Global J. Environ. Sci. Manage. 13(1): 303-326, Winter 2027, Serial #49

Global Journal of Environmental Science and Management
(GJESM)

Homepage: https://www.gjesm.net/

Podcasts

ORIGINAL RESEARCH ARTICLE

Life cycle assessment and identification of embodied carbon hotspots in a reinforced concrete factory

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ARTICLE INFO

Article History:
Received 21 May 2026
Revised 23 August 2026
Accepted 25 September 2026

Keywords:
Embodied carbon
Greenhouse gas
Industrial buildings
Life cycle assessment
Pre-use embodied carbon
Reinforced concrete

DOI:10.22034.gjesm.2027.01.14

ABSTRACT

BACKGROUND AND OBJECTIVES: Reducing embodied carbon is a key strategy for delivering low-carbon buildings because emissions from construction materials and activities represent a substantial share of total building life-cycle emissions. While extensive scholarly research has addressed embodied carbon within the residential and commercial sectors, comprehensive hotspot analyses concerning industrial facilities remain scarce, particularly within the geographical context of Thailand. The study objectives were to quantify the embodied carbon of a reinforced concrete factory building and identified carbon hotspots at the life-cycle module, building-component, and material levels to support evidence-based mitigation during the building pre-use stage.

METHODS: A reinforced concrete factory building in Thailand with a gross floor area of 90.00 square meters was selected as the case study. Embodied carbon was assessed using life cycle assessment in accordance with International Organization for Standardization 14040 and 14044 and British Standard European Norm 15978. The system boundary, established from a cradle-to-practical-completion perspective, encompassed the production and transport of construction materials, on-site energy consumption during construction, and construction waste management. Carbon hotspots were analyzed at the life-cycle module, building-component, and resource type levels.

FINDINGS: The total embodied carbon was 29,353.47 kilograms of carbon dioxide equivalent, corresponding to 326.15 kilograms of carbon dioxide equivalent per square meter. Construction material production was the dominant emission source, contributing 78.10 percent of total embodied carbon. On-site construction energy use accounted for 12.09 percent of the impact, followed by construction waste management at 5.25 percent, and the transportation of construction materials at 4.56 percent. The reinforced concrete structural system generated the highest embodied carbon at 10,533.29 kilograms of carbon dioxide equivalent, followed by the wall system at 7,527.36 kilograms of carbon dioxide equivalent. Concrete, structural steel, and corrugated steel roofing with associated components accounted for 23.13 percent, 18.31 percent, and 16.73 percent of the total impact, respectively. Collectively, these three resource categories accounted for 58.17 percent of total embodied carbon.

CONCLUSION: Construction material production represents the principal opportunity for reducing embodied carbon in reinforced concrete factory buildings. Improvements in construction energy efficiency and construction waste management can provide additional emission reductions. The proposed hotspot-based assessment framework establishes a comprehensive embodied carbon inventory for reinforced concrete industrial facilities in Thailand, thereby providing actionable guidance for low-carbon design architectural, material optimization, and construction management.

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NUMBER OF REFERENCES	NUMBER OF FIGURES	NUMBER OF TABLES
39	5	5

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Note: Discussion period for this manuscript open until March 01, 2027 on GJESM website at the "Show Article".

INTRODUCTION

The building sector is a major source of greenhouse gas (GHG) emissions, primarily from construction material production, transportation, and on-site construction activities. As countries pursue carbon neutrality and sustainable development, life cycle assessment (LCA) and carbon accounting have become important tools for systematically identifying major emission sources and supporting evidence-based decision-making for low-carbon buildings and sustainable infrastructure (Pomponi and Moncaster, 2016; Röck *et al.*, 2020; de Cadenet *et al.*, 2025). LCA serves as a systematic methodology for systematically evaluating the environmental burdens of products and systems across sequential life-cycle phases. By quantifying impacts at each stage, LCA facilitates the identification of emission-intensive processes and highlights critical targets for mitigation (Rashif *et al.*, 2025). Accordingly, LCA and carbon footprint assessment are increasingly used to support sustainability decision-making, including comparing alternatives, evaluating GHG mitigation measures, and identifying environmental hotspots to inform evidence-based decisions (Rashif *et al.*, 2025; de Cadenet *et al.*, 2025; Firmansyah *et al.*, 2025). In building LCA, GHG emissions are frequently evaluated through the framework of whole life carbon (WLC), which encompasses both embodied and operational carbon components. Embodied carbon arises from material production, transportation, construction, maintenance, replacement, demolition, and end-of-life processes, whereas operational carbon results from energy consumption during building use (Cabeza *et al.*, 2014; Lützkendorf and Balouktsi, 2022). As energy-efficient building strategies become more widespread, the relative share of operational carbon has decreased, whereas embodied carbon has emerged as an increasingly significant component of total life-cycle emissions, particularly within high-performance structures (Pomponi and Moncaster, 2016; Röck *et al.*, 2020; Lützkendorf and Balouktsi, 2022). Early design decisions, including building form, structural systems, and material selection, can substantially influence embodied carbon (Gauch *et al.*, 2023). Consequently, reliable embodied carbon datasets are essential for identifying carbon hotspots and prioritizing mitigation strategies, including the adoption of low-carbon materials, enhanced structural efficiency, and optimized construction practices (Myint and Shafique, 2024; Amarasinghe *et al.*, 2025). However, studies specifically assessing the embodied carbon of built assets in Thailand remain limited. Although recent research has quantified the embodied carbon of roads and drainage systems in Thai housing developments (Suriyanon *et al.*, 2026), studies focusing on buildings—particularly reinforced concrete factory buildings, remain scarce. Consequently, the Thai construction industry lacks empirical evidence and benchmark values to support comparison, target setting, and the selection of appropriate GHG mitigation measures during the building pre-use stage. In recent years, scholarly investigation into embodied building carbon (EBC) has expanded significantly, encompassing comparative evaluations of alternative design and construction strategies, component-level hotspot identification, and the advancement of specialized assessment methodologies and decision-support tools. Studies of residential, commercial, and high-rise buildings have consistently shown that structural systems and major construction materials frequently dominate embodied carbon emissions. For example, Monahan and Powell (2011) compared embodied carbon across alternative affordable housing construction systems in the United Kingdom, while Jayawardana *et al.* (2021) identified masonry wall systems as a major hotspot in multi-storey residential buildings in Sri Lanka. Similar assessments have been conducted for commercial buildings and green office buildings (Samson and Pope, 2012; Sandaruwan *et al.*, 2024), as well as

residential construction projects in North America (Zuluaga and Saxe, 2025). Investigations into high-rise and large-scale structures have further analyzed how structural systems, building configurations, and construction methodologies influence embodied carbon emissions. Wan Omar (2018) evaluated the embodied carbon intensity of several building types in Malaysia, while Teng and Pan (2019) assessed a prefabricated public residential building in Hong Kong at material and whole-building levels. More recent studies have evaluated modular high-rise reinforced concrete structures, public housing complexes, and high-rise residential buildings, generating critical hotspot data and benchmark values to facilitate low-carbon design and decision-making (Sachchithananthan *et al.*, 2024; Agustiningtyas *et al.*, 2024; Zhang and Wang, 2016). In Thailand, Liwthaisong *et al.* (2025) assessed a six-storey reinforced concrete outpatient building and found that concrete and reinforcing steel were the major sources of embodied carbon. Furthermore, methodological advancements in embodied carbon assessment have been achieved through the application of process-based, input–output, and hybrid LCA frameworks (Li *et al.*, 2014; Zhang and Wang, 2016). In addition, the integration of building information modeling (BIM) with LCA enables more rapid quantity take-off, carbon estimation, and visualisation during the design stage (Huang *et al.*, 2023; Kanangkaew *et al.*, 2026). Recent reviews further highlight the potential of machine learning and multi-criteria decision-making frameworks to improve the efficiency, contextual relevance, and practical application of embodied carbon assessments (Shi *et al.*, 2025). At the macro-systemic level, researchers have underscored the critical need for reliable benchmarks, localized environmental product declarations, harmonized assessment standards, and robust institutional and policy frameworks to ensure effective implementation (Drewniok *et al.*, 2023; Greer *et al.*, 2023; Amarasinghe *et al.*, 2025; Santos *et al.*, 2025). Despite these advances, research on industrial buildings remains limited relative to that on residential and commercial buildings. Rodrigues *et al.* (2018) assessed an industrial building and found that construction materials were the primary contributors to embodied carbon. Nevertheless, findings from international studies cannot be directly extrapolated to Thailand because embodied carbon is heavily governed by context-specific determinants, such as material emission factors, national energy grid characteristics, and regional construction practices. Therefore, assessing reinforced concrete factory buildings in Thailand and identifying carbon hotspots at the building-component, material, and life-cycle-stage levels are essential for establishing locally relevant evidence and prioritising effective mitigation measures. In the present study, the dataset was augmented with supplementary entries and subsequently subjected to comprehensive review and revision to enhance data fidelity. It builds on earlier work by Watkate and Suriyanom (2024), which reported a preliminary assessment of the building's embodied carbon (EBC). The scope of the study was also expanded to provide a more in-depth analysis of carbon hotspots across building components, resource types, and life-cycle stages. The findings are intended to inform engineering decisions pertaining to architectural design, material specification, procurement strategies, on-site energy utilization, and waste management practices. The study also provides data and a methodological foundation for future benchmark development and embodied carbon assessments of buildings in Thailand. Conducted in 2024, this study evaluates the embodied carbon of a reinforced-concrete industrial facility in Thailand through a LCA framework focusing specifically on the pre-use stage.

MATERIALS AND METHODS

Case study and study scope

A reinforced concrete factory building located in Chiang Mai Province, Thailand, with a gross floor area of 90.00 square meters (m^2), was selected as

the case study. This particular project was adopted for evaluation as its architectural configuration and material framework closely mirror the baseline characteristics of small-sized manufacturing buildings throughout Thailand. The building is a single-storey industrial facility. The assessment scope covered GHG emissions associated with structural works, architectural works, and construction support works, while mechanical, electrical, and plumbing (MEP) systems were excluded. The scope was established based on two primary considerations. First, the assessment focused on building elements characterized by high material consumption, as these components predominantly drive embodied carbon and constitute likely carbon hotspots. Second, MEP systems were excluded to minimize analytical uncertainty stemming from project-specific service installations, which vary substantially according to facility functions, operational parameters, and system configurations. This variability limits meaningful cross-project comparisons and reduces the value of the results for benchmarking. In addition, MEP systems comprise a wide range of materials and equipment with diverse manufacturing routes and raw material compositions, meaning that emission estimation often relies on numerous assumptions when selecting appropriate emission factors (EFs). Consequently, the exclusion of MEP systems enhances the reliability and consistency of the embodied carbon findings, thereby reinforcing their utility as a benchmark reference case for industrial facilities within the Thai construction sector. Nevertheless, excluding MEP systems may result in an underestimation of the total pre-use embodied carbon; therefore, the reported results should be interpreted as representing only the structural, architectural, and construction-support works included within the defined system boundary. The structural system of the subject building comprised reinforced concrete spread footings, columns, and floor slabs, whereas the roof framework was constructed using structural steel members. Architectural works comprised two external wall systems—painted, cement-rendered concrete block walls and corrugated steel sheet cladding on steel framing—as well as expanded polystyrene (EPS) sandwich-panel internal partitions, corrugated steel sheet roof covering, and a smooth plaster ceiling finish. Regarding construction support activities, the life cycle inventory (LCI) accounted for general electricity consumption, administrative air-conditioning use, wastewater treatment via an on-site facility system, and solid waste management. Additionally, auxiliary resources, including temporary office container units and operational consumable materials such as A4 paper, were integrated into the life-cycle inventory. These activities were defined according to the available project records to represent greenhouse gas emissions generated during the pre-use stage of the building life cycle. The primary data used for developing the LCI and assessing embodied carbon and carbon hotspots during the pre-use stage were obtained from the construction drawings, technical specifications, and the bill of quantities (BOQ). These project documents furnished the quantitative parameters necessary to conduct material take-off and subsequent embodied carbon computations.

Research framework

The research framework adopted in this study was formulated in accordance with LCA principles for embodied carbon evaluation. The assessment commenced with the definition of the study objectives and system boundary, followed by data collection for the preparation of the LCI. Appropriate EFs were subsequently selected and integrated with the inventory data to quantify the embodied carbon associated with the case-study building. Subsequently, the computed results were then systematically analyzed to isolate primary carbon hotspots across both the life-cycle stages and structural building component, as illustrated in the overarching research framework presented in Fig. 1.

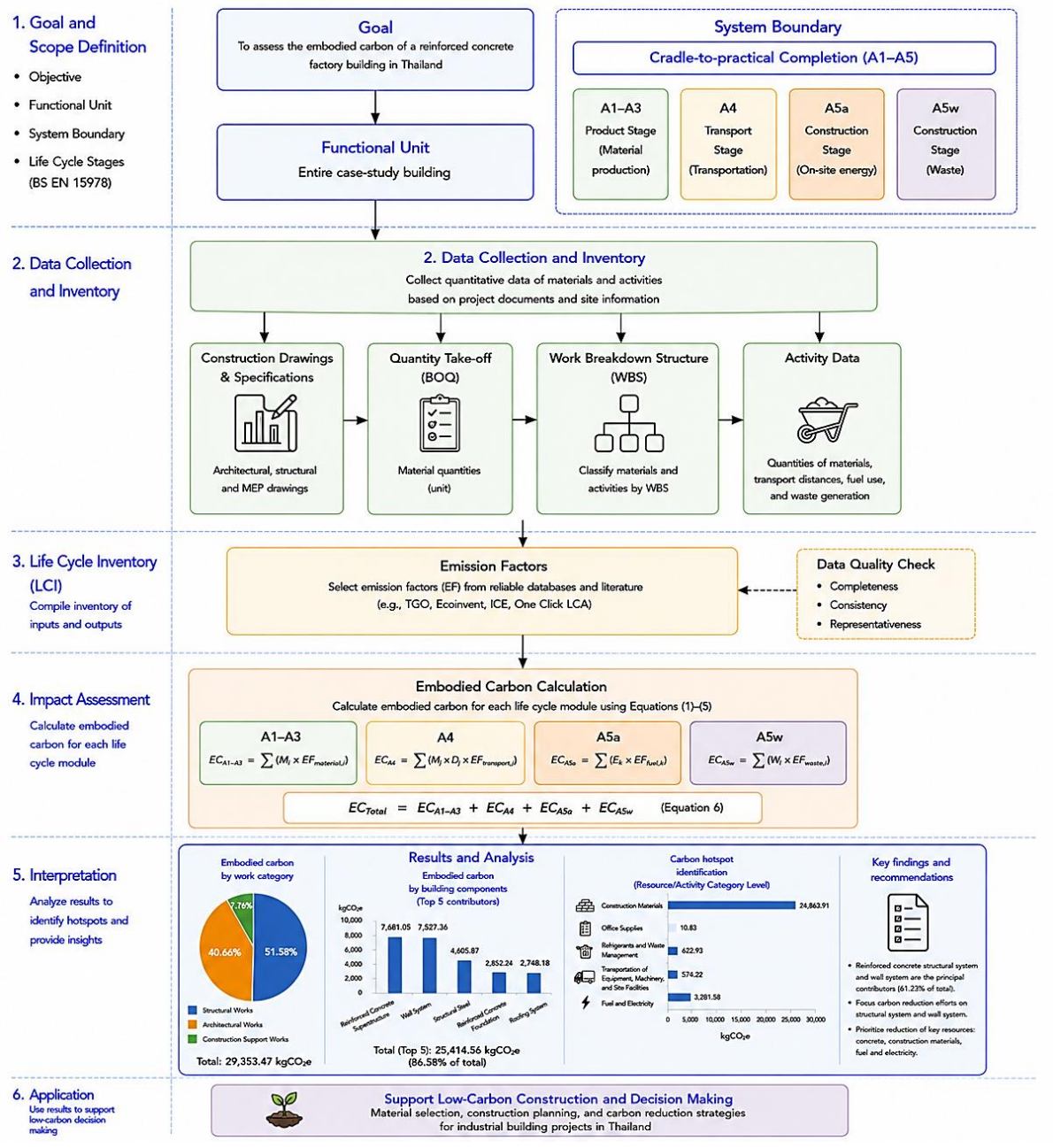


Fig. 1: Research framework adopted in this study

System boundary

The embodied carbon assessment was conducted following the principles of LCA in accordance with International Organization for Standardization (ISO) 14040:2006 (ISO, 2006a) and ISO 14044:2006 (ISO, 2006b), thereby ensuring that the assessment process was systematic, transparent, and reproducible. The system boundary at the building level was established based on BS EN 15978:2011 (BSI, 2011), with the assessment focusing exclusively on the pre-use stage of the building life

cycle. The system boundary was established under a cradle-to-practical completion approach, incorporating modules A1–A3 (material production), A4 (transportation), A5a (on-site energy use and construction activities), and A5w (waste management). In accordance with BS EN 15978, transportation of construction machinery and temporary site facilities was allocated to A4, while on-site fuel and electricity use, refrigerant emissions, and temporary site utility activities were allocated to A5a. Construction waste transportation and treatment were allocated to A5w. The use stage (modules B1–B7) and end-of-life stage (modules C1–C4) were omitted because the primary objective of this study was to identify embodied carbon hotspots and carbon mitigation opportunities addressable during the building design and construction phases. For the embodied carbon calculation, quantitative data obtained from the construction drawings and the BOQ were compiled into the LCI and linked with the corresponding EFs for construction materials, transportation, energy and fuel use, and construction waste management. This comprehensive inventory formed the methodological foundation for calculating greenhouse gas emissions across the established assessment boundary. The entire case-study building, with a gross floor area of 90.00 m^2, was defined as the reference unit for the assessment. To facilitate comparison with existing building LCAs, the outcomes were further normalized per square meter of gross floor area, expressed in kilogram carbon dioxide equivalent ($kgCO_2e/m^2$), establishing a standardized reference metric independent of structural scale. The system boundary implemented in this study is illustrated in Fig. 2.

Data collection

The data used in this study comprised both primary and secondary data sources. The primary data were quantified directly from the case-study project and included; 1) construction material quantities, 2) fuel and energy consumption of construction equipment during on-site activities, and 3) transportation distances for construction materials and equipment to the project site. The secondary data consisted of greenhouse gas EFs for construction materials, transportation, fuels, electricity consumption, and construction waste management. A work breakdown structure (WBS) was utilized to categorize the facility into discrete construction components, thereby systematically integrating material quantities, transportation activities, on-site processes, and construction waste management into the embodied carbon assessment. This structured methodology allowed the evaluation outcomes to be examined across both life-cycle modules and structural components, thereby supporting the efficient identification of primary carbon hotspots. Priority was given to EFs developed by domestic organizations and relevant stakeholders, such as manufacturer-published databases and the Thailand Greenhouse Gas Management Organization (TGO). Where local EFs were unavailable or insufficient, reliable data obtained from published studies and internationally recognized databases were adopted. This data selection strategy was formulated to enhance both the accuracy and representativeness of the evaluation while preserving full alignment with core LCA principles. Furthermore, this methodological strategy aligns with the recommendations of De Wolf *et al.* (2017), who stressed the necessity of utilizing granular activity data alongside well-defined system boundaries and transparent data sources to improve the reliability and comparability of embodied carbon evaluations.

Data quality, allocation, cut-off criteria, and assumptions

Project-specific data were used where available, while secondary EFs prioritized Thailand-specific and temporally relevant sources. To prevent double counting, resources and activities were allocated to their corresponding building components and life-cycle modules in accordance

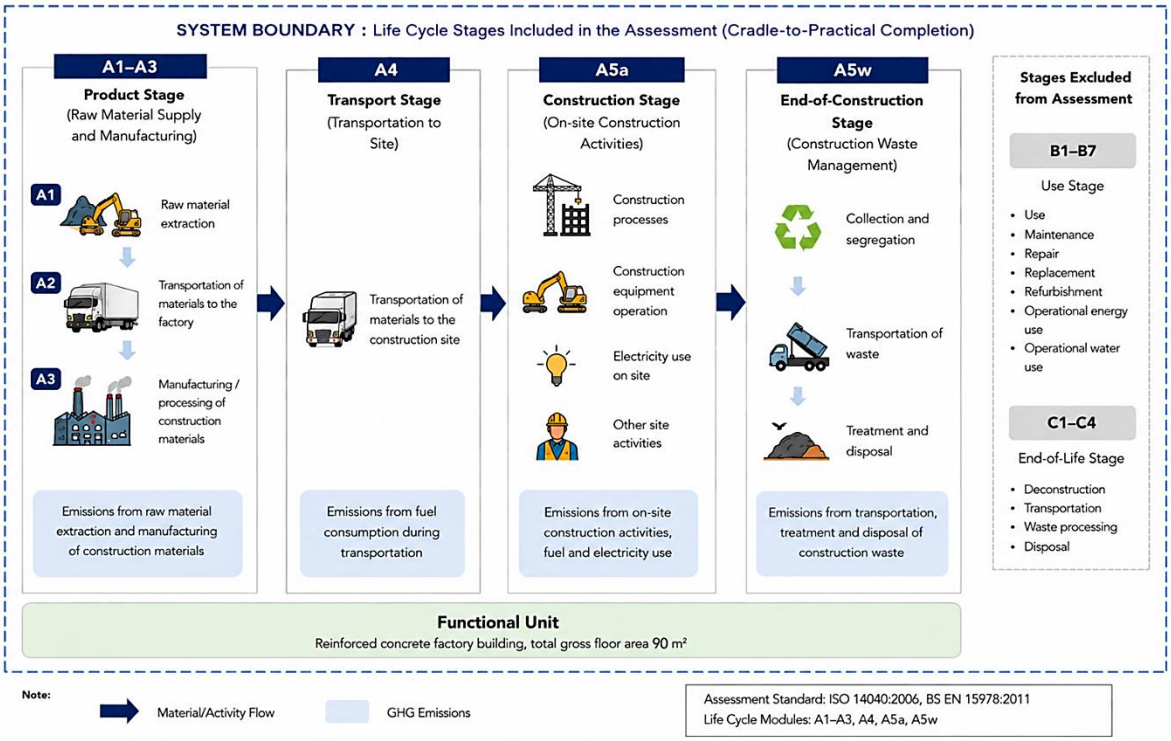


Fig. 2: System boundary of the embodied carbon assessment based on the cradle-to-practical completion approach

with the WBS and established system boundary, ensuring that no intentional cut-off criteria were applied to major activities within the assessment scope. Data quality was considered in terms of geographical, temporal, and technological representativeness and completeness. Secondary data and necessary assumptions were recognized as sources of uncertainty and considered in the sensitivity and uncertainty analysis. Emissions associated with air-conditioning refrigerant and on-site wastewater treatment were estimated from available project activity data combined with the corresponding secondary EFs. Where complete project-specific information was unavailable, necessary assumptions were applied; consequently, these figures should be interpreted as approximate contributions to construction-support emissions. A one-at-a-time sensitivity analysis was performed for the principal hotspot resources by varying the emission factors for concrete, structural steel, corrugated steel, diesel, and electricity by ±20% from the baseline values. Sensitivity analyses of relative contributions and hotspot classifications were conducted to verify outcome stability. Contributors were subsequently ordered by their proportional embodied carbon output to isolate critical hotspots. Principal carbon hotspots were defined as the highest-ranked contributors that collectively accounted for more than 50% of the total pre-use embodied carbon.

Embodied carbon calculation

The embodied carbon of the case-study building was quantified by multiplying the activity data associated with each process by the corresponding greenhouse gas emission factor (EF). This methodology facilitated the quantification of greenhouse gas emissions associated with individual activities across the

established system boundary. The embodied carbon calculation was performed using Eq. 1 (Gibbons *et al*., 2025):

$$EC_{Total} = \Sigma(Q_i \times EF_i) \quad (1)$$

Where: EC_{Total} is the total embodied carbon emissions in $kgCO_2e$, Q_i is the activity data for activity i (e.g., material quantity, transportation distance, fuel consumption, or electricity consumption), and EF_i is the greenhouse gas emission factor corresponding to activity i ($kgCO_2e$ per unit of activity). Upon disaggregating the assessment across the life-cycle modules encompassed by the system boundary, embodied carbon emissions were quantified independently for each individual stage.

1) Construction material production (A1–A3)

Embodied carbon emissions associated with the production of construction materials in modules A1–A3 were calculated by multiplying the quantity of each construction material by its corresponding greenhouse gas emission factor, using Eq. 2 (Gibbons *et al*., 2025):

$$ECA_{1-3} = \Sigma(M_i \times EF_{material,i}) \quad (2)$$

Where: ECA_{1-3} is the embodied carbon emissions from construction material production ($kgCO_2e$), M_i is the quantity of construction material item i (unit), and $EF_{material,i}$ is the greenhouse gas emission factor for construction material item i in kilogram carbon dioxide equivalent per unit ($kgCO_2e$/unit).

2) Transportation of construction materials (A4)

Embodied carbon emissions associated with the transportation of construction materials in module A4 were calculated from the material quantity, transportation distance, and corresponding transportation emission factor, using Eq. 3 (Gibbons *et al*., 2025):

$$ECA_4 = \Sigma(M_i \times D_i \times EF_{transport,i}) \quad (3)$$

Where: ECA_4 is the embodied carbon emissions from the transportation of construction materials ($kgCO_2e$), M_i is the quantity of construction material item i (unit), D_i is the transportation distance for construction material item i in kilometer (km), and $EF_{transport,i}$ is the greenhouse gas emission factor for the transportation of construction material item *i* ($kgCO_2e$/unit-km). Transportation emissions were quantified by multiplying material-specific transportation distances by their corresponding emission factors. Vehicle types and transport modes were assigned based on available project logistics records, whereas transport activity levels were quantified using the transported mass and delivery distance.

3) Fuel and energy use during construction (A5a)

Embodied carbon emissions associated with fuel and energy consumption during construction in module A5a were calculated by multiplying the quantity of each fuel or energy source consumed by its corresponding greenhouse gas emission factor, as expressed in Eq. 4 (Gibbonsn *et al*., 2025):

$$ECA_{5a} = \Sigma(F_i \times EF_{fuel,i}) \quad (4)$$

Where: ECA_{5a} is the embodied carbon emissions from fuel and energy consumption during construction ($kgCO_2e$), F_i is the quantity of fuel or energy source i consumed during construction (unit), and $EF_{fuel,i}$ is the greenhouse gas emission factor for fuel or energy source i ($kgCO_2e$/unit).

4) Construction waste management (A5w)

Embodied carbon emissions associated with construction waste management in module A5w were calculated by multiplying the quantity of each construction waste stream by its corresponding waste-management emission factor, using Eq. 5 (Gibbons *et al*., 2025):

$$ECA_{5w} = \Sigma(W_i \times EF_{waste,i}) \quad (5)$$

Where: ECA_{5w} is the embodied carbon emissions from construction waste management ($kgCO_2e$), W_i is the quantity of construction waste stream *i* (unit), and $EF_{waste,i}$ is the greenhouse gas emission factor for the management of construction waste stream i ($kgCO_2e$/unit). Emissions associated with construction waste were quantified based on the generated waste volume and its corresponding waste-management emission factors. Waste-treatment pathways were determined in accordance with available project documentation, supplemented by reasoned assumptions where granular records were absent. The total embodied carbon of the building was calculated as the sum of greenhouse gas emissions from all life-cycle modules included within the system boundary, namely construction material production (A1–A3), transportation of construction materials (A4), fuel and energy use during construction (A5a), and construction waste management (A5w), using Eq. 6 (Gibbons *et al*., 2025):

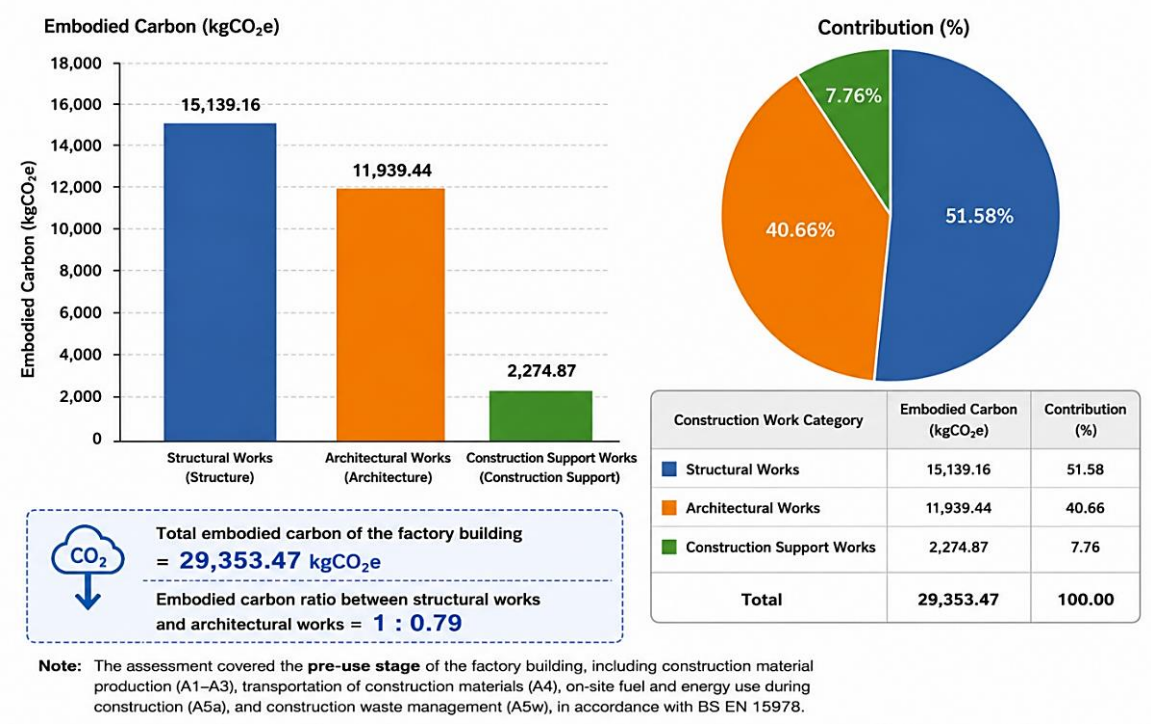
$$EC_{Total} = ECA_{1\text{-}3} + ECA_4 + ECA_{5a} + ECA_{5w} \quad (6)$$

Where: EC_{Total} is the total embodied carbon emissions of the building ($kgCO_2e$), $ECA_{1\text{-}3}$ is the embodied carbon emissions from construction material production ($kgCO_2e$), ECA_4 is the embodied carbon emissions from the transportation of construction materials ($kgCO_2e$), ECA_{5a} is the embodied carbon emissions from fuel and energy consumption during construction ($kgCO_2e$), and ECA_{5w} is the embodied carbon emissions from construction waste management ($kgCO_2e$). Eqs. 1 through 6 were utilized to quantify embodied carbon across the project, building-component, and life-cycle-module levels. Subsequently, the computed outcomes were utilized to evaluate the distribution of embodied carbon emissions, isolate primary carbon hotspots, and inform the formulation of targeted greenhouse gas mitigation strategies for reinforced-concrete factory industrial facilities. The resource-level, building-component, and life-cycle-module results were cross-checked to ensure consistency, and all classification totals reconciled with the overall pre-use embodied carbon of 29,353.47 $kgCO_2e$. The refrigerant-related emission reported under module A5a originated from temporary construction-site office air conditioning and were consequently classified as construction-site office and was therefore treated as a construction-support activity rather than components of the permanent building MEP systems.

RESULTS AND DISCUSSION

Embodied carbon by building component

The embodied carbon assessment of the reinforced concrete manufacturing facility was conducted for the pre-use stage, encompassing material production, transport logistics, on-site energy consumption, and waste management. The results indicated that the building generated a total embodied carbon of 29,353.47 $kgCO_2e$ (Fig. 3), corresponding to an embodied carbon intensity of 326.15 kilogram carbon dioxide equivalent per square meter ($kgCO_2e/m^2$) based on the total gross floor area. As shown in Fig. 3, structural works contributed the largest share of embodied carbon, accounting for 15,139.16 $kgCO_2e$, followed by architectural works with 11,939.44 $kgCO_2e$, and construction support works with 2,274.87 $kgCO_2e$. The corresponding embodied carbon ratio for structural works: architectural works: construction support works was 1 : 0.79 : 0.15. The findings reveal that the embodied carbon of the analyzed building was largely driven by structural and architectural categories, whereas construction-support operations accounted for only a minor fraction of overall emissions. This distribution suggests that overall embodied carbon reduction strategies should primarily target structural and architectural components, where the greatest mitigation potential can be achieved, before extending improvement measures to construction support activities. To isolate the primary drivers of embodied carbon, a granular evaluation was conducted at the building-component level. These findings are detailed in Table 1 and Fig. 4.



Construction Work Category	Embodied Carbon ($kgCO_2e$)	Contribution (%)
Structural Works	15,139.16	51.58
Architectural Works	11,939.44	40.66
Construction Support Works	2,274.87	7.76
Total	29,353.47	100.00

Fig. 3: Total embodied carbon emissions of the case-study factory building classified by construction work category

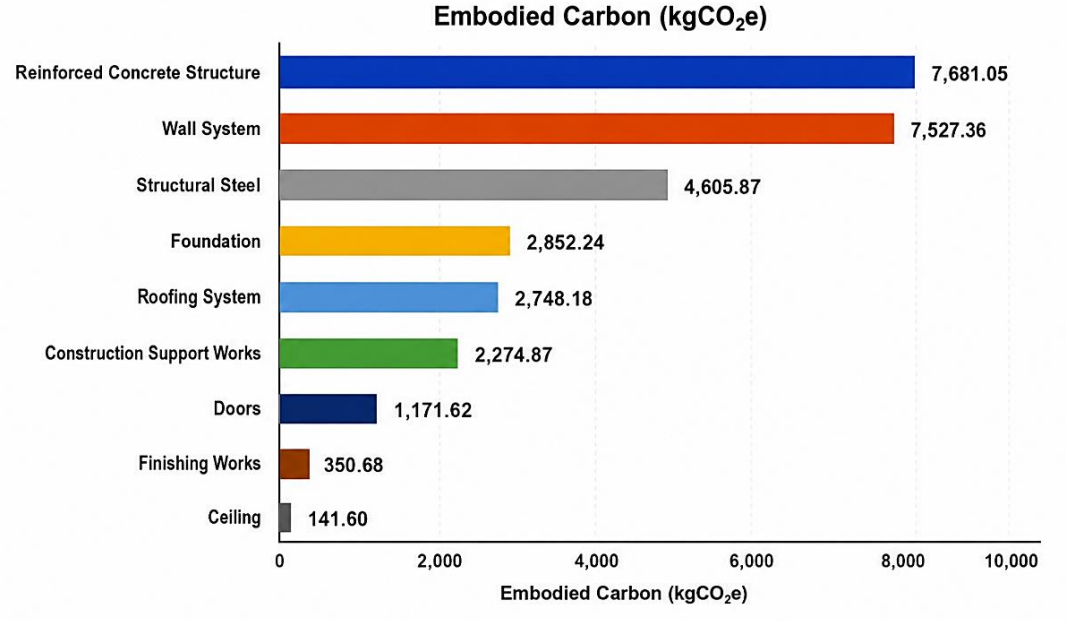


Fig. 4: Embodied carbon emissions and their distribution by building component

Table 1. Embodied carbon emissions and contribution classified by building component

Building component	Embodied carbon ($kgCO_2e$)	Contribution in percent (%)
Structural works		
– Reinforced Concrete Foundation	2,852.24	9.72
– Reinforced Concrete Superstructure	7,681.05	26.17
– Structural Steel	4,605.87	15.69
Architectural works		
– Roofing System	2,748.18	9.36
– Wall System	7,527.36	25.64
– Doors	1,171.62	3.99
– Finishing Works	350.68	1.19
– Ceiling	141.60	0.48
Construction support works		
– Construction Support Works	2,274.87	7.75
Total	29,353.47	100.00

As presented in Table 1 and Fig. 4, within the structural works category, the reinforced concrete structural system (including both the foundation and superstructure) generated a total embodied carbon of 10,533.29 $kgCO_2e$, which was substantially higher than that of the structural steel system, accounting for 4,605.87 $kgCO_2e$. The embodied carbon ratio between the reinforced concrete structural system and the structural steel system stood at 1 : 0.44, demonstrating that reinforced concrete served as the primary contributor to embodied carbon within the structural works category. Within the architectural works category, the wall system generated 7,527.36 $kgCO_2e$, whereas the remaining architectural components, including the roof, doors, finishes, and ceiling system, contributed a combined embodied carbon of 4,412.08 $kgCO_2e$. The corresponding embodied carbon ratio between the wall system and the remaining architectural components stood at 1 : 0.59, indicating that embodied carbon within the architectural works category was heavily concentrated in the wall assembly. When these results were considered collectively, the reinforced concrete structural system (foundation and superstructure) together with the wall system accounted for a combined embodied carbon of 18,060.65 $kgCO_2e$, representing 61.53% of the total embodied carbon of the building. This finding demonstrates that these two building elements served as the primary sources of embodied carbon throughout the pre-use phase. Consequently, prioritizing carbon reduction measures for the reinforced concrete structural system and the wall assembly is expected to yield the highest mitigation potential for reducing the overall embodied carbon of reinforced concrete industrial facilities before addressing secondary building components.

Embodied carbon by resource type

In addition to the analysis at the building-component level, embodied carbon emissions were further classified according to resource type to provide an alternative perspective on the sources of greenhouse gas emissions within the project. This analysis was designed to isolate the specific materials and resources driving overall embodied carbon, accounting for the fact that individual building components generally incorporate diverse materials with varying greenhouse gas emission intensities. Classifying embodied carbon at the resource level provides a more detailed basis for identifying material-specific carbon hotspots and supports the development of targeted carbon reduction strategies through improved material selection

and construction management practices. Furthermore, these insights offer valuable guidance for decision-making during the building design and procurement phases, enabling embodied carbon reduction opportunities to be integrated early in the project lifecycle. The classification results are presented in Table 2. As presented in Table 2, concrete was the largest contributor to embodied carbon, accounting for 6,790.47 $kgCO_2e$ (23.13%), followed by structural steel with 5,374.10 $kgCO_2e$ (18.31%), and corrugated steel sheets and associated materials with 4,911.09 $kgCO_2e$ (16.73%). Cumulatively, these three material classifications accounted for 58.17% of the project's aggregate embodied carbon. This disproportionate contribution—whereby a mere triad of resource categories generated over half of the cumulative emissions—demonstrates that greenhouse gas outputs were heavily skewed toward a select subset of inputs rather than uniformly distributed across the construction material resources. Accordingly, these three resource categories can be clearly identified as resource-level carbon hotspots, representing the highest-priority targets for further analysis and the development of embodied carbon reduction strategies. The concentration of embodied carbon in these materials can be attributed to the combined effects of their relatively large quantities and emission-intensive production processes. While concrete was predominantly utilized across the foundation and superstructure, structural and corrugated steel were extensively integrated within the primary framing, roofing assemblies, and wall enclosures. Consequently, both material quantity and emission intensity contributed to their dominant shares of pre-use embodied carbon. When considered together with the results of the building-component analysis (Table 1), a consistent pattern emerged. Concrete (6,790.47 $kgCO_2e$; 23.13%) together with reinforcing steel (1,529.78 $kgCO_2e$; 5.21%) constituted the principal materials used in the reinforced concrete structural system, which generated a combined embodied carbon of 10,533.29 $kgCO_2e$. constituted the primary resource linked to high-emission elements, predominantly driving the structural steel framework (4,605.87 $kgCO_2e$) while making substantial contributions to the wall assembly, which recorded a cumulative embodied carbon of 7,527.36 $kgCO_2e$. Correspondingly, corrugated steel sheeting and ancillary materials (4,911.09 $kgCO_2e$; 16.73%) served as the principal inputs for the roofing subsystem (2,748.18 $kgCO_2e$; 9.36%), alongside maintaining a notable material presence within the wall system. In addition, EPS panels (1,652.76 $kgCO_2e$; 5.63%) were identified as another major resource directly associated with the wall system. These findings are consistent with the observation that the wall system was the largest contributor to embodied carbon within the architectural works category. Among the energy-related resources, diesel fuel generated 1,645.06 $kgCO_2e$ (5.60%), while electricity consumption contributed 1,625.74 $kgCO_2e$ (5.54%). Both resources individually accounted for more than 5% of the total embodied carbon, indicating that energy use during the pre-use stage represented another significant source of greenhouse gas emissions. Combined, diesel fuel and electricity accounted for 3,270.80 $kgCO_2e$, representing to 11.14% of the total embodied carbon, thereby identifying these inputs as significant energy-related carbon hotspots within the project lifecycle. In contrast, gasoline contributed only 10.78 $kgCO_2e$ (0.04%), representing a negligible contribution compared with diesel fuel and electricity. Conversely, several resources, including crushed stone, sand, office paper, gasoline, partition wall accessories, steel formwork, and office containers, each contributed less than 1% of the total embodied carbon. Although these resources inputs were operationally essential for project execution, their cumulative contribution to overall embodied carbon remained comparatively negligible relative to the primary resource categories. Consequently, carbon reduction measures focusing exclusively

Table 2: Embodied carbon emissions and contribution classified by resource type

Resource	Embodied Carbon ($kgCO_2e$)	Contribution (%)
Construction materials		
Crushed stone	39.28	0.13
Sand	145.15	0.49
Eucalyptus Timber	871.63	2.97
Reinforcing Steel	1,529.78	5.21
Concrete	6,790.47	23.13
Cement	817.25	2.78
Structural Steel	5,374.10	18.31
Welding Electrode	217.05	0.74
Tap Water	378.87	1.29
Concrete Blocks	444.43	1.51
Corrugated steel sheets and associated materials	4,911.09	16.73
EPS Panels	1,652.76	5.63
Partition Wall Accessories	49.27	0.17
Clear Glass	183.39	0.62
Extruded Aluminum	339.40	1.16
Rolling Steel Door	648.10	2.21
Ceiling panels and associated materials	141.53	0.48
Paint	330.36	1.13
Office supplies		
A4 Paper	10.83	0.04
Refrigerants and Waste Management		
Refrigerant (R-143a)	238.26	0.81
Methane from the On-site Septic Tank	211.68	0.72
Solid waste disposal	172.99	0.59
Transportation of equipment, machinery, and site facilities		
Steel Formwork	39.52	0.13
Construction Machinery	411.22	1.40
Construction Tools	64.40	0.22
Office Container	59.08	0.20
Fuel and electricity		
Diesel Fuel	1,645.06	5.60
Gasoline	10.78	0.04
Electricity	1,625.74	5.54
Total	29,353.47	100.00

on these low-contributing resources are unlikely to achieve substantial reductions in the overall embodied carbon of the project when compared with strategies targeting the identified carbon hotspots. Overall, categorized by both resource type and building component exhibited a consistent pattern, demonstrating that the embodied carbon footprint of the case-study building was predominantly governed by a select subset of key material inputs concentrated within the highest-emission building components. These resources included the principal materials used in the reinforced concrete structural system, the structural steel system, and the roofing and wall systems within the architectural works category. In addition, diesel fuel and electricity emerged as prominent energy-related emission sources warranting explicit integration into life-cycle carbon reduction frameworks. These findings collectively indicate that mitigation strategies should prioritize high-emission inputs—specifically concrete, structural steel, corrugated steel assemblies, alongside operational diesel and electricity consumption. Improving material selection while enhancing fuel and energy efficiency during construction is expected to achieve the greatest reduction in the overall embodied carbon of reinforced concrete factory building projects. Sensitivity analysis showed that varying the emission factors of the five principal hotspot resources by ±20% affected the total embodied carbon but did not substantially change

the overall hotspot pattern. Concrete remained the dominant contributor, while structural steel and corrugated steel remained among the three major material hotspots. Similarly, diesel fuel and electricity continued to function as notable energy-related contributors. These findings demonstrate that the primary carbon hotspots identified in this investigation exhibited overall robustness against plausible fluctuations in associated emission factors.

Embodied carbon by life-cycle module

Following the building-component and resource-type evaluations, which isolated the primary embodied carbon contributors at both the assembly and material building-component and resource levels, this section examines embodied carbon through a complementary lens by categorizing greenhouse gas emissions according to life-cycle modules. The analysis considers the four modules included within the assessment boundary, namely construction material production (A1–A3), transportation of construction materials (A4), fuel and energy use during construction (A5a), and construction waste management (A5w). Classification by life-cycle module provides additional insight into the distribution of embodied carbon by identifying system-level carbon hotspots, thereby indicating where greenhouse gas emissions predominantly occur rather than which materials are responsible for the emissions. This perspective facilitates the development of mitigation strategies better synchronized with the operational dynamics of distinct life-cycle stages. For instance, when the preponderance of embodied carbon stems from the material production stage, primary emphasis must be directed toward low-carbon material substitution, environmentally preferable suppliers selection, and material specification optimization. Conversely, where emissions are primarily associated with transportation, construction energy use, or construction waste management, greater attention should be directed toward logistics optimization, improved energy efficiency, and waste minimization during construction. Consequently, the life-cycle module analysis corroborates the insights established in preceding sections, thereby furnishing a more robust foundation for prioritizing embodied carbon abatement strategies. The life-cycle module breakdown of the embodied carbon assessment (Fig. 5) showed that construction material production (A1–A3) contributed 22,926.93 $kgCO_2e$, accounting for 78.10% of the total embodied carbon. This was followed by fuel and energy use during construction (A5a) with 3,547.33 $kgCO_2e$ (12.09%), construction waste management (A5w) with 1,540.83 $kgCO_2e$ (5.25%), and transportation of construction materials (A4) with 1,338.38 $kgCO_2e$ (4.56%). These results indicate that the embodied carbon of the case-study factory building was predominantly concentrated in the construction material production stage (A1–A3). In comparison, fuel and energy use during construction (A5a) and construction waste management (A5w) played secondary roles, together accounting for 17.34% of the total embodied carbon. Among all evaluated life-cycle modules, material transportation (Module A4) accounted for the lowest share of cumulative embodied carbon within the scope of this study. Overall, the life-cycle module analysis demonstrates that the majority of embodied carbon originated from the construction material production stage (A1–A3), with additional contributions from fuel and energy use during construction, construction waste management, and transportation of construction materials. These findings furnish a critical empirical baseline for the holistic interpretation of outcomes, bridging them with the component-level and material-specific evaluations detailed in the subsequent section.

Integrated analysis of embodied carbon by building component, resource/activity type, and life-cycle module

Although the analyses of building components, resource/activity types, and life-cycle modules

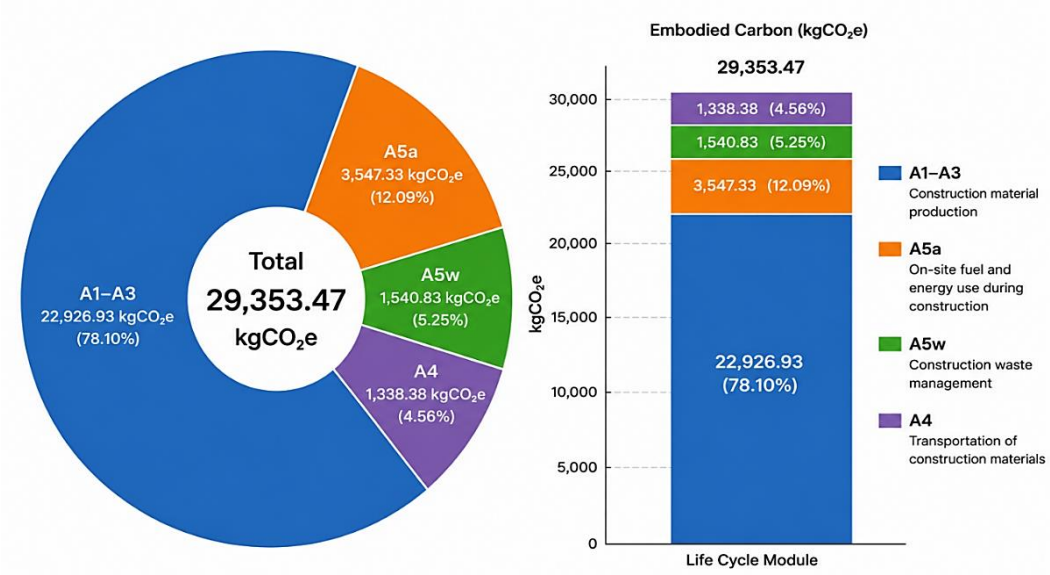


Fig. 5: Embodied carbon emissions and percentage contribution classified by the life-cycle module of the factory building

successfully identified the major sources of embodied carbon from different perspectives, consideration of each dimension independently does not fully reveal the practical relationships among them. Specifically, it fails to identify which resources or construction activities drive the embodied carbon of individual building components, nor does it specify the life-cycle modules where these emissions predominantly occur. To address this limitation, this section presents an integrated analysis of embodied carbon based on the combined framework of building component–resource/activity–life-cycle module (A1–A3, A4, A5a, and A5w). This integrated classification identifies the primary emission-contributing resources and activities associated with individual building components, alongside the specific life-cycle modules where greenhouse gas emissions are concentrated. These results are presented in Tables 3 to 5. The integrated analysis presented in Table 3 shows that the structural works generated a total embodied carbon of 15,139.16 $kgCO_2e$. The majority of emissions originated from the construction material production stage (A1–A3), which accounted for 11,842.17 $kgCO_2e$ (78.22%). The principal material contributors were concrete, with a total embodied carbon of 6,790.47 $kgCO_2e$ (44.85%), including 6,457.69 $kgCO_2e$ from A1–A3; structural steel, contributing 3,868.70 $kgCO_2e$ (25.55%), of which 3,657.82 $kgCO_2e$ originated from A1–A3; and reinforcing steel, contributing 1,514.38 $kgCO_2e$ (10.00%), including 1,348.75 $kgCO_2e$ from A1–A3. For the transportation stage (A4), total emissions amounted to 894.37 $kgCO_2e$ (5.91%), with transportation of construction machinery representing the largest individual contributor (346.36 $kgCO_2e$). During the construction stage (A5a), total embodied carbon was 1,230.69 $kgCO_2e$ (8.13%), with diesel fuel consumption accounting for the majority of emissions (1,208.34 $kgCO_2e$). In the construction waste management stage (A5w), total emissions reached 1,171.93 $kgCO_2e$ (7.74%), of which eucalyptus timber contributed the largest share (788.83 $kgCO_2e$). The integrated analysis presented in Table 4 indicates that the architectural works generated a total embodied carbon of 11,939.44 $kgCO_2e$, with emissions overwhelmingly concentrated in the construction material production stage (A1–A3), which accounted for 11,079.01 $kgCO_2e$ (92.79%).

Table 3: Embodied carbon emissions and contribution of structural works classified by resource/activity type and life-cycle module

Resource/activity	A1–A3	A4	A5a	A5w	Total	Contribution (%)
Construction materials						
– Sand	54.08	51.15	–	–	105.23	0.70
– Steel Formwork	–	39.52	–	–	39.52	0.26
– Eucalyptus Timber	67.98	14.82	–	788.83	871.63	5.76
– Reinforcing Steel	1,348.75	110.81	–	54.82	1,514.38	10.00
– Concrete	6,457.69	112.02	–	220.76	6,790.47	44.85
– Cement	3.97	1.37	–	11.31	16.65	0.11
– Structural Steel	3,657.82	114.67	–	96.21	3,868.70	25.55
– Welding Electrode	133.53	4.89	–	–	138.42	0.91
Transportation of machinery, tools and temporary site facilities						
– Construction Machinery	–	346.36	–	–	346.36	2.29
– Construction Tools	–	64.40	–	–	64.40	0.43
Fuel and electricity						
– Diesel Fuel	117.57	30.17	1,208.34	–	1,356.08	8.96
– Gasoline	0.78	4.19	5.81	–	10.78	0.07
– Electricity	–	–	16.54	–	16.54	0.11
Total	11,842.17	894.37	1,230.69	1,171.93	15,139.16	100.00

Table 4: Embodied carbon emissions and contribution of architectural works classified by resource/activity type and life-cycle module

Resource/activity	A1–A3	A4	A5a	A5w	Total	Contribution (%)
Construction materials						
– Concrete Blocks	386.34	56.36	–	1.73	444.43	3.72
– Reinforcing Steel	13.51	1.05	–	0.84	15.40	0.13
– Crushed Stone	7.30	30.64	–	1.34	39.28	0.33
– Sand	17.96	16.99	–	4.97	39.92	0.33
Tap Water	378.87	–	–	–	378.87	3.17
Cement	770.67	29.89	–	0.04	800.60	6.71
Corrugated steel sheets and associated materials	4,768.48	15.35	–	127.26	4,911.09	41.13
Structural Steel	1,404.98	48.10	–	52.32	1,505.40	12.61
Welding Electrode	76.50	2.13	–	–	78.63	0.66
EPS Panels	1,604.50	46.83	–	1.43	1,652.76	13.84
Partition Wall Accessories	49.21	0.00	–	0.06	49.27	0.41
Clear Glass	174.75	8.64	–	–	183.39	1.54
Extruded Aluminum	333.85	5.55	–	–	339.40	2.84
Rolling Steel Door	630.18	17.92	–	–	648.10	5.43
Ceiling panels and associated materials	120.92	16.71	–	3.90	141.53	1.19
Paint	315.94	14.42	–	–	330.36	2.77
Transportation of machinery, tools and temporary site facilities						
Construction machinery	–	64.86	–	–	64.86	0.54
Fuel and electricity						
Diesel Fuel	25.05	6.43	257.50	–	288.98	2.42
Electricity	–	–	27.17	–	27.17	0.23
Total	11,079.01	381.87	284.67	193.89	11,939.44	100.00

The largest material contributor was corrugated steel sheets and associated materials, with a total embodied carbon of 4,911.09 $kgCO_2e$ (41.13%), comprising 4,768.48 $kgCO_2e$ from A1–A3 and 127.26 $kgCO_2e$ from A5w. This was followed by EPS panels, contributing 1,652.76 $kgCO_2e$ (13.84%), including 1,604.50 $kgCO_2e$ from A1–A3 and 46.83 $kgCO_2e$ from A4, and structural steel, contributing 1,505.40 $kgCO_2e$ (12.61%), of which 1,404.98 $kgCO_2e$ originated from A1–A3 and 48.10 $kgCO_2e$ from A4. During the construction stage (A5a), total embodied carbon amounted to 284.67 $kgCO_2e$, with diesel fuel consumption representing the largest individual contributor (257.50 $kgCO_2e$). Within the transportation stage (A4), transportation of construction machinery was identified as another notable emission source, contributing 64.86 $kgCO_2e$. The integrated analysis

Table 5. Embodied carbon emissions and contribution of construction support works classified by resource/activity type and life-cycle module

Resource/activity	A1–A3	A4	A5a	A5w	Total	Contribution (%)
Office supplies						
A4 Paper	5.75	3.06	–	2.02	10.83	0.48
Refrigerants and waste management						
Air-Conditioning Refrigerant (R-143a)	–	–	238.26	–	238.26	10.47
Methane from the On-site Septic Tank	–	–	211.68	–	211.68	9.31
Transportation of machinery, tools and temporary site facilities						
Office Container	–	59.08	–	–	59.08	2.60
Construction waste management						
Construction Waste	–	–	–	172.99	172.99	7.60
Fuel and electricity						
Electricity	–	–	1,582.03	–	1,582.03	69.54
Total	5.75	62.14	2,031.97	175.01	2,274.87	100.00

presented in Table 5 shows that the construction support works generated a total embodied carbon of 2,274.87 $kgCO_2e$, exhibiting a markedly different emission pattern from the other two work categories. Emissions were overwhelmingly concentrated in the construction stage (A5a), contributing 2,031.97 $kgCO_2e$ (89.32%) of the total embodied carbon. Electricity consumption emerged as the dominant emission hotspot, occurring entirely within module A5a and accounting for 1,582.03 $kgCO_2e$ (69.54%). Additional major contributors included air-conditioning refrigerant (238.26 $kgCO_2e$) and methane emissions from the onsite septic tank (211.68 $kgCO_2e$). Within the construction waste management stage (A5w), the principal hotspot was construction waste, contributing 172.99 $kgCO_2e$, whereas in the transportation stage (A4), the largest contributor was the transportation of office containers, accounting for 59.08 $kgCO_2e$. These results indicate that the embodied carbon associated with construction support works stems primarily from energy consumption and temporary site utility systems. Overall, the integrated building component–resource/activity–life-cycle module classification demonstrates that embodied carbon hotspots are highly specific to individual work categories and their respective emission mechanisms. For the structural works, embodied carbon was predominantly driven by structural materials during the production stage (A1–A3), alongside stage-specific hotspots linked to diesel fuel consumption in stage A5a and eucalyptus timber in stage A5w. The architectural works were dominated by materials used in the building envelope and roofing systems, with emissions concentrated almost entirely in A1–A3. In contrast, the construction support works were principally driven by energy consumption and temporary site utility systems during A5a. These findings provide a comprehensive foundation for interpreting embodied carbon emissions from an engineering perspective and establish a robust basis for comparison with previous studies in the subsequent Discussion section.

Engineering implications and practical applications

The findings of this study demonstrate that the embodied carbon of the reinforced concrete factory building was predominantly associated with the construction material production stage (A1–A3) and was concentrated in a limited number of high-emission building components. Notably, the reinforced concrete structural system, wall system, and structural steel system collectively accounted for 67.50% of the building's total embodied carbon. From an engineering perspective, these findings advocate for a hotspot-based approach to embodied carbon mitigation, prioritizing reduction efforts on highy-emission

building components before addressing elements with lower relative contributions. Such an approach is expected to achieve greater reductions in the overall embodied carbon of the project than strategies that distribute mitigation efforts uniformly across all building components. This finding aligns with the broader application of LCA in environmental management, where identifying key environmental hotspots serves as an established foundation for prioritizing mitigation strategies and supporting evidence-based decision-making across diverse infrastructure and facility systems (Buadit *et al.,* 2026). The results further indicate that the design stage represents the most influential decision point for reducing embodied carbon because it determines the selection of construction materials, material quantities, and structural systems, all of which directly influence greenhouse gas emissions during the construction material production stage (A1–A3). Consequently, decisions made during the early design phase have a substantial influence on the embodied carbon performance of the building throughout the pre-use stage and provide the greatest opportunity for implementing effective carbon reduction measures. Consequently, design-phase mitigation strategies should be tailored to address the specific emission mechanisms driving the highest-emitting building components. For the reinforced concrete structural system, highly effective mitigation measures include adopting low-carbon concrete, the incorporating supplementary cementitious materials (SCMs), utilizing reinforcing steel with high recycled content, and implementing material-efficient structural designs (Cabeza *et al.,* 2014). For the structural steel system, priority should be given to selecting steel products with higher recycled content and optimizing structural detailing and member configurations to minimize material consumption (Akbarnezhad and Xiao, 2017). For wall system, mitigation efforts should prioritize selecting low-carbon construction materials while simultaneously minimizing material losses and enhancing installation efficiency (Pomponi and Moncaster, 2016). These mitigation measures are presented as potential strategies based on the identified hotspots rather than as quantitatively evaluated alternatives. Their actual carbon-reduction potential depends on project-specific material availability, emission factors, structural requirements, and design constraints; therefore, quantitative scenario assessment is recommended for future research. These strategies are particularly relevant because wall systems typically encompass extensive surface areas, rendering them more vulnerable to material waste generated during cutting, fitting, and installation processes. Although the construction material production stage (A1–A3) represented the dominant source of embodied carbon in the present study, the results also highlight the management significance of the remaining life-cycle modules, particularly A4 (transportation of construction materials) and A5 (construction activities). Emissions associated with stage A4 are highly dependent on transportation distances and project-specific logistics, increasing substantially when construction materials are procured from geographically distant suppliers (Zuluaga and Saxe, 2025). Likewise, emissions generated during stage A5a (fuel and energy consumption during construction) and stage A5w (construction waste management) reflect the efficacy of onsite management practices, indicating that reductions can be achieved through improved energy conservation, optimized equipment utilization, and enhanced waste diversion strategies (Myint and Shafique, 2024). Accordingly, mitigation measures targeting the A4–A5 modules should be regarded as complementary strategies that enhance overall carbon reduction performance, even though their contributions remain lower than those of A1–A3. From an engineering perspective, embodied carbon assessment should be embedded into the building design process as a core decision-making criterion to optimize both material carbon intensity and required material

quantities. This objective can be achieved by incorporating the principles of material efficiency (Drewniok *et al.,* 2023) and structural optimization (Abushama *et al.,* 2025), together with the systematic use of Environmental Product Declarations (EPDs) to support transparent and evidence-based comparisons of alternative construction materials (Santos *et al.,* 2025). Ultimately, low-carbon factory building design must be anchored in the localization of primary embodied carbon hotspots, guiding the deployment of targeted mitigation measures aligned with their respective emission drivers. These measures should be complemented by improvements in logistics planning and onsite construction management during the A4–A5 life-cycle modules to maximize embodied carbon reduction at the project level.

Comparison with previous studies

Comparisons with previous studies should be interpreted cautiously because of differences in system boundaries, building size, reference units, and included materials. Compared to the industrial factory building evaluated by Rodrigues *et al.* (2018), the case-study building in this research exhibited lower embodied carbon values across both total emissions and emissions per unit floor area. This difference is likely attributable to variations in building characteristics and functional requirements. The factory building evaluated by Rodrigues *et al.* (2018) was larger and structurally more complex, featuring greater building height, multiple stories, and basement levels. Furthermore, as a heavy industrial facility, it required substantially thicker reinforced concrete floor slabs to support heavy machinery and large inventory loads. Climatic variations may also have influenced the performance requirements of the building envelope, thereby elevating the embodied carbon associated with specific architectural components relative to the present case study. Overall, the findings of the present study reinforce a consistent trend reported in the embodied carbon literature, namely that the construction material production stage (A1–A3) constitutes the dominant source of embodied carbon in buildings. This observation aligns with the findings of Cabeza *et al*. (2014), Röck *et al*. (2020), and Myint and Shafique (2024), who demonstrated that the production of primary construction materials, notably cement and steel, is highly energy-intensive, serving as the primary driver of greenhouse gas emissions during the pre-use stage of buildings. These findings also corroborate the recommendations of Santos *et al*. (2025), who underscored that embodied carbon reduction must commence during the design phase, as material selection and specification decisions critically dictate emissions associated with stages A1–A3. Overall, the findings of this study support the growing body of evidence demonstrating that A1–A3 is the primary contributor to embodied carbon in buildings. Concurrently, these findings underscore that the relative importance of other life-cycle stages, specifically modules A5a and A5w, depends heavily on project-specific variables, including building type, functional requirements, and construction practices. These findings further reinforce the importance of adopting a LCA-based approach to identify project-specific carbon hotspots and prioritize mitigation strategies according to their relative contribution to overall greenhouse gas emissions, as recommended in recent environmental management studies. Consequently, the interpreting embodied carbon results and designing mitigation strategies must account for individual project characteristics alongside prior empirical evidence, ensuring that carbon reduction measures remain both technically sound and practically effective for factory construction within the Thai construction context. Furthermore, transparent quantification of embodied carbon can provide reliable evidence to support sustainability reporting, improve environmental transparency, and facilitate evidence-based decision-making for low-carbon construction practices across diverse project contexts and scales.

Limitations and future research

Although this study provides a systematic assessment of the embodied carbon for a reinforced concrete factory building and identifies primary carbon hotspots across both life-cycle and building-component levels, several limitations should be considered when acknowledged the findings. First, the assessment was limited to the pre-use stage, comprising construction material production (A1–A3), transportation of construction materials (A4), fuel and energy use during construction (A5a), and construction waste management (A5w), in accordance with BS EN 15978. The use stage (B1–B7) and end-of-life stage (C1–C4) were excluded, the findings primarily reflect pre-use embodied carbon and do not capture the full life-cycle environmental impacts of the building. Second, the embodied carbon calculations were based on EFs obtained from published databases and reference sources. These figures may deviate from the specific carbon intensities linked to products provided by individual manufacturers. As a result, the accuracy of the assessment depends on the extent to which the selected EFs represent the materials used in the project. The use of product-specific Environmental Product Declarations (EPDs) would improve both the accuracy and transparency of future embodied carbon assessments. Third, because this study relies on a single factory building case study, caution is warranted when generalizing these findings to alternative building typologies or construction projects characterized by differing architectural configurations, structural configurations, material specifications, and operational conditions. Nevertheless, the assessment framework and analytical approach developed in this study can readily be applied to other projects by adapting the activity data and EFs to reflect project-specific conditions. Future research should address these limitations by extending the assessment to Whole Life Carbon, incorporating both the use stage (B1–B7) and the end-of-life stage (C1–C4) to provide a more comprehensive understanding of the environmental impacts throughout the building life cycle. In addition, future studies should improve data quality by utilizing product-specific EPDs and considering variations in manufacturing processes, material sources, and construction practices under real project conditions. Generalizing these insights would benefit from incorporating broader case studies that capture varying facility typologies, structural frameworks, and material profiles, thereby allowing a more rigorous appraisal of the determinants governing embodied carbon. Furthermore, future research should focus on developing assessment tools and decision-support frameworks that facilitate the integration of embodied carbon assessment into the building design process. This could be achieved through the integration of Building Information Modeling (BIM) with EPD databases, enabling real-time embodied carbon assessment during the design stage. Such advancements would also facilitate structural optimization and the evaluation of low-carbon material alternatives by concurrently balancing embodied carbon, construction cost, and structural performance, thereby delivering practical and evidence-based solutions for project-level mitigation.

CONCLUSION

This study assessed the embodied carbon of a reinforced concrete factory building in Thailand using the LCA methodology. The assessment was limited to the pre-use stage, encompassing construction material production (A1–A3), transportation of construction materials (A4), fuel and energy use during construction (A5a), and construction waste management (A5w). The results showed that the building generated a total embodied carbon of 29,353.47 $kgCO_2e$, equivalent to 326.15 $kgCO_2e/m^2$ based on a gross floor area of 90.00 m^2. Classification by building component revealed that embodied carbon was predominantly concentrated in elements requiring high volumes of construction materials. The reinforced concrete structural system generated the highest embodied carbon

(10,533.29 $kgCO_2e$), followed by the wall system (7,527.36 $kgCO_2e$). Consequently, these two building components emerged as the primary carbon hotspots within the case-study facility. This trend aligns with the resource-based analysis, which demonstrated that embodied carbon is predominantly driven by a select group of major construction materials. Concrete contributed 6,790.47 $kgCO_2e$ (23.13%), followed by structural steel with 5,374.10 $kgCO_2e$ (18.31%), and corrugated steel sheets and associated materials with 4,911.09 $kgCO_2e$ (16.73%). Collectively, these three resource categories accounted for 58.17% of the total embodied carbon. Concrete was primarily associated with the reinforced concrete structural system, whereas structural steel and corrugated steel sheets predominated in the steel framework and the building envelope, particularly within the wall and roofing assemblies. Furthermore, construction-phase energy resources made substantial contributions, with diesel fuel accounting for 1,645.06 $kgCO_2e$ (5.60%) and electricity consumption contributing 1,625.74 $kgCO_2e$ (5.54%), underscoring potential pathways for emission mitigation via enhanced energy governance and optimized onsite practices. Classification by life-cycle module further demonstrated that the dominant source of embodied carbon was construction material production (A1–A3), contributing 22,926.93 $kgCO_2e$ (78.10%), followed by fuel and energy use during construction (A5a) with 3,547.33 $kgCO_2e$ (12.09%), construction waste management (A5w) with 1,540.83 $kgCO_2e$ (5.25%), and transportation of construction materials (A4) with 1,338.38 $kgCO_2e$ (4.56%). These findings suggest that carbon reduction frameworks must prioritize manufacturing-phase emissions from construction materials, alongside optimizing onsite energy performance and curbing construction waste. When the results were examined collectively across the dimensions of building component–resource–life-cycle module, distinct emission mechanisms were identified for each work category. The structural works were primarily driven by structural materials during A1–A3, with additional stage-specific emissions arising from diesel fuel consumption during A5a and eucalyptus timber during A5w. Conversely, the architectural works were governed by materials employed in the building envelope and roofing assemblies, with emissions overwhelmingly concentrated in stages A1–A3. Conversely, the construction support works were characterized by emissions associated predominantly with energy consumption and temporary site utility systems during stage A5a. This integrated analysis enabled the systematic identification of both the critical construction materials and onsite construction activities responsible for embodied carbon emissions within each work category, thereby providing a robust basis for developing mitigation strategies tailored to their respective emission mechanisms. Consequently, these insights hold meaningful implications for both future research directions and professional execution. Designers, structural engineers, and architects can utilize the identified carbon hotspots to optimize design solutions and incorporate low-carbon materials at the early design stage. Project owners and procurement teams can use the hotspot rankings to establish material specifications and prioritize mitigation measures with the greatest carbon reduction potential. Project managers and construction contractors can utilize these outcomes to refine operational energy strategies and minimize waste generation during site implementation. Furthermore, government agencies and professional organizations may use the results as supporting evidence for developing embodied carbon management guidelines and benchmark values for factory buildings within the Thai construction sector, promoting consistent assessment practices and informed decisions.

AUTHOR CONTRIBUTIONS

N. Suriyanon contributed to the overall project conceptualization of the study, research methodology, data collection, interpretation of the results, and review of the manuscript.

W. Suriyanon, the corresponding author, contributed to research supervision, interpretation of the results, and review and revision of the manuscript. Nakorn Suriyanon contributed to the life cycle assessment, embodied carbon and hotspot analyses, interpretation and discussion of the results, preparation of figures and tables, and manuscript preparation. N. Watkate contributed to data collection, verification of construction-related data, interpretation of the results, and review of the manuscript.

ACKNOWLEDGEMENT

The authors gratefully acknowledge the support and cooperation of the project owner and construction personnel involved in the case-study factory building in Chiang Mai Province, Thailand, for providing the construction drawings, technical specifications, Bill of Quantities (BOQ), and other relevant project information used in this study. The authors also acknowledge Chiang Mai University and Rajamangala University of Technology Lanna for their academic support and facilities that contributed to the completion of this study.

CONFLICT OF INTEREST

The authors declare that there is no conflict of interests regarding the publication of this manuscript. In addition, the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, and redundancy have been completely observed by the authors.

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During the preparation of this work, the authors used ChatGPT (OpenAI) to assist with English language editing, grammatical correction, and improving the clarity and readability of the manuscript. After using this tool/service, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

ABBREVIATIONS

%	Percent
A1–A3	Construction material production
A4	Transportation of construction materials
A5a	Fuel and energy use during construction
A5w	Construction waste management
BIM	Building Information Modeling
BOQ	Bill of Quantities
BS EN	British Standard European Norm
CO_2	Carbon dioxide
CO_2e	Carbon dioxide equivalent

EF	Emission factor
EPD	Environmental Product Declaration
EPS	Expanded polystyrene
GHG	Greenhouse gas
ISO	International Organization for Standardization
$kgCO_2e$	Kilogram carbon dioxide equivalent
km	Kilometer
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
MEP	Mechanical, Electrical, and Plumbing
m^2	Square meter
SCMs	Supplementary Cementitious Materials
TGO	Thailand Greenhouse Gas Management Organization (Public Organization)
WBS	Work Breakdown Structure
WLC	Whole Life Carbon

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HOW TO CITE THIS ARTICLE:
Suriyanon, N.; Suriyanon, W.; Suriyanon, N.; Watkate, N., (2027). Life cycle assessment and identification of embodied carbon hotspots in a reinforced concrete factory. Global J. Environ. Sci. Manage., 13(1): 303-326.

DOI: 10.22034.gjesm.2027.01.14
URL: https://www.gjesm.net/article_736221.html