$) of emissions within the structural works domain.

3.2 Transportation stage

The material transportation phase required a synthesis of material types by category and accurate determination of total distances for both the outward (Factor to construction site) and return (Construction site to factory) trips. Our analysis of carbon emissions for each category reveals:

As presented in Table 3, the structural works category once again dominates, emitting 427,397 $kgCO_2eq$, which represents an overwhelming 95.07% of total transportation-related emissions. This disproportionate contribution can be attributed to the conveyance of high-mass, voluminous materials such as concrete, reinforced steel, and structural steel. The sheer weight and quantity of these materials significantly amplify their greenhouse gas emission profile during transportation.

Table 3 Carbon Emissions and Costs by Category during Manufacturing and Transportation Stages

Categories	Carbon emission ($kgCO_2eq$)		Total cost (USD)
	Manufacturing stage	Transportation stage	
▪ Structural works	3,649,496	427,397	2,026,103
▪ Architectural works	1,783,825	15,786	3,051,728
▪ Electrical systems	883,468	3,446	2,776,135
▪ Sanitary systems	42,473	4	301,786
▪ Fire protection systems	22,603	7	241,840
▪ Air conditioning and ventilation systems	71,971	2,305	1,009,710
▪ Medical gas systems	5,424	275	223,422
▪ Interior architecture works	47,661	345	387,192
Total carbon emissions	6,506,921	449,565	10,017,916

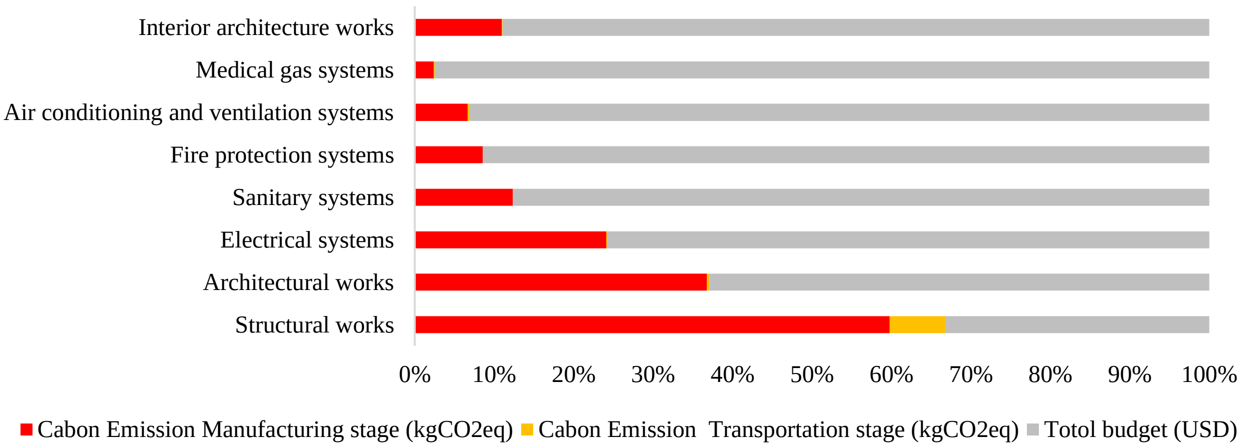

Figure 4 Comparative analysis of carbon emissions ($kgCO_2eq$) and costs (USD) across work categories

The data in Figure 4 illustrates the relationship between carbon emissions, derived from manufacturing and transportation stages, and the associated costs across various construction categories. While the primary focus of this study is on carbon emissions, total costs are included to identify opportunities for synergistic improvements. Addressing costs alongside emissions highlights the potential for interventions that not only reduce environmental impacts but also improve economic efficiency, which is particularly relevant for sustainable construction practices.

The findings reveal that categories with the highest costs, such as Structural works and Architectural works, also exhibit the highest carbon emissions. These results reflect the extensive use of energy-intensive materials like cement and steel, which dominate the manufacturing stage. These categories present significant opportunities for material substitution and process optimization to achieve both carbon and cost reductions.

In contrast, categories with lower total costs, such as Sanitary systems and Fire protection systems, show correspondingly low emissions. This reflects limited material requirements and the potential benefits of localized sourcing. By targeting categories with high emissions and costs, significant reductions can be achieved without substantial trade-offs in economic feasibility.

The analysis further indicates that transportation emissions contribute a smaller fraction compared to manufacturing emissions across all categories. This highlights the need to prioritize material efficiency in the manufacturing stage, which remains the dominant source of emissions, this was still secondary to the manufacturing emissions. Efficient logistics planning, such as reducing transportation distances and adopting low-emission vehicles, remains a viable strategy for minimizing emissions in this phase.

To align with the main objective of this study, which focuses on reducing carbon emissions, the inclusion of cost data provides a broader context for identifying economically feasible solutions. Interventions such as material substitution with low-carbon alternatives, optimizing production energy through renewable sources, and improving logistics efficiency can simultaneously reduce emissions and costs. For categories like Structural works and Architectural works, where emissions and costs are highest, targeted strategies can yield the greatest benefits.

In conclusion, the relationship between carbon emissions and total costs demonstrates the interdependence of environmental and economic factors in construction projects. By addressing high-emission hotspots through practical solutions, such as material innovations and process optimization, both carbon reductions and cost savings can be achieved. This integrated approach supports the development of sustainable construction practices that align with both environmental goals and economic priorities.

3.3 Construction stage

This study has delineated the construction process into three principal sectors of energy utilization: gasoline and other fuel energy consumption, electricity usage, and water utilization. The quantification of greenhouse gas emissions for each category yields the following results:

Table 4 illustrates that the electricity usage category emerges as the primary emitter, contributing 29,053 kgCO_2eq, which accounts for 49.30% of total emissions during the construction phase. Within this category, electric welding machines and tower cranes are the predominant sources, responsible for 25.00% and 22.00% of category emissions, respectively. The fuel energy usage category closely parallels electricity in terms of emissions, with backhoes being the primary contributor, accounting for 78.00% of greenhouse gas emissions within this category.

Table 4 Carbon Emissions during Construction Stages

Categories	Consumption	Emission factor (kgCO_2eq)	Carbon emission	Percentage
Fuel energy usage	63,706.71 L	0.3522	22,437	38.08
Electricity usage	48,584.34 kWh	0.598	29,053	49.30
Water usage	13,742.51 m^3	0.541	7,434	12.62
Total Carbon Emission			**58,924**	**100.00**

3.4 Comprehensive carbon emissions analysis of reinforced concrete construction

Figure 5 presents a holistic view of greenhouse gas emissions across the entire reinforced concrete construction project. The material production phase emerges as the most significant contributor, emitting 6,506,921 kgCO_2eq (6.506 ktCO_2eq), which constitutes 92.75% of total project emissions. The material transportation phase follows, contributing 449,565 kgCO_2eq (0.449 ktCO_2eq), representing 6.41% of the total. The construction phase itself accounts for the least emissions, generating 58,924 kgCO_2eq (0.058 ktCO_2eq), a mere 0.84% of total project emissions.

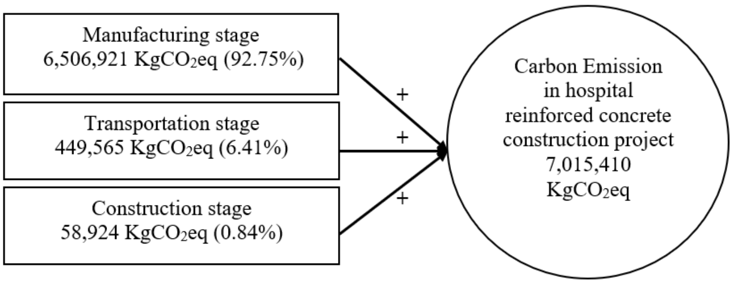

Figure 5 Distribution of embodied carbon emissions in the reinforced concrete construction project

This study provides a nuanced analysis of carbon emissions across manufacturing and transportation stages for various construction categories, juxtaposed with their associated costs in USD. This granular breakdown elucidates the proportional contribution of each lifecycle stage to both total carbon emissions and costs. Notably, carbon emission percentages are distributed as follows: Structural works (56.09%), Architectural works (27.41%), with lower contributions from systems such as electrical (13.58%) and sanitary (0.65%).

The significance of these percentages lies in their capacity to identify primary contributors to overall emissions, thereby informing targeted carbon footprint reduction strategies. The substantial emissions associated with Structural works, for instance, highlight a critical area for the implementation of advanced, low-carbon materials and techniques.

Our findings reveal a compelling dichotomy: while "Structural works" dominate carbon emissions in both manufacturing (56.09%) and transportation (95.07%) phases, "Architectural works" incur the highest costs, comprising 30.49% of the total project expenditure. This disparity between emission intensity and cost across categories (illustrated in Figure 4) presents opportunities for synergistic improvements in sustainability and cost-efficiency.

These results underscore significant variations in carbon emissions and associated costs across construction categories, pinpointing critical areas for intensified sustainability efforts. This approach not only aids in prioritizing environmental initiatives but also aligns with economic imperatives, potentially guiding future policy formulation and practical measures within the construction industry to optimize the balance between environmental impact and financial efficiency. To this end, we propose the following interventions:

3.5 Manufacturing stage: The crux of carbon emissions

3.5.1 Concrete: Revolutionizing the foundation

Given that 90% of carbon emissions in conventional concrete are attributable to cement content [21, 40], our strategies primarily focus on cement reduction or substitution:

- Clinker Replacement with Alternative Materials: Replacing regular Portland cement with fly ash, slag, and calcined clay/metakaolin provides a very good opportunity for emission control. According to the literature, this approach can lead to a potential reduction of up to 12% of emissions [41].
- Integration of Supplementary Cementitious Materials: The use of supplementary cementitious materials such as fly ash, slag, and silica fume in concrete mixtures is cost-effective and efficient for emission reduction [27]. This approach also helps reduce environmental effects and optimize resource use while reducing the need for landfill [42].
- Adoption of Low Carbon Aggregates: The use of recycled aggregates like construction and demolition waste, glass fines, marble chips, ceramic tiles, and recycled tire rubber has the advantages of reduced emissions and cost-effectiveness [27]. In addition, applying low-carbon materials in the construction industry as a replacement for conventional materials can greatly reduce the carbon footprint [25, 27, 43].
- Carbon Capture and Utilization Technologies: Despite the potential, the application of carbon capture from industrial processes for concrete production is challenged by economic factors mainly because of the high costs of technology integration [27, 44]. However, this avenue has to be explored and developed even further.

3.5.2 Rebar and steel: Strengthening sustainability

- Deployment of High-Strength Steel: The use of high-strength steel helps reduce cross-sectional area and weight, which can lead to a reduction in steel weight by about 19%. According to Kechidi and Banks [21], this can result in a 10% decrease in carbon emissions in the 'Cradle to site' phases. Furthermore, high-strength steel, which has a longer service life, helps to use resources more effectively in the long run [45, 46].
- Innovative Design Approaches: The use of low-carbon materials [43, 47] and designing methods [48] that reduce the use of steel or replace it with other materials can significantly decrease the carbon impact of construction projects [22, 25, 45].

3.6 Transport stage: Navigating towards sustainability

Our research also shows that the carbon emissions related to material transportation are relatively low due to overland transportation and domestic products; however, there is still room for improvement [49]. The shift from traditional fuel-fueled vehicles to Battery Electric Vehicles (BEVs) offers an opportunity to eliminate direct carbon emissions during transport. However, it is essential to consider the so-called Scope 2 emissions, the indirect emissions from electricity consumption. However, the carbon footprint of diesel fuel consumption remains higher than that of electricity generation [50], which indicates that this shift may be useful.

3.7 Construction stage: Harnessing renewable energy

The use of renewable energy sources, especially solar thermal energy for electricity generation can offer the chance to cut carbon emissions by 30% [45]. It also fits well with the international climate change initiatives and places the construction industry as one of the leaders in sustainable industrial development.

Therefore, our research sheds light on several important factors that can be used to decrease the carbon intensity of reinforced concrete construction projects in Thailand. The construction industry can go a long way in environmental sustainability by concentrating efforts on innovations in material composition, transportation, and energy. Further studies should be conducted on the economic viability and the future effects of these suggested interventions on the environment in order to give a holistic approach to construction sustainability.

4. Conclusions

The findings of this study confirm that the manufacturing stage is the most significant contributor to carbon emissions in Thai reinforced concrete construction projects, particularly due to the use of high-carbon materials like cement and steel. Structural works, dominated by concrete and reinforcement steel, accounted for 56.09% and 39.78% of total manufacturing emissions, respectively. To address this, the study identifies several strategies for reducing carbon emissions, including substituting traditional materials with alternatives such as supplementary cementitious materials (SCMs) like fly ash, slag, and recycled aggregates. These substitutes have demonstrated significant potential to lower embodied carbon emissions while maintaining structural integrity.

However, reducing carbon emissions must also consider the economic and practical implications of material substitution. While alternative materials offer environmental benefits, their cost and availability within the local market must be carefully evaluated to ensure their feasibility for widespread implementation. Additionally, maintaining construction quality and performance standards is essential when adopting these substitutes, as any compromise in durability or structural reliability could undermine their long-term sustainability benefits.

This study highlights the importance of balancing carbon reduction strategies with economic and construction quality considerations. For example, materials such as high-strength steel, while reducing the overall quantity of material required, may incur higher upfront costs. Similarly, integrating prefabrication techniques or low-carbon technologies can enhance material efficiency but must align with budgetary constraints and local supply chain capabilities.

Future research should prioritize the economic feasibility of low-carbon materials, as their adoption hinges on balancing environmental benefits with financial viability. Conducting lifecycle cost analyses to evaluate long-term economic impacts of substitutes like supplementary cementitious materials (SCMs) and high-strength steel is crucial. This includes assessing market availability, pricing trends, and potential cost savings from reduced material usage.

By focusing on these aspects, future research can provide actionable strategies that align economic feasibility with environmental sustainability, accelerating the transition to low-carbon construction practices.

5. Acknowledgements

The authors would like to express their gratitude to the hospital, contractor, and consultancy organizations for their support in conducting this research. This research was financially supported by Mahasarakham University, which also provided the research facilities.

6. References

[1] International Energy Agency. Global status report for buildings and construction 2019. Paris: IEA; 2019.
[2] United Nations Environment Programme. Global status report for buildings and construction: beyond foundations: mainstreaming sustainable solutions to cut emissions from the buildings sector. Nairobi: UNEP; 2024.
[3] United Nations Environment Programme. 2020 Global status report for buildings and construction: towards a zero-emission, efficient and resilient buildings and construction sector. Nairobi: UNEP; 2020.
[4] Röck M, Saade MRM, Balouktsi M, Rasmussen FN, Birgisdottir H, Frischknecht R, et al. Embodied GHG emissions of buildings–The hidden challenge for effective climate change mitigation. Appl Energy. 2020;258:114107.
[5] Amiri A, Emami N, Ottelin J, Sorvari J, Marteinsson B, Heinonen J, et al. Embodied emissions of buildings - a forgotten factor in green building certificates. Energy Build. 2021;241:110962.
[6] Zhang L, Liu B, Du J, Liu C, Li H, Wang S. Internationalization trends of carbon emission linkages: a case study on the construction sector. J Clean Prod. 2020;270:122433.
[7] Lai KE, Rahiman NA, Othman N, Ali KN, Lim YW, Moayedi F, et al. Quantification process of carbon emissions in the construction industry. Energy Build. 2023;289:113025.
[8] Hurst LJ, O'Donovan TS. Embodied impacts of key materials for UK decarbonised domestic retrofit: Differences between sources of embodied carbon and embodied energy data. Energy Build. 2024;319:114515.
[9] Office of Natural Resources and Environmental Policy and Planning. Thailand's nationally determined contribution roadmap on mitigation 2021-2030. Thailand: Ministry of Natural Resources and Environment; 2020.
[10] Office of Natural Resources and Environmental Policy and Planning. Thailand's Fourth National Communication. Thailand: Ministry of Natural Resources and Environment; 2024.
[11] Cheng S, Zhou X, Zhou H. Study on carbon emission measurement in building materialization stage. Sustainability. 2023;15(7):5717.
[12] United Nations Environment Programme. Emissions gap report 2023: broken record—temperatures hit new highs, yet world fails to cut emissions (again). Nairobi: UNEP; 2023.
[13] International Energy Agency. Tracking clean energy progress 2023. Paris: IEA; 2023.
[14] United Nations Environment Programme. 2022 Global status report for buildings and construction: towards a zero-emission, efficient and resilient buildings and construction sector. Nairobi: UNEP; 2022.
[15] Limsawasd C. GHG emission quantification for pavement construction projects using a process-based approach. Eng Appl Sci Res. 2017;44(1):27-33.
[16] Liang R, Zheng X, Liang J, Hu L. Energy efficiency model construction of building carbon neutrality design. Sustainability. 2023;15(12):9265.
[17] Le Nguyen K, Uddin M, Pham TM. Generative artificial intelligence and optimisation framework for concrete mixture design with low cost and embodied carbon dioxide. Constr Build Mater. 2024;451:138836.
[18] Gauch HL, Dunant CF, Hawkins W, Serrenho AC. What really matters in multi-storey building design? a simultaneous sensitivity study of embodied carbon, construction cost, and operational energy. Appl Energy. 2023;333:120585.
[19] British Standards Institution. PAS 2080: 2016: Carbon management in infrastructure. United Kingdom: BSI; 2016.
[20] The Royal Institution of Chartered Surveyors (RICS). Whole life carbon assessment for the built environment. RICS Professional Standards and Guidance. London: RICS; 2017.
[21] Kechidi S, Banks N. Minimising upfront carbon emissions of steel-framed modular housing: a case study. J Build Eng. 2023;72:106707.
[22] McGarry H, Martin B, Winslow P. Delivering low carbon concrete for network rail on the routemap to net zero. Case Stud Constr Mater. 2022;17:e01343.
[23] Kanafani K, Magnes J, Lindhard SM, Balouktsi M. Carbon emissions during the building construction phase: A comprehensive case study of construction sites in Denmark. Sustainability. 2023;15(14):10992.
[24] Kwok KYG, Kim J, Chong WKO, Ariaratnam ST. Structuring a comprehensive carbon-emission framework for the whole lifecycle of building, operation, and construction. J Archit Eng. 2016;22(3):04016006.
[25] Helal J, Stephan A, Crawford RH. The influence of structural design methods on the embodied greenhouse gas emissions of structural systems for tall buildings. Structures. 2020;24:650-65.
[26] Liu N, Wang Y, Bai Q, Liu Y, Wang PS, Xue S, et al. Road life-cycle carbon dioxide emissions and emission reduction technologies: a review. J Traffic Transp Eng (Engl Ed). 2022;9(4):532-55.
[27] Althoey F, Ansari WS, Sufian M, Deifalla AF. Advancements in low-carbon concrete as a construction material for the sustainable built environment. Dev Built Environ. 2023;16:100284.
[28] Xu X, You J, Wang Y, Luo Y. Analysis and assessment of life-cycle carbon emissions of space frame structures. J Clean Prod. 2023;385:135521.
[29] Gursel AP, Shehabi A, Horvath A. Embodied energy and greenhouse gas emission trends from major construction materials of US office buildings constructed after the mid-1940s. Build Environ. 2023;234:110196.
[30] He Z, Ma S, Deng Z, Meng Y. Carbon emission reduction enabled by informatization construction: an analysis of spatial effects based on China's experience. Environ Sci Pollut Res. 2024;31:35595-608.
[31] Xu A, Zhu Y, Wang Z, Zhao Y. Carbon emission calculation of prefabricated concrete composite slabs during the production and construction stages. J Build Eng. 2023;80:107936.

[32] Zhao Y, Xu Y, Yu M. An approach for measuring and analyzing embodied carbon in the construction industry chain based on emergy accounting. Ecol Indic. 2024;158:111481.

[33] Hanifa M, Agarwal R, Sharma U, Thapliyal PC, Singh LP. A review on CO_2 capture and sequestration in the construction industry: Emerging approaches and commercialised technologies. J CO2 Util. 2023;67:102292.

[34] International Organization for Standardization. ISO 14040:2006 environmental management-life cycle assessment-principles and framework. Geneva: International Organization for Standardization; 2006.

[35] Dong Q. Research methods of carbon emissions. Highl Sci Eng Technol. 2023;40:412-7.

[36] Thailand Greenhouse Gas Management Organization. Emission factor (CFP) [Internet]. 2024 [cited 2024 Oct 2]. Available from: https://thaicarbonlabel.tgo.or.th/index.php?lang=TH&mod=Y0hKdlpIVmpkSE5mWlcxcGMzTnBiMjQ9.

[37] IPCC. IPCC emission factor database [Internet]. 2007 [cited 2024 Oct 2]. Available from: https://ghgprotocol.org/Third-Party-Databases/IPCC-Emissions-Factor-Database.

[38] Hammond G, Jones C. Inventory of carbon & energy (ICE). Bath: University of Bath; 2008.

[39] Thailand Greenhouse Gas Management Organization. Local Performance Assessment: LPA [Internet]. 2018 [cited 2024 Oct 2]. Available from: https://www.dla.go.th/en/o3.jsp.

[40] Wang Y, Jiang Z, Li L, Qi Y, Sun J, Jiang Z. A bibliometric and content review of carbon emission analysis for building construction. Buildings. 2023;13(1):205.

[41] García-Gusano D, Herrera I, Garraín D, Lechón Y, Cabal H. Life cycle assessment of the Spanish cement industry: implementation of environmental-friendly solutions. Clean Techn Environ Policy. 2015;17:59-73.

[42] El-Chabib H. Properties of SCC with supplementary cementing materials. In: Siddique R, editor. Self-compacting concrete: Materials, properties and applications. Cambridge: Woodhead Publishing; 2020. p. 283-308.

[43] Myint NN, Shafique M. Embodied carbon emissions of buildings: Taking a step towards net zero buildings. Case Stud Constr Mater. 2024;20:e03024.

[44] Witoon T. Capture and Separation Technologies of CO_2 from Combustion of Fossil Fuel. KKU Eng J. 2011;38(4):453-67.

[45] Huang Z, Zhou H, Miao Z, Tang H, Lin B, Zhuang W. Life-cycle carbon emissions (LCCE) of buildings: implications, calculations, and reductions. Engineering. 2024;35:115-39.

[46] Lu H, You K, Feng W, Zhou N, Fridley D, Price L, et al. Reducing China’s building material embodied emissions: Opportunities and challenges to achieve carbon neutrality in building materials. IScience. 2024;27(3):109028.

[47] Zheng M, Yu F, Guo S. Discussion on the effects of carbon trading for construction-related activities based on hybrid defuzzification strategy. Sustain Prod Consum. 2022;34:412-39.

[48] Xu J. Carbon emission of construction materials and reduction strategy: take prefabricated construction in China as an example. Highl Sci Eng Technol. 2022;28:401-6.

[48] Satiennam T, Satiennam W, Gadsadayurat S, Aranyasen S, Srisa-ard K. Vehicle kilometers of travel and fuel consumption rate for estimating CO2 emission of vehicles in Khon Kaen city. KKU Eng J. 2014;41(3):333-46.

[49] Wang H, Zhang H, Zhao L, Luo Z, Hou K, Du X, et al. Real-world carbon emissions evaluation for prefabricated component transportation by battery electric vehicles. Energy Rep. 2022;8:8186-99.

[50] Dubisz D, Golińska-Dawson P, Koliński A. Measuring CO_2 emissions level for more sustainable distribution in a supply chain. Eng Appl Sci Res. 2022;49(6):804-10.