



Carbon footprint accounting of prefabricated buildings: A circular economy perspective

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ABSTRACT

Prefabricated buildings have gained significant attention as a solution for reducing carbon footprint in the construction industry. However, there is a lack of a comprehensive accounting approach tailored to the construction features of prefabricated buildings. To address this issue, this study develops a framework to account the life-cycle carbon footprint of prefabricated buildings within the circular economy principles. The developed framework is applied to a prefabricated building in Chengdu, China, revealing that a significant carbon footprint is attributed to the material production and transportation stages. Moreover, an uncertainty analysis is conducted based on Data Quality Indicator evaluation method and Monte Carlo Simulation to validate the accounting framework, and a minor deviation of 0.085 % between the uncertain and calculated values validates the proposed accounting framework. Furthermore, key processes to mitigate the carbon footprint are identified. The results show that cast-in-place concrete is a key process at the construction materials level. Building upon these findings, this study offers recommendations on accurately and efficiently accounting the carbon footprint of prefabricated buildings. The research findings contribute to fostering the accounting of the life-cycle carbon footprint for prefabricated buildings, establishing a theoretical and empirical basis for circular economy implementation in prefabricated buildings, and offering insights for making informed carbon emission reduction decisions in prefabricated buildings.

1. Introduction

Prefabricated buildings, also known as assembled or modular buildings, are constructed using prefabricated components manufactured off-site and then assembled on-site [1]. This construction method follows a “material-component-module” paradigm, presenting significant environmental benefits including conservation of materials, diminished water and land utilization, decreased energy consumption, and the mitigation of construction waste [2]. Consequently, prefabricated buildings have emerged as a sustainable solution for mitigating the carbon footprint within the building sector. A number of countries have enacted policies aimed at fostering the adoption of prefabricated buildings. For instance, as early as 1966, Japan’s Ministry of Construction introduced the “Basic Conception of the Industrialization of Residential Building Construction”, which advocated for the prefabricated production of construction materials and components, superseding conventional on-site casting practices [3]. In 1974, the United

Nations issued the “Guidelines for the Government’s Policy and Measures for the Progressive Implementation of Building Industrialization”, serving as a programmatic document to facilitate global prefabrication development [4]. Moreover, China has delineated a goal of achieving a 30 % proportion of prefabricated buildings in all new constructions by 2026 [4]. These policy initiatives indicate the widespread implementation of prefabricated construction in certain countries.

Moreover, the circular economy is gaining widespread acceptance and has been included in the legislations of numerous countries. For instance, the Chinese State Council put forth a directive in 2015 to actively promote the development of the circular economy, emphasizing the principles of “reduction, reuse, and recycling” [5]. The concept of the circular economy, initially proposed by D. Pearce and P. K. Turner [6], delineates an economic system characterized by the closed-loop circulation of resources. There are various definitions of the circular economy, and these definitions can be elucidated from three perspectives: technological paradigm, resource utilization and ecological

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environment. In terms of the technological paradigm, the circular economy concept signified a shift away from the linear “resource-product-waste” model towards a closed-loop paradigm incorporating “resource-product-waste-renewable resource” [7]. The resource utilization perspective considers resource conservation and recycling as the characteristics of the circular economy, increasing the value of materials [8]. From an ecological standpoint, the concept seeks to foster economic growth while safeguarding the environment, curbing waste in production processes, and advocating for low-carbon and sustainable concepts through circular economic principles [9]. Based on these three perspectives, this study defines the circular economy as a closed-loop material flow model encompassing “resource-product-waste-recycling”, aiming to extend the lifespan of building materials and components, enhance material utilization through reuse and recycling, and thereby optimize resource efficiency while minimizing waste generation and environmental impact of future buildings.

The concept of circular economy has garnered increasing attention within the construction sector. Embracing the concept of circular economy throughout a building’s life cycle involves designing for deconstruction, optimizing material usage, prolonging material lifespan, incorporating secondary materials, employing off-site construction methods, minimizing waste generation, reducing maintenance needs, implementing selective demolition, and promoting the reuse of products and components, as well as closed-loop or open-loop recycling [10]. The implementation of closed-loop material circulation systems has the potential to reduce the carbon footprint associated with resource consumption, with reduction of 30–50 % [11]. However, despite its contributions to mitigating carbon footprint, the application of circular economy principles in construction encounters several challenges, including the lack of a holistic approach to integrating design, construction, facility management and end-of-life activities. In this regard, prefabricated buildings align well with the principles of the circular economy due to their standardized and modular design, factory production, and the potential for recycling prefabricated components. These buildings offer an opportunity to incorporate a circular economy into the construction industry by promoting standardized building design and enhancing efficiency and effectiveness in construction methods. Therefore, it is crucial to examine the life-cycle carbon footprint of prefabricated buildings from the perspective of the circular economy.

2. Literature review

Previous research on the carbon footprint of prefabricated buildings can be categorized into micro-level and meso-level studies. Micro-level studies focus on assessing the carbon emissions associated with specific elements of prefabricated buildings, such as building materials and components. For example, a study explored the frameworks associated with the assessment of carbon emissions during the production stage of prefabricated components [12]. In another study, Balasbaneh et al. [13] compared the environmental impacts of steel precast structures and precast concrete structures, emphasizing the lower carbon footprint of concrete. Carbon emissions of other prefabricated components have been examined, including prefabricated wall panels, floor slabs, and concrete piles [14]. Previous research has emphasized the importance of employing low-carbon materials to mitigate the carbon footprint associated with prefabricated buildings [15]. In another study, On the other hand, meso-level studies involve a comparison of the overall carbon footprint of prefabricated buildings with that of traditional buildings. In the study by Du et al. [16], a comparative analysis was conducted, examining the carbon footprint of prefabricated buildings and traditional buildings, spanning from production to the construction site. The findings show slightly lower carbon emissions associated with prefabricated buildings. Similarly, Ji et al. [2] found that prefabricated buildings contribute to a 3.1 % reduction in carbon emissions compared to traditional buildings.

The life cycle of prefabricated buildings includes four stages, including building material preparation, building construction, building use and maintenance, and building demolition and recycling. A couple of studies have assessed the carbon footprint of prefabricated buildings across various stages of their life cycle. For instance, Bonamente et al. [17] analysed the carbon footprint of prefabricated buildings during the embodied stage, encompassing material extraction, production, transportation, and construction processes. In some cases, the recycling phase is considered together with the end-of-life phase. Notably, a significant emphasis has been placed on assessing the carbon footprint during the embodied stage, given its substantial contribution to the overall life-cycle carbon footprint. For example, Mao et al. [18] focused on assessing the carbon footprint of prefabricated buildings with the construction processes. Several studies have examined the material preparation stage as part of carbon footprint accounting. However, limited research has been conducted on the carbon footprint of prefabricated buildings during the end-of-life stage. Typically, the assessment of carbon emissions associated with the demolition and recycling of prefabricated buildings relies on estimations derived from the proportions of building material recycling [19].

The principles of the circular economy within the construction sector have been summarised as follows: 1) Enhancing material productivity by achieving equivalent or greater output with reduced input; 2) Eliminating waste by categorizing materials as either technical or biological nutrients, enabling them to be within closed material loops – often referred to as ‘waste as food’; 3) Preserving or enhancing the value of materials, both environmentally and economically; and 4) Adopting a systems-thinking approach by examining the flows of material and energy within industrialised systems, understanding interconnections, mutual influences, and their ramifications, thereby enabling closed-loop processes where waste serves as an input [10]. A couple of previous studies have examined the implementation of these circular economy principles within the construction sector. For instance, Ginga [20] explored the effectiveness and limitations of applying circular economy principles to the reuse and recycling of construction waste. Moreover, the importance of maximizing the recycling of materials during the initial design stage to achieve a circular economy in construction has been highlighted [21]. Implementing recycling practices during the end-of-life stage has the potential to reduce environmental impact by 5 % [21]. Additionally, using recyclable materials instead of virgin materials can lead to an overall reduction of up to 30 % in environmental impact. In another study [11], the relationship between the circular economy and the carbon footprint of buildings was examined through practical examples. The findings indicated that closed-loop material circulations have the potential to reduce the carbon footprint by 30–50 %. Furthermore, a few studies have investigated the application of circular economy principles in prefabricated buildings. One such study evaluates the environmental benefits of modular buildings designed for disassembly and reuse [22]. This study also compared the differences in carbon footprint between traditional material recycling and reuse of components [22]. Another study by Minunno’s team [23] analysed the applicability of the circular economy framework in both traditional and prefabricated buildings. Employing a qualitative analysis, they examined the advantages of prefabricated components in terms of reduction, repeatability, and recyclability, and proposed a novel approach to achieving a circular economy in the construction industry, underscoring the necessity of adopting prefabricated buildings and circular economy [23].

The above discussion reveals four limitations in previous research: Firstly, there is a lack of a comprehensive carbon footprint accounting framework tailored to the construction features of prefabricated buildings. A second limitation is the inconsistent division of life cycle stages across studies, with a predominant focus on the embodied phase, yet lacking consensus on its sub-processes [24]. Moreover, the end-of-life stage and recycling process associated with prefabricated buildings have not been effectively and sufficiently analysed [19]. Thirdly, the

exploration of uncertainty factors and their optimization to improve the accuracy and reliability of accounting models is insufficient [25]. Lastly, limited research is conducted on the application of circular economy principles in quantifying the carbon footprint for prefabricated buildings. These research gaps hinder our understanding of the carbon footprint of prefabricated buildings and how a circular economy can effectively contribute to reducing emissions in the prefabricated building sector.

The novelty of this study is to address the above limitations. The purpose of this study is to establish a carbon footprint accounting approach tailored to the construction features of prefabricated buildings and the characteristics of closed-loop material circulations of circular economy. Therefore, this study aims to develop an accounting framework for quantifying the life-cycle carbon footprint of prefabricated buildings through the integration of circular economy. Meanwhile, some effective suggestions are proposed for effectively and efficiently accounting for the carbon footprints of prefabricated buildings.

3. Research methodology

This study integrates the characteristics of closed-loop material circulations of circular economy and the construction characteristics of prefabricated buildings to develop a framework for the comprehensive assessment of the life-cycle carbon footprint of prefabricated buildings.

The characteristics of prefabricated buildings are initially examined by comparing them with traditional buildings. The construction processes of prefabricated and traditional buildings are presented in Fig. 1.

As shown in Fig. 1, the most significant distinction between prefabricated and traditional buildings is the approach to production, processing, and on-site installation. Prefabricated buildings involve manufacturing prefabricated components in specialized factories. These components are then transported to the construction site for direct assembly. The transportation process may involve the use of flatbed trucks, trailers, or shipping containers. Once on-site, the prefabricated components are lifted and installed into their designated positions using cranes or other heavy machinery. Additionally, prefabricated components can be disassembled and reused as needed. On the other hand, in traditional construction, most building elements are typically constructed on-site, with materials and components being assembled and installed directly at the location. Given the characteristics of prefabricated buildings and the principles of circular economy within the construction sector outlined in Section 2, the implementation of circular economy concept in the life cycle of prefabricated buildings involves: (1)

Standardized design and factory production to promote lean construction; (2) Incorporating recycled materials such as recycled aggregates into construction materials; (3) Reusing components to minimize waste generation; (4) Leveraging the modular and standardized design of prefabricated buildings to enhance the adaptability of space and architectural elements; (5) Standardized and modular components to facilitate disassembly design; (6) Recycling concrete and steel components; (7) Ensuring traceability of prefabricated components using BIM and RFID. Strategies (2), (3), (5), and (6) will be explored in this study, while strategies (1), (4), and (7) will be addressed separately in a subsequent article focusing on the design aspects of prefabricated buildings.

3.1. Framework for accounting life-cycle carbon footprint of prefabricated buildings

The framework for accounting the life-cycle carbon footprint of prefabricated buildings is built upon a process-based LCA method, which is defined in ISO 14040 and 14,044 standards [26,27]. The ISO-based framework includes four steps: definition of goal and scope, life cycle inventory (LCI) analysis, life cycle impact assessment (LCIA), and life cycle interpretation. The definition of goal and scope stage is to establish the purpose and boundaries of the study, including the system boundaries, functional units, and data inputs and outputs for inventory analysis and impact evaluation. The LCI analysis collects data on material and energy flows throughout the life cycle. This information is used to compile an inventory of input (such as resources and energy) and output data (such as waste and emission). Additionally, inventory data can be analysed based on the cut-off principle, and uncertainty analysis is conducted to ensure the reliability and validity of the data. The LCIA stage involves converting the inventory analysis data into environmentally relevant information. The interpretation analysis of life cycle results provides a detailed examination of the overall environmental assessment results.

3.1.1. Goal and scope

Adhering to the ISO-based LCA framework, the first step of the life-cycle carbon footprint accounting framework for prefabricated buildings involves determining the scope, system boundary and functional units of carbon footprint assessment.

In line with the life cycle stages in construction works set by the BS EN 15978, the life cycle of a prefabricated building comprises four phases: the product phase (A1-A3), the construction phase (A4 -A6), the use phase (B) the end-of-life phase (C) and beyond the life cycle - the

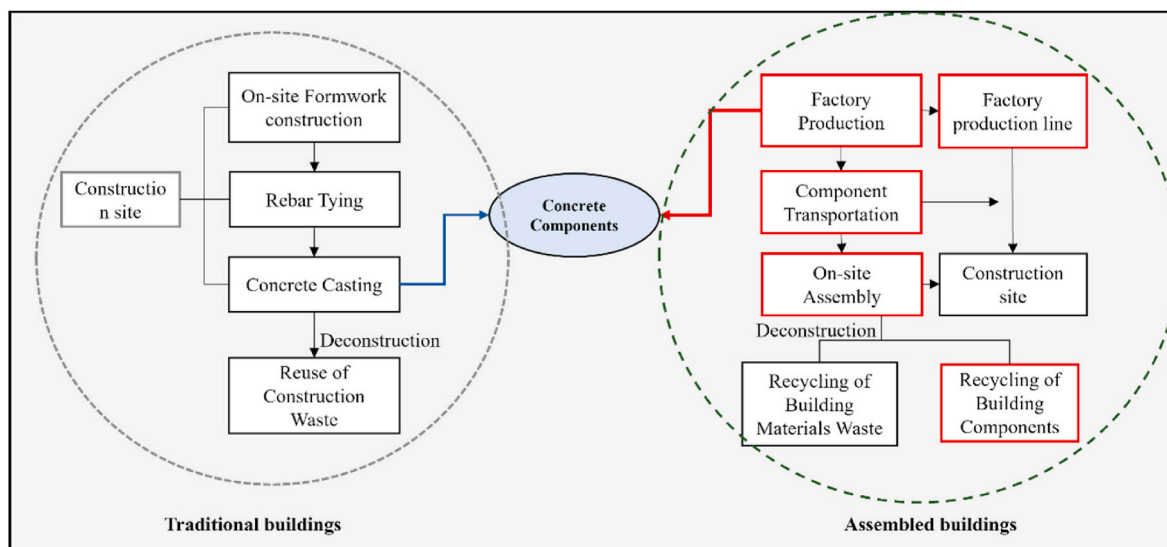


Fig. 1. The construction processes of prefabricated and traditional buildings.

recycling phase (D). The procedural details of each phase are shown in Fig. 2.

The system boundary for accounting for the carbon footprint of prefabricated buildings in this study is illustrated in Fig. 3. The carbon footprint of prefabricated buildings is examined from three dimensions: time (i.e., life cycle phases), space, and the building composition.

As shown in Fig. 3, in time terms, this research covers the three phases (A, C, and D) of a prefabricated building. The product and construction phases (A) include four stages: production and transportation of raw materials (A1-A2), factory production (A3), prefabricated components transport (A4), and on-site construction and assembly (A5-A6). However, the study excludes the use phase (B) from its system boundary since the carbon footprint during this phase is not directly impacted by the construction attributes of prefabricated buildings or the implementation of circular economy strategies. Additionally, rapid urbanization often leads to buildings being demolished before reaching their intended service life, so the carbon footprint related to maintenance, repair, and replacement is also not considered within the study's system boundary. The end-of-life phase (C) involves the dismantling of the structure, along with the disposal of construction waste. The beyond life cycle-the recycling phase (D) entails the reuse or recycling of building

materials and components.

On the other hand, in spatial terms, this study considers the carbon footprint within and outside the construction site. Within the construction site, the carbon footprint is generated by the mechanical equipment used. Outside the construction site, the carbon footprint is related to the production and transportation of building materials and prefabricated components, as well as the transportation and disposal of construction waste and recycled components.

In terms of the building composition, this study focuses on three levels: materials, components, and the overall building.

The functional unit serves as a quantitative description of the accounting results. In this research, the functional unit was defined as one square meter of the total construction area of a prefabricated building. Moreover, this study uses global warming potential with 100-year time horizons for the calculation of the potency of greenhouse gas relative to CO₂. They are expressed as "kgCO₂e/m²". "CO₂e" denotes carbon dioxide equivalent, the standardized unit for measuring greenhouse gas emissions.

3.1.2. Life cycle inventories

The second step in the life-cycle carbon footprint accounting

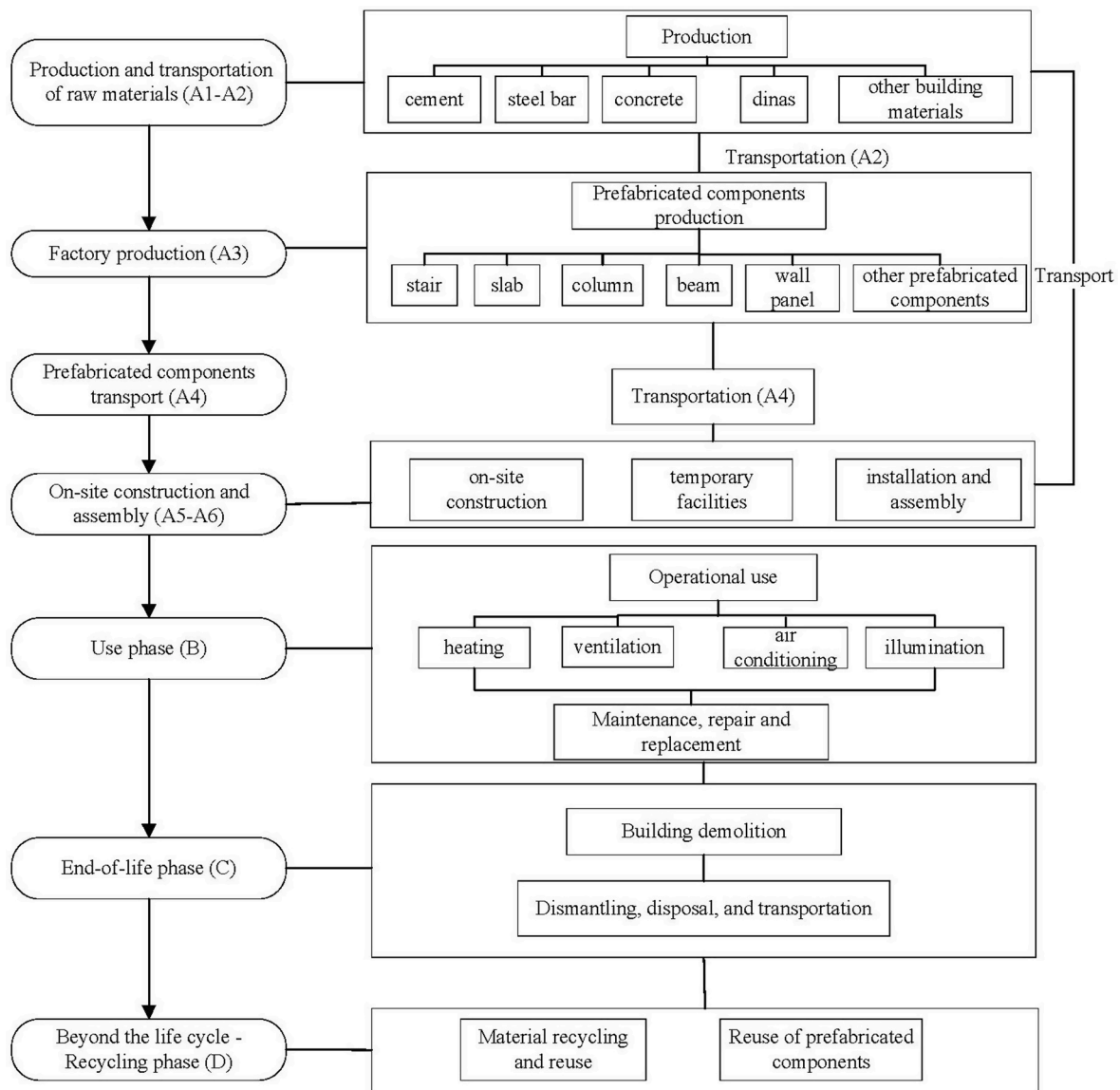


Fig. 2. Life cycle stages of prefabricated buildings.

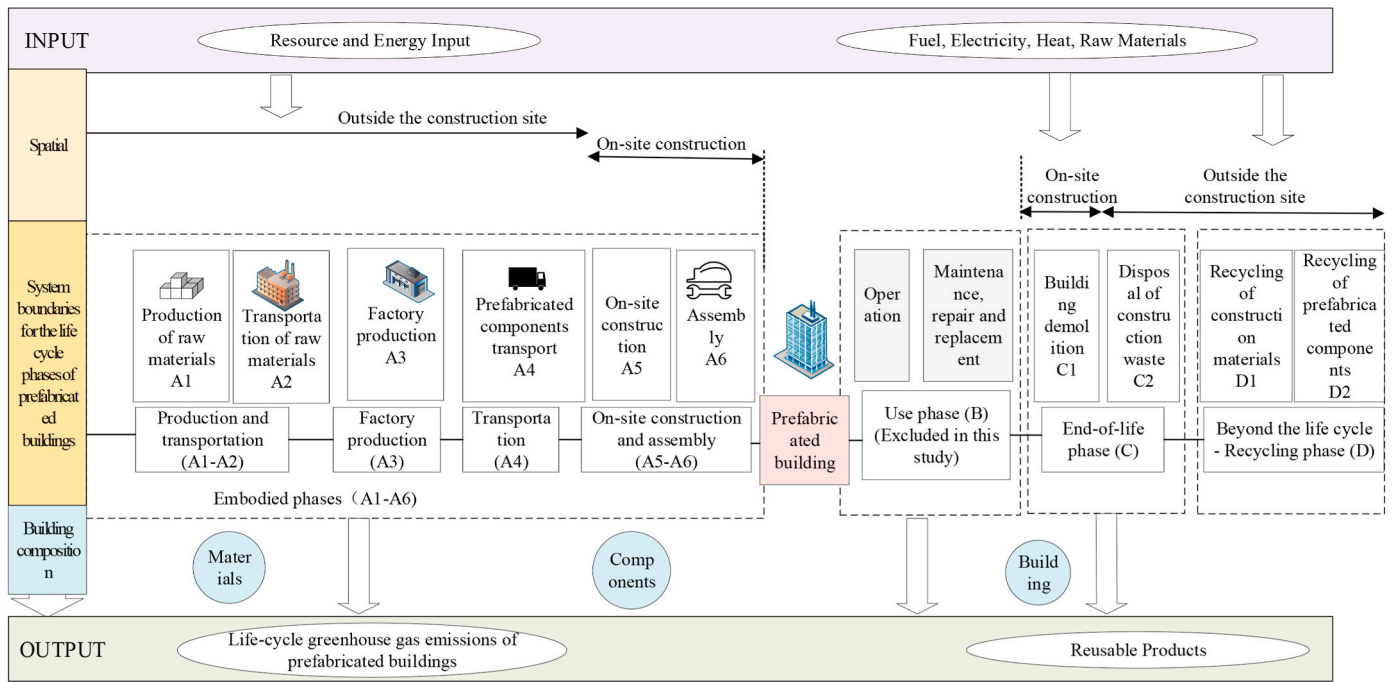


Fig. 3. System boundary of the framework for carbon footprint accounting of prefabricated buildings.

framework for prefabricated buildings involves collecting various types of carbon footprint factors. In this study, the following priority principle is adopted to select carbon footprint factors: The first choice is to collect data from national databases such as CLCD (China Life Cycle Database), Ecoinvent, ELCD (European Life Cycle Database), and carbon footprint databases from authoritative institutions; In the absence of the national databases, the study retrieves data from related literature or calculates the carbon footprint factors by establishing resources and energy flows. The factors from other countries are adjusted to suit the local context. For example, the “Default Emission Factors for Stationary Source Combustion in Manufacturing Industries and Buildings” published by IPCC offers average values for different countries regarding carbon footprint for CH_4 and N_2O . To align with the local situation, a formula is developed to adjust the carbon footprint factor, as shown in Equation (1):

$$E_E = \left(C_c R_o \times \frac{44}{12} + 28C_{\text{CH}_4} + 256C_{\text{N}_2\text{O}} \right) \cdot C_v \quad (1)$$

Where, C_c and R_o denote the carbon content of the fuel (kg C/TJ) and the oxidation rate of fuel (%), respectively. The expression $C_c R_o \times \frac{44}{12}$ represents the effective carbon footprint factor; C_{CH_4} and $C_{\text{N}_2\text{O}}$ are the default carbon factors (kg/TJ) of CH_4 and N_2O , respectively, sourced from the IPCC data; C_v represents the average lower heating value of fuel (TJ/kg), retrieved from the General Principles for Comprehensive Energy Consumption Calculation (GB/T2589-2020) [28].

The framework has inherent uncertainty due to missing or inaccurate life cycle inventory data and assumptions for end-of-life and recycling phases. Therefore, uncertainty analysis is necessary to ensure the reliability and validity of the carbon footprint accounting results. In this study, a combined approach of Data Quality Indicator (DQI) evaluation method and Monte Carlo Simulation (MCS) is employed to analyse the uncertainty in the carbon footprint assessment of prefabricated buildings [29,30]. The DQI method involves experts judging and quantifying data based on their experience, providing scores for uncertainty assessment using descriptive indicators [31]. The assessed data includes life inventory data such as the quantity take-offs, carbon footprint factors, transportation distance and others. Five indicators are used to assess data quality: the data source, data reliability, representativeness

of geography, representativeness of skills, and representativeness of timing. The DQI score is then converted into a log-normal distribution following principles from the Ecoinvent database, where parameter uncertainty, expressed by deviation, includes basic uncertainty from random errors and additional uncertainty from inaccurate data. Therefore, the data uncertainty can be expressed as:

$$\sigma_t^2 = \sigma_b^2 + \sum_{i=1}^5 \sigma_{a,i}^2 \quad (2)$$

Where σ_t^2 denotes the total uncertainty, σ_b^2 is the basic uncertainty, and the $\sigma_{a,i}^2$ is the additional uncertainty of indicator i . The σ_b^2 value for construction activities is 0.0006 in Ecoinvent [32]. The uncertainty obtained through the DQI method is considered as additional uncertainty. Finally, the overall uncertainty σ_t^2 is determined, leading to the probability density function of the lognormal distribution.

The DQI method establishes the probability distribution of the life cycle inventory data, while MCS is utilized to quantify the uncertainty of the total life-cycle carbon footprint for a prefabricated building based on the probability distribution of the life cycle inventory data. The number of simulation times for MCS is determined by testing convergence using experimental methods. Multiple sets of mean and standard deviation are obtained from different simulation times, and the convergence trend is analysed to determine the final number of simulations. The MCS is performed using Crystal Ball software for its accuracy, visual representation of results, and operation flexibility [33]. With uncertainties in input parameters (life cycle inventories) determined by DQI method, MCS generates corresponding output values (predicted parameters). Further examination of the sample mean, standard deviation and coefficient of variation, is conducted to quantify the degree of uncertainty. This information, combined with the accounting carbon footprint (also called as deterministic carbon footprint), is used to identify the key process. The Mean Relative Error (MRE) is defined as the ratio of the standard deviation to the sample mean, which is used to compare the deterministic and uncertain carbon footprint.

3.1.3. Accounting life-cycle carbon footprint from the perspective of circular economy

The total carbon footprint for the life cycle of prefabricated buildings is the sum of the carbon footprint in each stage, as shown in Equation (3).

$$G_{LC} = G_{A1-A2} + G_{A3} + G_{A4} + G_{A5-A6} + G_C + G_D \quad (3)$$

Where G_{LC} is the total carbon footprint (kg CO₂e) of the prefabricated building over its life cycle. G_{A1-A2} , G_{A3} , G_{A4} , G_{A5-A6} , G_C and G_D denote the carbon footprint of the production and transportation of raw materials, factory production, prefabricated components transport, on-site construction and assembly, end-of-life phase, and recycling phase, respectively.

The final conversion to a unified functional unit for analysis of results.

$$G_{UX} = \frac{G_X}{A} \quad (4)$$

Where G_{UX} is the total carbon footprint per unit area (kg CO₂e/m²), G_X is the carbon footprint (kg CO₂e) for X phase (i.e., product, construction, end-of-life, or recycling phase), and A is the floor area (m²).

The formula for accounting for carbon footprint in each stage is presented in Table 1.

3.1.4. Carbon footprint contribution analysis based on three dimensions

This study measures the contribution of the life-cycle carbon footprint of prefabricated buildings in terms of three dimensions: time, spatial, and building composition.

4. Implementation of case study

4.1. Case study

The case selected for this paper is the West District Nursing Home, located in Chengdu, Sichuan Province. The building is an assembled monolithic concrete frame structure, featuring a basement with 1 floor and 6 floors above ground. The total height of the building is 22.2 m with a total construction area of 6764.1 m².

The prefabricated components used in this building include prefabricated columns, beams, laminated panels, and Autoclaved Lightweight Concrete (ALC) prefabricated wall panels. The quantities and volumes of prefabricated components are shown in Table 2.

4.2. Quantification of life-cycle carbon footprint of prefabricated case

4.2.1. Carbon footprint from raw material product and transport (A1-A2)

The production process of building materials was divided into two groups: the production process for cast-in-place materials and the production process for prefabricated materials. The quantities of the construction materials were obtained from the contractors. The calculation processes and results of the carbon footprint of cast-in-place materials are shown in Table A-1 in Appendix A.

According to Table A-1, concrete, steel and bricks and blocks produce over half of the total carbon footprint generated in the production process of cast-in-place building materials.

The calculation processes and results of the carbon footprint for prefabricated materials are shown in Table A-2.

According to Table A-2, the concretes and reinforcing steel produce the highest carbon footprint, while steel formwork exhibits the lowest. This discrepancy can be attributed to the reusability of steel formwork in construction practices, resulting in reduced consumption of steel formwork.

In referring to the carbon footprint produced in the transportation process of building materials (A2), the transportation distance was determined by referencing the transportation routes from the building

materials suppliers to the construction site or prefabricated components factory using Baidu Map [36]. The carbon footprint of the transportation process of buildings materials is shown in Table A-3.

Table A-3 reveals that the carbon footprint associated with transporting the building materials to the construction site amounts to 73671.86 kgCO₂e, while the transportation of building materials to the prefabricated components factory results in a carbon footprint of 23769.61 kgCO₂e. Consequently, a total carbon footprint of 97441.47 kgCO₂e is produced for the transportation process of the building materials in this particular case, and the unit carbon footprint is calculated to be 14.41 kgCO₂e/m².

4.2.2. Carbon footprint from factory production (A3)

The prefabricated components include prefabricated columns, beams, laminated panels, and ALC wall panels.

Having acquired data through field studies and on-site visits to precast plants, it was determined that in a typical unit shift, precast columns and beams can yield approximately 30 pieces each, while precast laminated panels can be produced in quantities of 50 pieces within the same shift duration. ALC lightweight wall panels can achieve an annual production output of nearly 300,000 square meters. The calculation process and results of the carbon footprint for precast production and in-site transportation are shown in Table A-4.

According to Table A-4, the carbon footprint associated with the prefabricated component production process amounts to 4172.08 kgCO₂e. Furthermore, the carbon footprint for the on-site transportation process is recorded as 6294.07 kgCO₂e/m². Therefore, the factory production stage contributes a carbon footprint value of 10466.15 kgCO₂e, resulting in a unit carbon footprint of 1.55 kgCO₂e/m².

4.2.3. Carbon footprint from prefabricated components in transportation phase (A4)

Carbon footprint produced by the transportation of prefabricated components is illustrated in Table A-5. The carbon footprint of the vertical transportation phase is 9615.25 kgCO₂e.

Carbon footprint produced by the horizontal transportation of prefabricated components is illustrated in Table A-6. The production suppliers for prefabricated columns, beams, and laminated panels in this case are in another city adjacent to the project site.

The horizontal transportation process contributes a carbon footprint of 17587.36 kgCO₂e. Combining this with the carbon footprint in the vertical transportation process, the total carbon footprint of the component transportation phase for the prefabricated building in this case amounts to 27202.61 kgCO₂e. Therefore, the unit carbon footprint is 4.02 kgCO₂e/m².

4.2.4. Carbon footprint from on-site construction and assembly phase (A5-6)

The carbon footprint of on-site construction and assembly is produced by the energy consumption of machinery, equipment and temporary facilities during the construction process and the prefabricated component assembly process. Table A-7 presents its calculation process and results of the carbon footprint produced by the use of machinery and equipment required for on-site construction activities.

The carbon footprint factor is determined based on the 2019 "Consumption of Housing Construction and Decoration Engineering" quota and the "Sichuan Province Construction Bill of Quantities Pricing Quotas [47]. As shown in Table A-7, the total carbon footprint generated by the on-site construction process is 61951.3 kgCO₂e, and the unit carbon footprint is 9.16 kgCO₂e/m² accordingly.

Furthermore, temporary facilities are necessary on the construction site, including offices, dormitories, canteens, and bathrooms. The carbon footprint associated with these temporary facilities is primarily generated by energy consumption. The construction duration spans approximately 11 months totaling 87 days at 8 h per day. The cooling period is from June 15 to August 31, spanning 77 days at 7 h per day.

Table 1
Formula for accounting for carbon footprint at each stage.

Stage	Calculation category	Formula for accounting for carbon footprint	Notes
Production and transportation of raw materials (A1-A2)	The carbon footprint in the phase of production and transportation phase of raw materials (G_{A1-A2})	$G_{A1-A2} = G_{A1} + G_{A2}$	Where G_{A1} , G_{A2} denote the carbon footprint of the production process and the transportation process of building materials, respectively.
	The carbon footprint in the production process of building materials (G_{A1})	$G_{A1} = \sum_{i=1}^n Q_i \times E_{ci}$	Where Q_i is the amount of the i th building material. E_{ci} denotes the carbon footprint factor of the i th building material (kg CO ₂ e/unit).
	The quantities of construction turnover materials ($\overline{Q_{z,i}}$), such as formwork, support system, and piecemeal jigs	$\overline{Q_{z,i}} = Q_{z,i} \times \frac{[1 + r_i \cdot (T_i - 1)]}{T_i}$	where $Q_{z,i}$ is the average quantity of the i th turnover material. $Q_{z,i}$ is the quantity of the i th turnover material. r_i is the waste rate of the i th turnover material. T_i is the average number of turnovers for the i th turnover material. The value of Q_i is obtained from the quantity list of the assembly building materials or building model data. The parameters r_i and T_i are derived from the <i>Instructions for the Preparation of National Uniform Construction Foundation Quotas</i> [34].
	The carbon footprint produced in the transportation process of building materials (G_{A2})	$G_{A2} = \sum_{i=1}^n Q_i \times D_i \times E_{ysi} + \sum_{m=1}^n Q_m \times D_m \times E_{ysm}$	Where Q_i and Q_m denote the quantity of building materials transported to the prefabrication factory and the construction site, respectively. They are obtained from the quantity list for assembly building materials provided by the prefabrication product supplier. D_i and D_m denote their transportation distances respectively. They are determined by using mapping services based on the addresses of suppliers, the prefabrication factory, and the construction site. E_{ysi} and E_{ysm} denote the carbon footprint factor of the transportation mode (kg CO ₂ e/km). They are obtained according to the principles set in section 3.1.2.
Factory Production (A3)	The carbon footprint of prefabricated components in the factory production process (G_{A3})	$G_{A3} = G_{sc} + G_{cn}$	Where G_{sc} , G_{cn} denotes the carbon footprint of the manufacturing process and the transportation process of prefabricated components in the prefabricated factory, respectively.
	The carbon footprint of the manufacturing process (G_{sc})	$G_{sc} = \sum_{i=1}^n \frac{Q_{yi}}{q_{y,i}} \times P_{s,i} \times E_e$	Where Q_{yi} represents the quantity of i th prefabricated component. $q_{y,i}$ represents the quantity of i th prefabricated component produced by the production line per shift. $P_{s,i}$ denotes the electricity required by the production line per shift for producing i th prefabricated component (kwh/shift). $q_{y,i}$, $P_{s,i}$ are average empirical data derived from prefabrication factories. E_e denotes the carbon footprint factor of electricity.
	The carbon footprint of the transportation process (G_{cn})	$G_{cn} = \sum_{i=1}^n (Q_{yi} \times T_{yij} \times R_{yj}) \times E_j$	Where Q_{yi} is the quantity of the i th prefabricated component. The bill of quantity is provided by the supplier of prefabricated components. T_{yij} is the electricity consumption (per shift) of the j th transportation machinery for transporting the i th prefabricated component in the prefabricated factory. R_{yj} is the energy consumption per shift of the j th transport machinery. Electricity consumption is determined based on the consumption quotas specified in national or local standards for housing construction and decoration of assembly buildings [35].
Prefabricated components transport (A4)	The carbon footprint for the process of transporting prefabricated components from prefabricated factories to the construction workplace (G_{A4})	$G_{A4} = G_{cz1} + G_{sp} + G_{cz2}$	The process of transporting prefabricated components from prefabricated factories to the construction workplace can be subdivided into three modes: (1) the first vertical transport which denotes the process of lifting and transferring from the factory to transport vehicles (also called loading); (2) horizontal transport: the process of transporting prefabricated components from the factory to the construction site; (3) the second vertical transport which denotes the process of lifting and loading the prefabricated components from the transport vehicle to the site stacking point (also called unloading). G_{cz1} and G_{cz2} denote the carbon footprint of the first and the second vertical transport, respectively (kg CO ₂ e); and C_{sp} is the carbon footprint produced during the horizontal transport process (kg CO ₂ e).
	The carbon footprints produced by the vertical transport processes ($G_{cz1} + G_{cz2}$)	$G_{cz1} + G_{cz2} = 2 \times \sum_{i=1}^n (Q_{yi} \times T_{ycj} \times R_{ycj}) \times E_j$	Where Q_{yi} is the quantity of the i th prefabricated component. T_{ycj} is the shift waste of the j th type of transportation machinery. R_{ycj} is the energy consumption per shift of the j th transport machinery.

(continued on next page)

Table 1 (continued)

Stage	Calculation category	Formula for accounting for carbon footprint	Notes
	The carbon footprint during the horizontal transportation process (G_{sp})	$G_{sp} = \sum_{i=1}^n QM_{y,i} \times D_{y,i} \times E_{ys,i}$	Where $QM_{y,i}$ is the weight of the i th transporting prefabricated component (t). The weight is calculated by multiplying the bill of quantity of the prefabricated components by the individual weight. $D_{y,i}$ is the transportation distance between the factory and the construction site (km). Transportation distance is measured through Baidu Map [36]. $E_{ys,i}$ is the carbon footprint factor per kilometer of certain transportation mode for the i th prefabricated component (kg CO ₂ e/unit-km).
On-site construction and assembly (A5-A6)	The carbon footprint of on-site construction and assembly (G_{A5-A6})	$G_{A5-A6} = G_{A5} + G_{A6}$	Where G_{A5} and G_{A6} denote the carbon footprint produced during the construction process and the prefabricated component assembly process, respectively.
	The carbon footprint of the on-site construction process (G_{A5})	$G_{A5} = G_{sg} + G_{ls}$	The carbon footprint of the on-site construction process (G_{A5}) is caused by the energy consumption of machinery, equipment, and temporary facilities. Where G_{sg} is the carbon footprint of machinery and equipment during on-site construction (kg CO ₂ e). G_{ls} is the carbon footprint of the operation of temporary facilities (kg CO ₂ e).
	The carbon footprint generated by the machinery and equipment of the construction process (G_{sg})	$G_{sg} = \sum_k \sum_h Q_{s,h} \times EQ_{h,k} \times E_{e,k}$	Where $Q_{s,h}$ is the quantity per shift of the h th type of construction machinery. $EQ_{h,k}$ is the consumption of k type energy per unit shift of the h th type of construction machinery. $E_{e,k}$ is the carbon footprint factor of k type energy (kgCO ₂ e/kg).
	The carbon footprint for the operation of the temporary facilities (G_{ls})	$G_{ls} = \sum_{i=1}^n EQ_{ls,i} \times E_{e,i}$ $EQ_{ls} = EQ_{bg} + EQ_{sh}$ $EQ_{bg} = S_{bg} \times (f_{zm} \times T_{zm} + f_{gn} \times T_{gn} + f_{zl} \times T_{zl})$ $EQ_{sh} = S_{sh} \times (f_{zm} \times T_{zm} + f_{gn} \times T_{gn} + f_{zl} \times T_{zl})$	Where $EQ_{ls,i}$ is the consumption of i type of energy during the operation of the temporary facility. EQ_{ls} is the total energy consumption consumed of the temporary facility. EQ_{bg} , EQ_{sh} are the total energy consumption consumed in the office area and in the living area, respectively. S_{bg} and S_{sh} is the area of office and living places (m ²), respectively. The area can be obtained from the drawings of temporary facilities and construction plans. f_{zm} and f_{gn} and f_{zl} denote the energy consumption coefficient of lighting, heating, and cooling per square meter of office/living area. T_{zm} and T_{gn} and T_{zl} are the hours of lighting, heating and cooling per square meter of office/living area. The time is estimated according to the duration and season.
	The carbon footprint produced during the prefabricated component assembly process (G_{A6})	$G_{A6} = G_{dz} + G_{zp}$ $G_{dz} = \left(\sum_{i=1}^n P_i \times T_i \times E_e \right) \times N_i$ $G_{zp} = \sum_j (R_{gs,j} \times E_j \times T_{gs,j}) \times Q_{gs,i}$	Where G_{dz} and G_{zp} are the carbon footprint of the lifting process and the assembly process, respectively (kgCO ₂ e). P_i is the power (kw) of the machine for lifting the i th prefabricated component. T_i is the average lifting time of a prefabricated component of type i (h). N_i is the quantity of the i th prefabricated component. $Q_{gs,i}$ is the quantity of the i th prefabricated component to be assembled. $T_{gs,j}$ is the shift consumption of the j th type of machinery under the connection method corresponding to the i th type of prefabricated components (shifts). $R_{gs,j}$ is the energy consumption per unit shift for the j th type of construction machinery.
End-of-life phase (C)	The carbon footprint produced at the end-of-life phase G_C	$G_C = G_{C1} + G_{C2}$	Where the G_{C1} and G_{C2} denote the carbon footprint in the disassembly process and the waste disposal process, respectively
	The carbon footprint of the disassembly process (G_{C1})	$G_{C1} = (G_{sg} + G_{A6}) \times 90\%$	According to the initial design and connection method of prefabricated buildings, dismantling can be categorized into destructive, partial destructive, and non-destructive methods. Prefabricated buildings lacking detachable design and wet connections are destructively dismantled into materials, while those with detachable design or dry connections are disassembled into parts or components for recycling. Predicting the demolition process accurately during early design stages is challenging, but it can be simplified as a reverse construction process. Based on existing literature [37], the disassembly process's carbon footprint is estimated at 90% of the on-site construction and assembly footprint.
	The carbon footprint in the waste disposal process (G_{C2})	$G_{C2} = D_t \times Q_f \times E_{ys}$	The waste disposal process involves transporting the demolished construction waste to designated landfills or recycling sites for disposal. Where D_t is the average transportation distance from the

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Table 1 (continued)

Stage	Calculation category	Formula for accounting for carbon footprint	Notes
			construction site to the disposal site (km). The transportation distance can be obtained from the construction organization and design plan. If there is no planning data available, it can take 30 km according to the literature [38]. Q_f is the quantity of waste generated from the demolished building (kg). The total amount of construction waste can be estimated according to the generation index in the Technical Specification for Construction Waste Reduction [39]. E_{ys} is the carbon footprint factor of the transportation modes for transporting construction waste (kg CO ₂ e/kg-km). Where G_{D1} is the carbon footprint of the recycling process of construction materials. G_{D2} is the carbon footprint of the recycling process of prefabricated components.
Recycling phase (D)	The carbon footprint produced at the recycling phase (G_D)	$G_D = G_{D1} + G_{D2}$	Where Q_{hsi} is the quantity of the i th recyclable material. α_i is the recycling ratio of the i th recyclable material. The recycling ratios of the recycled materials are derived from previous study [40]. F_{hsi} denotes the carbon footprint generated by the resources for recycling 1t of construction waste (kg CO _{2e} /t). The carbon footprint can be obtained by multiplying the amount of mechanical resource consumption for recycling materials by the corresponding carbon footprint factor. $E_{c,i}$ is the carbon footprint factor of the i th recyclable material.
	The carbon footprint of the recycling process of constructions materials (G_{D1})	$G_{D1} = \sum_{i=1}^n (Q_{hs,i} \times \alpha_i \times F_{hs,i}) - \sum_{i=1}^n (Q_{hs,i} \times \alpha_i \times E_{c,i})$	For the recycling process of prefabricated components, it consists of three processes: disassembly and lifting, transporting components to the recycling sites, and recycling.
	The carbon footprint of the recycling process of prefabricated components (G_{D2})	$G_{D2} = G_{xh,1} + G_{xh,2} - G_{xh,3}$ $G_{xh,1} = \left(\sum_{i=1}^n G E_i \times P_i \times T_i \right) \times N_i \times \beta_{xh}$ $G_{xh,2} = \sum_{i=1}^n Q_{xh,i} \times D_{xh,i} \times E_{ys,i}$ $G_{xh,3} = \sum_i^n [(Q_{xh,i} \times E_{c,i}) + C_2 + C_{sp}] \times \beta_{xh}$	Where $C_{xh,1}$ is the carbon footprint of the process of lifting the components to the transport vehicle. $C_{xh,2}$ is the carbon footprint of the process of transferring prefabricated components to the recycling site. $C_{xh,3}$ is the carbon footprint reduction of the prefabricated components involved in the recycling process (including the savings in the production process of building materials of the components, the factory production process, and the process of transporting them to the construction site). β_{xh} is the percentage of prefabricated components that are recycled and reused. $Q_{xh,i}$ is the quantity of the i th recyclable prefabricated components. $D_{xh,i}$ is the average distance of transporting the i th recyclable prefabricated components from the construction site to the recycling site.

Table 2
Prefabricated components in the prefabricated building.

Type of prefabricated components	Places where components are used in	Number of components (pcs)	Volume of components (m ³)
Prefabricated columns	1-6 floors	98	91.39
Prefabricated beams	1-6 floors	364	325.21
Prefabricated laminated panels	1-6 floors	603	224.8
ALC prefabricated wall panels	Internal partition wall	5245	622.27

There are 4 air conditioners in the offices and 10 air conditioners in the dormitories. Each air conditioner has a power rating of 1.2kw. The specific calculation process and results of the carbon footprint for

Table 3
Amount of building materials waste after demolition.

Category	Concrete	Bricks and Blocks	Mortar	Metal	Glass	Wood	Other Materials
Demolition volume (t)	9178.86	2063.91	1465.63	347.2	26.84	28.26	856.39

temporary facilities are shown in Table A-8.

The assembly process of prefabricated components includes two steps of lifting and installation. The prefabricated components stacked at the construction site to the designated location requires professional lifting machinery, and the carbon footprint during this process is generated by the energy consumption of the lifting machinery. Tower crane and special spreader are employed for the lifting process. The lifting time is estimated based on the previous working experience of constructors. The calculation process and results of the carbon footprint for the lifting process are shown in Table A-9. The lifting process of prefabricated components contributes to a carbon footprint of 4980.53 kgCO_{2e}.

Moreover, the prefabricated components are bonded together by using two connection methods: dry connection using mechanical fasteners, adhesives, welding, or interlocking mechanisms, and wet connection using wet materials such as concrete, mortar, grout or other liquid adhesives. The carbon footprint of wet connections is discarded in

Table 4
Life-cycle carbon footprint for the case study.

Sub-processes	Carbon footprint value (kgCO ₂ e)	Unit carbon footprint (kgCO ₂ e/m ²)	portions of carbon footprint	Sub-stage
A1 raw materials production process	2916521.56	431.18	80.84 %	Embodied phase: 463.09 kgCO ₂ e/m ²
A2 building materials transportation process	97441.47	14.41	2.70 %	
A3 Factory production stage	10466.15	1.55	0.29 %	
A4 component transportation stage	27202.61	4.02	0.75 %	
A5 on-site construction process	75066.87	11.1	2.08 %	
A6 assembly process	5679.64	0.84	0.16 %	
C1 disassembly process	60867.84	9	1.69 %	End-of-life phase: 16.22 kgCO ₂ e/m ²
C2 waste disposal process	48842.32	7.22	1.35 %	
D1 material recycling process	-365848.07	-54.09	-10.14 %	Recycling phase: 54.09 kgCO ₂ e/m ²
Total carbon footprint value: 2876240.39 kgCO ₂ e, carbon footprint per square meter: 425.22 kgCO ₂ e/m ²				

this study because the carbon footprint of materials used for wet connections can be neglected. The carbon footprint in dry connections is primarily generated by the energy consumption of mechanical equipment. In this building, the ALC lightweight wall panels are connected using pipe clips. The calculation process and results of carbon footprint of installation process are shown in Table A-10. The carbon footprint result is 699.11 kgCO₂e.

Overall, the carbon footprint of the on-site construction phase of the assembly building in this study is 5679.64 kgCO₂ e, and the unit carbon footprint is 0.84 kgCO₂ e/m².

4.2.5. Carbon footprint from end-of-life phase (C)

The carbon footprint of the end-of-life phase produced in the disassembly process and the waste disposal process. The disassembly process is considered as the reverse process of the assembly process. The total carbon footprint associated with the disassembly process is 60867.84 kg CO₂e using the formula for calculating the carbon footprint of the disassembly process (G_{C1}), and the unit carbon footprint is estimated to be approximately 9 kg CO₂ e/m².

Table 3 presents the estimated amount of waste generated from each building material after demolition.

Part of the generated building materials waste is recycled, while the rest is disposed of using methods like incineration, landfilling, and others. Due to the negative environmental impact of incineration,

Table 5
Carbon footprint of prefabricated components.

Prefabricated parts	Building Materials	Formwork	Production	Transport	Installation	End-of-life stage	Recycling phase	Carbon footprint kgCO ₂ e	Carbon footprint per unit volume kgCO ₂ e/m ³
Prefabricated columns	68733.41	196.35	999.87	3175.01	296.35	627.55	-16540.44	57488.10	629.04
Prefabricated beams	216221.71	124.74	3637.92	11298.24	1391.04	2233.12	-58858.92	175950.73	541.04
Prefabricated laminated panels	149462.32	43.89	2640.64	7809.86	1823.47	1543.63	-40685.97	122570.71	545.24
ALC lightweight wall panels	103961.03	-	3187.73	4919.49	1469.66	4191.65	4274.71	122004.27	196.06

landfilling is chosen as the method for disposing of construction material waste. The waste materials are transported to the Fei Li construction waste disposal site. The carbon footprint calculation process and results are shown in Table A-11. The carbon footprint of the whole end-of-life stage for the case is 109710.2 kg CO₂e, and the unit carbon footprint is 16.22 kg CO₂e/m².

4.2.6. Carbon footprint from recycling phase (D)

In recycling phase, the carbon footprint is generated by the recycling of building materials and components. However, for this specific building project, recycling prefabricated components is not feasible due to limitations in using such components in concrete structural buildings. This is mainly attributed to the challenges posed by the connection technologies between recycled components. The recycling process of building materials involves the processing and reusing. The carbon emissions resulting from processing material are presented in Table A-12. The carbon footprint amounts to 70883.92 kg CO₂e, and the unit carbon footprint is 10.47 kgCO₂e/m².

The reusing building materials considered in this case include concrete, bricks and blocks, steel and metal, glass, and wood. The calculation process and results of carbon footprint saved from the reuse of materials are presented in Table A-13. The total carbon reduction amounts to 436,732 kgCO₂e.

As shown in Table A-13, steel recycling has the largest carbon reduction, accounting for 87.06 %. However, it is important to note that steel production also contributes a significant percentage of the carbon footprint in the building materials production phase. The final carbon footprint for the recycling cycle is -365848.07 kgCO₂e, representing carbon footprint savings. Consequently, the unit carbon footprint reduction is 54.09 kgCO₂e/m².

5. Results and discussion

5.1. Life-cycle carbon footprint results

The carbon footprint produced in each phase is shown in Table 4, and the total life-cycle carbon footprint of this case is 2876240.39 kg CO₂e. Accordingly, the unit carbon footprint is 425.22 kgCO₂e/m².

Building upon the life-cycle carbon footprint results, Fig. 4 illustrates the contribution of carbon footprint generated by the prefabricated building in terms of the three dimensions of the system boundary

Table 6
Carbon footprint of other similar studies (kgCO₂e/m²).

Literature	Time	Location	Embodied stage (A1-A6)	End-of-life stage (B)	Recycle stage (C)
[41]	2019	Zhuhai	484.58	-	-
[42]	2019	Fujian	464.97	-	-
[43]	2019	Chengdu	447.48	-	-
[44]	2019	Xi'an	392.59	22.86	-133.75
[45]	2017	Shenyang	320.70	15.65	-7.75
[46]	2011	Shanghai	606.43	19	-
This case	2020	Chengdu	463.44	16.59	-54.32

defined in this study.

In terms of the time dimension, as shown in Fig. 4, the biggest portion of carbon emissions (86.82 %) comes from the embodied phase (A1-A6). Among these stages, the production of building materials (A1) is responsible for the majority (80.8 %) of the embodied carbon. However, the carbon footprint associated with the production, transportation, and assembly of prefabricated components (A3, A4, A6) is relatively small (0.29 %, 0.75 %, and 0.16 % respectively). The end-of-life phase (C1–C2) accounts for 3.04 % of the total carbon footprint, mainly produced by the construction machinery and transportation vehicles. Recycling of building materials makes up 10.17 % of the total carbon footprint.

The carbon footprint produced within the construction site represents approximately 3.93 % of the total life-cycle carbon footprint, amounting to 20.94 kgCO₂e/m². The on-site construction process is the main contributor, responsible for a direct carbon footprint of 6.78 kgCO₂e/m². On the other hand, the carbon footprint outside the construction site plays a crucial role, accounting for approximately 96.07 % of the total life-cycle carbon footprint.

From the perspective of building composition, the carbon footprint generated by each prefabricated component in this study is presented in Table 5.

According to Table 5, prefabricated beams have the highest carbon footprint, accounting for 36.81 % of the total carbon footprint (175,950.73 kg CO₂e). This is because they serve as main load-bearing elements in the frame structure, requiring higher concrete grades and more concentrated reinforcement ratios. Therefore, special attention should be paid to prefabricated columns. The carbon footprints of prefabricated laminated panels and ALC lightweight wall panels are similar in magnitude. However, prefabricated columns have the smallest carbon footprint. Moreover, in the production, transport, and installation of prefabricated components, transportation contributes significantly to the carbon footprint. This highlights the importance of the prefabricated component plant's location and the choice of transportation method.

5.2. Compared to related studies

The results in this study were compared with other similar studies for verification, as shown in Table 6.

As shown in Table 6, a large variation can be found in the carbon footprint at embodied stage of each building. The variability can be attributed to the differences in design and the choice of building materials. Nevertheless, the embodied carbon footprint of the studied case aligns closely with the findings of previous studies and is comparable to another case conducted in the same city, Chengdu. The results of this case exhibit slightly higher values, primarily due to variances in transportation distances for building components, the inclusion of the vertical transportation process, and variations in system boundaries.

Furthermore, as presented in Table 6, limited studies include the end-of-life stage of prefabricated buildings. Many studies estimated the carbon footprint by using proportional or predictive formulas. Moreover, carbon footprint in recycling stage is related to the use of building materials in the early stage, the specific recycling ratio, and construction periods, leading to the variations in the carbon footprint for the recycling stage.

Overall, the comparative analysis demonstrates a reasonable and comparable range in carbon footprint when compared to other case studies. This indicates that the established framework for assessing the life-cycle carbon footprint of prefabricated buildings is valid.

5.3. Uncertainty analysis on life-cycle carbon footprint accounting

The data quality scores of input parameters (life cycle inventories) were calculated using DQI method, as presented in Appendix B and C. Subsequently, the number of MSC was determined through a testing method. Starting with 1000 simulations, the number of simulations was increased incrementally by 1000. As the number of simulations increased to 15,000, the standard deviation tended to stabilize, and the fluctuation in the mean value began to decrease. Therefore, 15,000 simulations were selected as the final number for Monte Carlo simulations. Through 15,000 MCS, the standard deviation of the total life-cycle

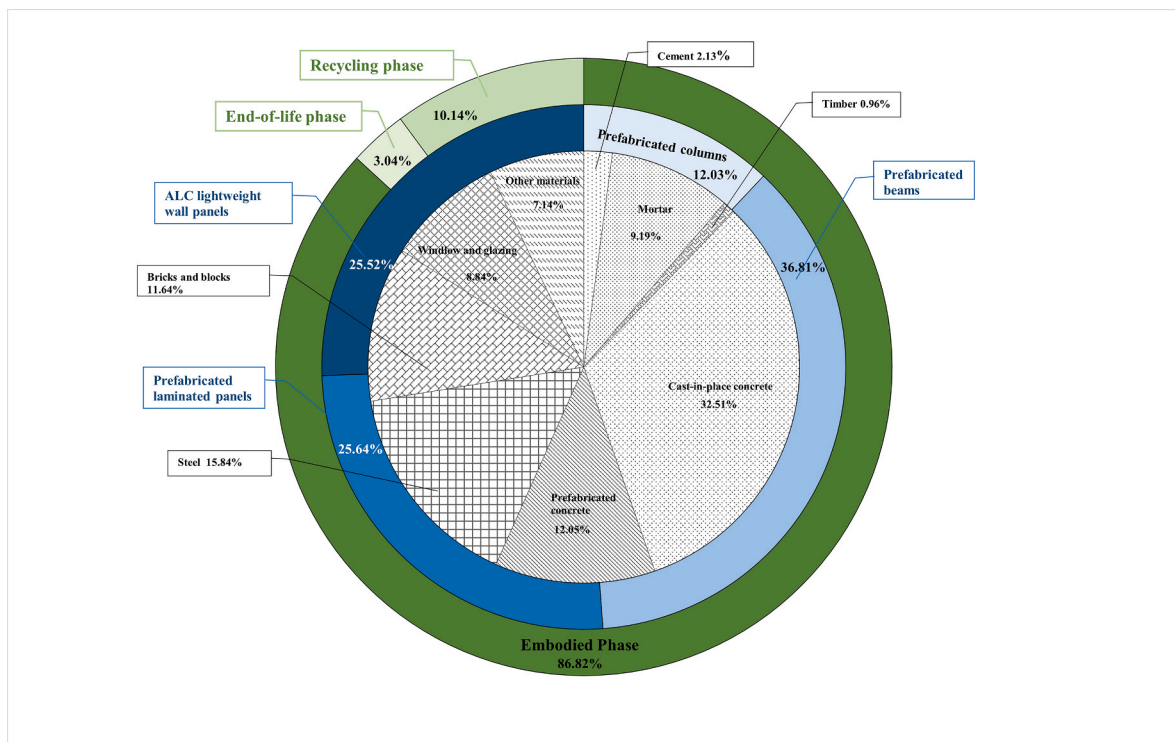


Fig. 4. Proportion of carbon footprint in terms of three dimensions.

carbon footprint value was found to be 138,216.28 kgCO₂e. Additionally, the standard error of the mean is only 0.82 % of the standard deviation. The 95 % confidence interval for this mean is [2582012.11,3131957.29] kgCO₂e. In the accounting analysis (deterministic carbon footprint), the sample mean is 2,876,240.39 kgCO₂e, while in the uncertain analysis, it is 2,873,804.98 kgCO₂e, resulting in a relative error of 0.085 %. This indicates that the established accounting framework for prefabricated buildings, within the context of a circular economy, is effective. Fig. 5 presents the results of the uncertainty analysis.

5.4. Key processes of life-cycle carbon footprint accounting for prefabricated buildings

The key processes in the life-cycle carbon footprint accounting of prefabricated buildings are determined by adopting a dual indicator approach, incorporating both the contribution degree and the uncertainty of each process, as shown in Fig. 6. The contribution degree signifies the proportion of building materials, components, or life-cycle stages in the total carbon footprint, while the coefficient of variation is derived from the uncertainty analysis of carbon footprint accounting results, as stated in Section 3.1.2. In the dual indicator approach, the vertical axis denotes the contribution degree, while the horizontal axis represents the coefficient of variation, as illustrated in Fig. 6. The criticality of each process is then assessed based on its relative position on the axes. In this study, if the building materials, components, or stages are in the area where the contribution degree surpasses the uncertainty degree, they are considered as the key processes for mitigating carbon footprint.

The key processes of the life-cycle carbon footprint for prefabricated buildings are identified at three levels and the results are shown in Fig. 7.

At the construction materials level, the cut off value is set at 20 % for both the contribution degree and uncertainty degree due to the significant share of building materials in total carbon footprint. Fig. 7 illustrates that cast-in-place concrete is the sole kind of building material that the contribution degree surpasses the uncertainty degree. In other words, cast-in-place concrete is the key process for mitigating carbon footprint at the construction materials level. On the other hand, precast concrete, brick, and mortar fall within the area of non-significant impact. Materials such as glass, cement, wood, and steel are in the area where the uncertainty degree outweighs the contribution degree. This phenomenon can be contributed to the distinct system boundaries for calculating the carbon footprint factors of these materials. Notably, steel has a high contribution and uncertainty degree, indicating a great potential to become a key factor once its uncertainty is mitigated.

At the prefabricated component level, the cut off value for both the contribution degree and the uncertainty degree is set at 10 %. According

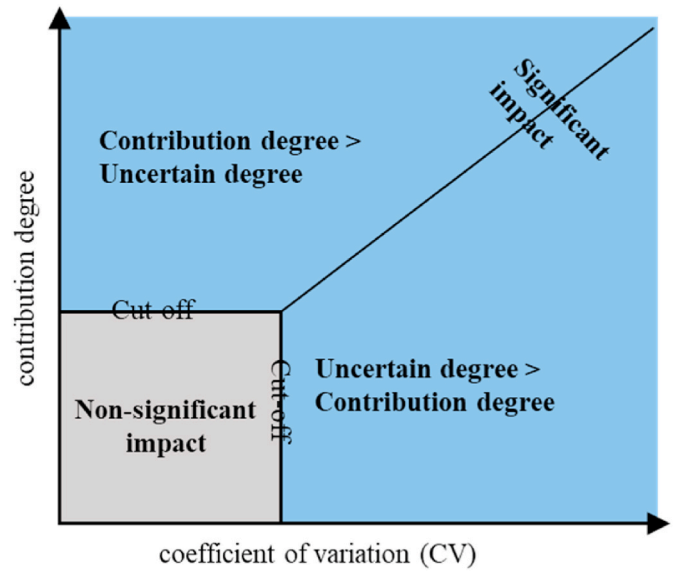


Fig. 6. A dual indicator approach for identifying the key processes.

to Fig. 7, all four types of prefabricated components fall within the area where the uncertainty degree exceeds the contribution degree. The finding is primarily attributed to the large uncertainties in the recycling processes for concrete and steel within these components. ALC precast wall panel has a low uncertainty degree, while their contribution degree is the lowest. Precast columns have a low contribution to the total carbon footprint. In contrast, precast beams and laminated slabs display higher contributions and uncertainties due to their large use and recycling. Moreover, the assembly rate and assembly scheme significantly impact the usage of prefabricated components. Consequently, the importance of prefabricated components in carbon footprint is closely associated with their recycling ratios as well as the assembly ratio of the building. It is important to note that the results and discussions presented in this paper are limited to frame structures. For prefabricated buildings with different structural types, such as assembled monolithic shear wall structures and assembled steel structures, separate discussions should be conducted to assess their impacts on the carbon footprint.

At the life-cycle stages level of prefabricated buildings, cut-off values of 20 % for both the contribution degree and uncertainty degree are set. The on-site construction stage (A5-6) and factory production stage (A3) fall within the area of non-significant impact. The building material production and transportation stages (A1-2) are in the area where the contribution impact exceeds the uncertainty impact. Therefore, the

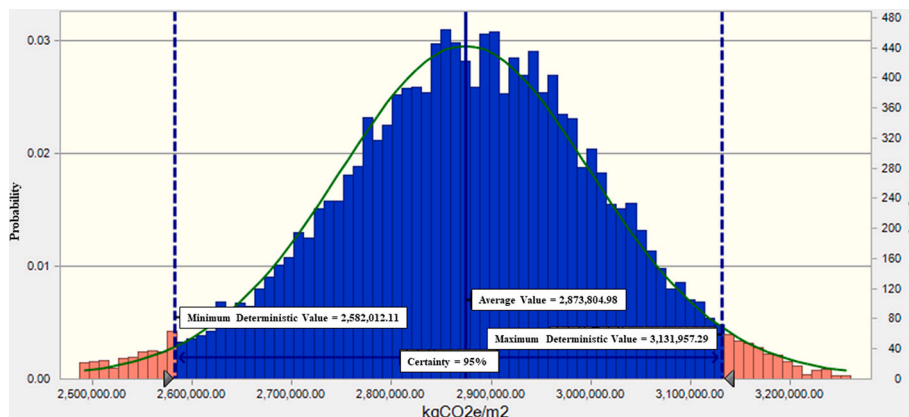


Fig. 5. Uncertainty analysis results of the studied case.

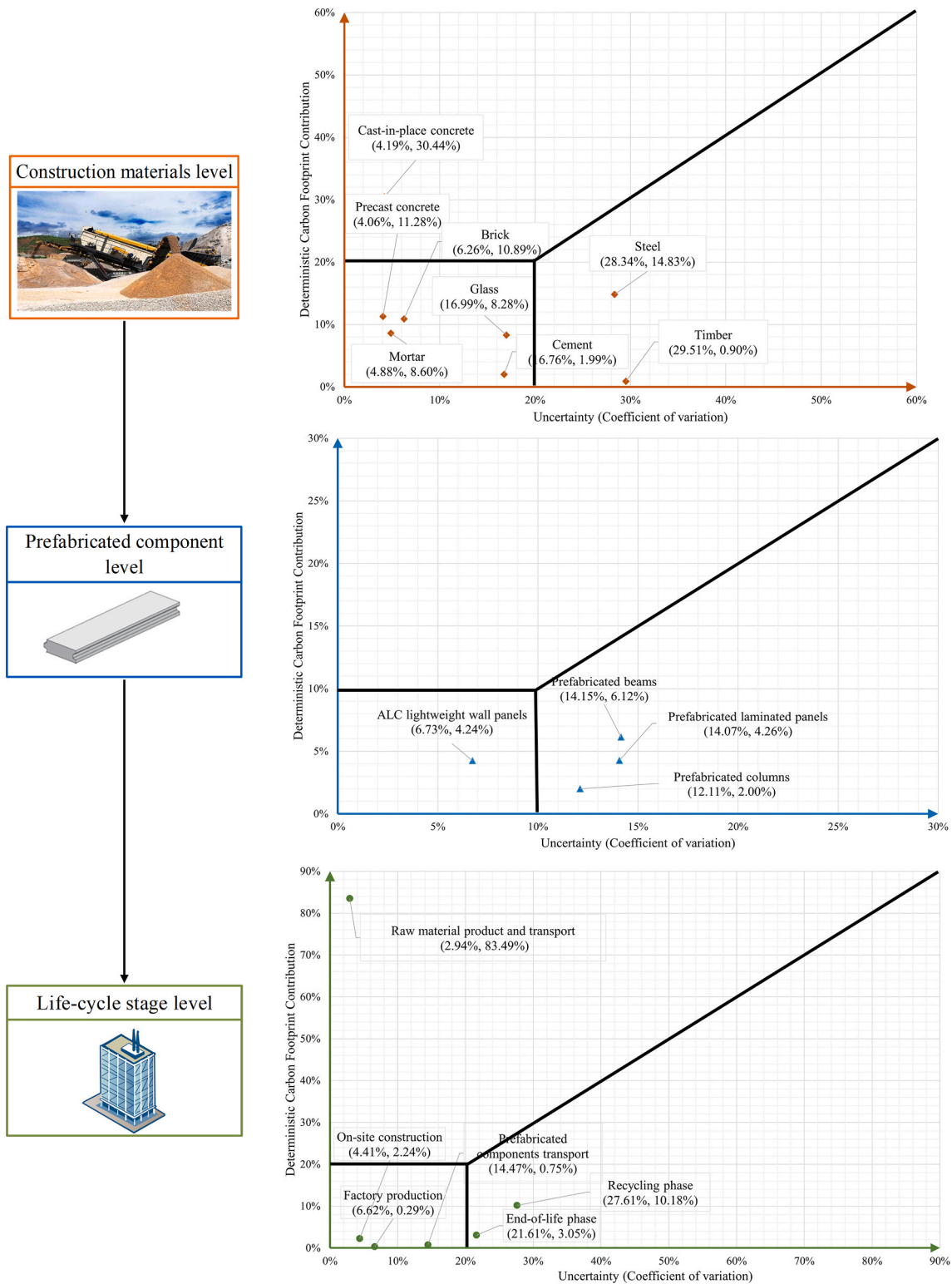


Fig. 7. Key processes based on the three levels of the dual indicators.

production of building materials is the key process to achieve energy savings and emission reductions. However, the transportation stage of prefabricated components (A4), the end-of-life phase of the building (C), and the recycling phase (D) fall within the region where the degree of uncertainty is greater than the contribution. The end-of-life and recycling phases exhibit significantly higher degrees of uncertainty compared to their contribution degrees. Therefore, it is crucial to pay attention to the reliability of data in the end-of-life and recycling phase.

6. Implications

Building upon the results and discussion, several implications can be drawn regarding the quantification methods for accurately and efficiently accounting for the carbon footprints of prefabricated buildings.

6.1. Adapting system boundaries to match the characteristics of prefabricated buildings

The system boundaries of the life-cycle carbon footprint accounting for buildings need to match the construction characteristics of prefabricated buildings. Specifically, the production and transportation stages of prefabricated components should be evaluated separately due to the complex processes. Furthermore, it is important to incorporate the demolition of building materials at the end-of-life phase, and to include the recycling of building parts in the system boundary. Therefore, the demolition and recycling phases should be differentiated at the end of the building's lifespan. Moreover, it is advisable to establish unified parameters and calculation frameworks for the end-of-life and the recycling phase of prefabricated buildings to mitigate the influence of uncertainty, considering the actual engineering context. In practice, the carbon footprint of operational stage can be included according to the requirements.

6.2. Improving accounting methods to enhance the effectiveness of accounting outcomes

Quantifying the carbon footprint of buildings is a data-intensive process that may involve incomplete or inaccurate information. To improve the effectiveness and reliability of accounting results, uncertainty analysis is required for the accounting of life-cycle carbon footprint. Specifically, it is important to establish evaluation criteria for data quality before the accounting process. For instance, when utilizing data from similar types of buildings, regions, or sources, uniform evaluation criteria should be adopted to minimize the evaluation differences. Moreover, selecting an appropriate uncertainty model is crucial to enhance the validity of calculation results.

Furthermore, the life-cycle carbon footprint accounting involves a large number of processes, building components and materials. Concentrating on key processes and elements could save assessment time and simplify the assessment process while keeping a high accurate result. It is advised to employ the proposed dual indicator approach to identify the key processes of the life-cycle carbon footprint accounting of prefabricated buildings. This integrated analysis approach enhances the reliability of the evaluated carbon footprint.

6.3. Building an inventory database for the carbon footprint of prefabricated components

A detailed assessment of the carbon footprint per unit for each type of prefabricated component could be conducted to improve the accuracy of the accounting results. This allows for the establishment of a comprehensive carbon footprint list and creation a carbon footprint factor library with prefabricated components as the fundamental database. By multiplying the quantities of prefabricated building components by their corresponding carbon footprint factors, the carbon footprint of prefabricated parts can be easily assessed.

Considering the wide variety of prefabricated components, it is advisable to develop specialized software for the evaluation of carbon footprints in prefabricated buildings. This software can provide accurate calculations and feedback on carbon footprint data, particularly in the architectural design stage where the selection of prefabricated components plays a significant role.

7. Conclusion

This study developed a framework for life-cycle carbon footprint accounting of prefabricated buildings from the circular economy perspective. A case study was used for empirical analysis, the uncertainty analysis of the accounting process was conducted, and key processes were identified using the dual-indicator approach of contribution and uncertainty degree.

The results revealed that in terms of the time dimension, the embodied stage had the largest carbon footprint contribution. In spatial terms, the carbon footprint outside the construction site accounted for approximately 96.07 % of the total life-cycle carbon footprint. From the perspective of building composition, prefabricated beams had the highest carbon footprint, accounting for 36.81 % of the total carbon footprint. The uncertainty analysis results indicated that the established accounting framework is effective. Moreover, cast-in-place concrete was identified as a key process for mitigating carbon footprint at the construction materials level. At the life-cycle stage level, the building material production and transportation stages were the key process. Finally, recommendations were proposed for improving life-cycle carbon footprint accounting of prefabricated buildings. These recommendations include adapting system boundaries to match the construction characteristics of prefabricated buildings, improving accounting methods to enhance the effectiveness of accounting outcomes, and building an inventory database of carbon footprint for prefabricated components.

Two limitations exist in this study: first, only major building materials were considered in the carbon footprint accounting. Moreover, this study focused solely on the carbon footprint of prefabricated frame structures and did not include other structural types. Future work will be focused on a comprehensive and dynamic carbon footprint factor database to overcome data limitations and ensure accuracy. Moreover, the research scope should be expanded to include different structural types of prefabricated buildings. Furthermore, future studies should incorporate the operational stage and examine the carbon footprint balance across different life cycle stages.

Nevertheless, this research establishes a framework for assessing the life-cycle carbon footprint of prefabricated buildings, contributing to the theoretical and empirical basis of circular economy implementation in this sector. Through a three-level analysis and dual indicators, this study identifies key processes influencing carbon footprint, offering crucial insights for informed decision-making in emission reduction strategies for prefabricated buildings. Furthermore, this research offers practical suggestions to enhance carbon footprint accounting for prefabricated buildings in the context of circular economy. These recommendations not only address current challenges but also contribute to advancing sustainability efforts in the construction industry.

CRediT authorship contribution statement

Clyde Zhengdao Li: Supervision, Conceptualization. **Vivian WY. Tam:** Supervision. **Xulu Lai:** Writing – original draft, Methodology, Data curation. **Yijun Zhou:** Writing – review & editing, Writing – original draft. **Shan Guo:** Writing – review & editing.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work the author(s) used ChatGPT in order to improve readability and language. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the publication.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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Appendix A. Results of life-cycle carbon footprint of the case study

Table A-1
Carbon footprint in the production process of cast-in-place building materials

Category	Cast-in-place materials	Unit	Amount	Carbon footprint factor (kgCO ₂ e/unit)	Carbon footprint (kgCO ₂ e)	Proportion of the carbon footprint generated in A1-A2
Raw Materials	Water	t	2885.04	0.17	484.69	1.35 %
	Gravel	t	504.21	2.18	1099.17	
	Sand	t	173.60	2.51	435.74	
	Wood	m ³	47.09	644.00	30328.04	
Cement	Cement (32.5)	t	55.56	604.00	32259.64	2.33 %
	Cement (42.5)	t	33.84	702.00	23755.68	
Mortar	Dry-mix floor mortar (M15)	m ³	150.60	426.34	64207.09	9.71 %
	Dry-mix floor mortar (M20)	m ³	7.22	503.30	3634.06	
	Dry-mix plastering mortar (M5)	m ³	182.84	271.15	49578.40	
	Dry-mix plastering mortar (M15)	m ³	167.06	426.34	71225.69	
	Dry-mix plastering mortar (M20)	m ³	28.38	503.30	14283.07	
	Dry-mix masonry mortar (M5)	m ³	181.00	141.34	25582.97	
	Dry-mix masonry mortar (M7.5)	m ³	5.03	157.04	789.61	
	Polymer cement waterproof mortar	m ³	5.34	367.03	1958.64	
	Anti-cracking mortar (according to plaster M10)	m ³	5.34	367.03	1958.64	
Concrete	C10	m ³	14.50	135.30	1962.39	33.71 %
	C15	m ³	238.13	166.55	39660.55	
	C20	m ³	274.47	208.98	57358.11	
	C25	m ³	277.33	247.46	68627.59	
	C30	m ³	1487.50	277.82	413258.08	
	C35	m ³	219.47	314.77	69082.57	
	C40	m ³	74.29	348.04	25855.89	
	Light Aggregate Concrete	m ³	336.57	260.92	87818.11	
	P6 waterproof concrete	m ³	198.54	231.92	46044.93	
Steel	Small section steel	t	10.92	2310	25229.82	23.35 %
	Medium section steel	t	4.55	2365	10765.48	
	Wires	t	9.74	2375	23132.50	
	Reinforcing Steel	t	205.61	2340	481122.60	
	Steel Pipe	t	6.48	3150	20412.00	
Other Metals	Iron Products	t	9.89	1920	18994.56	2.65 %
	Aluminum alloy	t	2.88	15,450	44547.15	
Bricks and Blocks	Thick-walled sintered hollow brick	m ³	352.47	250	88117.50	11.85 %
	Shale porous brick	m ³	422.59	215	90856.85	
	Shale hollow bricks	m ³	36.17	204	7379.09	
	Shale solid bricks	m ³	106.74	292	31168.08	
	Broken bricks	m ³	227.32	295	67058.52	
Thermal insulation	Polystyrene insulation	t	10.63	4620	49130.56	2.05 %
Waterproof	SBS modified asphalt waterproofing membrane	m ²	513.02	1.85	949.09	0.13 %
	Adhesive polyester tire modified asphalt waterproofing membrane	m ²	1194.52	1.85	2209.87	
Windows	Aluminum alloy thermal bridge window	m ²	813.41	194	157801.35	7.77 %
	Aluminum alloy heat-break bridge doors and windows	m ²	148.02	194	28715.30	
Glass	Tempered Glass	t	11.02	1790	19725.80	2.15 %
	low-E glass	t	15.82	2010	31798.20	
Painted coatings	Coatings	t	13.42	3550	47630.35	2.91 %
	Paint	t	6.27	3550	22258.50	
Total carbon footprint value: 2401551.72 kgCO ₂ e, carbon footprint per square meter: 355.04 kgCO ₂ e/m ²						

Table A-2
Carbon footprint in the production process of prefabricated building materials

Type of prefabricated components	Prefabricated materials	Unit	Amount	Carbon footprint factor (kgCO ₂ e/unit)	Carbon footprint (kgCO ₂ e)
Prefabricated columns	Concrete C35	m ³	30.45	314.77	9584.7465
	Concrete C45	m ³	60.94	390.16	23776.3504
Prefabricated beams	Reinforcing Steel	t	13.7085	2340	32077.89
	Concrete C30	m ³	325.21	277.82	90349.8422
Prefabricated laminated panels	Reinforcing Steel	t	48.7815	2340	114148.71
	Concrete C30	m ³	224.8	277.82	62453.936
ALC prefabricated wall panels	Reinforcing Steel	t	33.72	2340	78904.8
	Steam Pressurized Concrete	m ³	622.267	166.026124	103312.5781
Steel formwork	Steel formwork	t	0.156273	2310	360.9912075
Total carbon footprint value: 514969.84 kgCO ₂ e, carbon footprint per square meter: 76.13 kgCO ₂ e/m ²					

Table A-3
Carbon footprint produced by the transportation process of building materials

Process	Materials	Weight (t)	Shipping distance (km)	Shipping Method	Carbon footprint factor kg CO ₂ e/t km	Carbon Footprint (kg CO ₂ e)
Building material transportation (to construction site)	Gravel	504.21	43	Diesel truck (heavy duty 10t)	0.27	5865.56
	Sand	173.60	43	Diesel truck (heavy duty 10t)	0.27	2019.56
	Wood	28.26	20	Diesel truck (heavy duty 18t)	0.22	121.74
	Cement	89.40	10	Diesel trucks (heavy duty 30t)	0.13	116.45
	Mortar	1465.63	16	Diesel truck (heavy duty 18t)	0.22	5051.83
	Concrete	7328.37	18	Diesel truck (heavy duty 18t)	0.22	28417.51
	Reinforcing Steel	205.61	424	Diesel trucks (heavy duty 30t)	0.13	11355.78
	Other Steel	31.69	424	Diesel trucks (heavy duty 30t)	0.13	1750.47
	Other Metals	12.78	14	Diesel truck (heavy duty 18t)	0.22	38.53
	Brick	2063.91	33	Diesel truck (heavy duty 10t)	0.27	18426.23
	Thermal insulation	10.63	35	Diesel truck (heavy duty 10t)	0.27	100.70
	Waterproof	25.30	13	Diesel truck (heavy duty 10t)	0.27	88.98
	Windows	13.76	50	Diesel truck (heavy duty 18t)	0.22	148.22
Building material transportation (to prefabrication site)	Glass	26.84	17	Diesel trucks (heavy duty 30t)	0.13	59.44
	Coatings	13.42	24	Diesel truck (heavy duty 10t)	0.27	87.12
	Paint	6.27	14	Diesel truck (heavy duty 10t)	0.27	23.75
	Concrete	1539.36	54	Diesel truck (heavy duty 18t)	0.22	17907.71
	Reinforcing Steel	96.21	416	Diesel trucks (heavy duty 30t)	0.13	5213.44
	Steam Pressurized Concrete	311.13	16	Diesel trucks (heavy duty 30t)	0.13	648.45
	Total carbon footprint value: 97441.47 kgCO ₂ e, carbon footprint per square meter: 14.41 kgCO ₂ e/m ²					

Table A-4: Calculation process and results of carbon footprint in factory production stage

Process	Type of prefabricated components	Total shifts (shifts)	Unit shift consumption (kwh/shift)	Carbon footprint factor (kg CO ₂ e/kwh)	Carbon footprint (kg CO ₂ e)
Prefabricated component production	Prefabricated columns	3.27	288	0.432	406.43
	Prefabricated beams	12.27	288	0.432	1526.17
	Prefabricated laminated panels	4.50	608	0.432	1180.90
	ALC Lightweight Wall Panel	3.83	640	0.432	1058.59
Process	Type of prefabricated components	Total shift consumption (shifts)	Unit shift consumption (kg/shift)	Carbon footprint factor (kg CO ₂ e/kg)	Carbon footprint (kg CO ₂ e)

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Process	Type of prefabricated components	Total shifts (shifts)	Unit shift consumption (kwh/shift)	Carbon footprint factor (kg CO ₂ e/kwh)	Carbon footprint (kg CO ₂ e)
On-site transportation	Prefabricated columns	4.20	45.39	3.11	593.44
	Prefabricated beams	14.96	45.39	3.11	2111.75
	Prefabricated laminated panels	10.34	45.39	3.11	1459.74
	ALC Lightweight Wall Panel	19.29	35.49	3.11	2129.14
Total carbon footprint value: 10466.15 kgCO ₂ e, carbon footprint per square meter: 1.55 kgCO ₂ e/m ²					

Table A-5

Carbon footprint of vertical transportation of prefabricated components

Process	Type of prefabricated components	Transportation machinery	Total shift consumption (shifts)	Unit shift consumption (kwh/shift)	Carbon footprint factor (kg CO ₂ e/kg)	Carbon footprint (kg CO ₂ e)
Vertical Transportation	Prefabricated columns	Truck-mounted crane 30t	6.85	42.14	3.11	898.29
	Prefabricated beams	Truck-mounted crane 30t	24.39	42.14	3.11	3196.54
	Prefabricated laminated panels	Truck-mounted crane 30t	16.86	42.14	3.11	2209.59
	ALC Lightweight Wall Panel	Truck-mounted crane 12t	34.85	30.55	3.11	3310.83
Total carbon footprint value: 9615.25 kgCO ₂ e, carbon footprint per square meter: 1.42 kgCO ₂ e/m ²						

Table A-6

Carbon footprint of horizontal transportation of prefabricated components

Process	Type of prefabricated components	Weight (t)	Shipping Method	Shipping distance (km)	Carbon footprint factor (kg CO ₂ e/t-km)	Carbon footprint (kg CO ₂ e)
Horizontal Transportation	Prefabricated columns	233.04	Diesel trucks (heavy duty 30t)	75	0.13026	2276.73
	Prefabricated beams	829.29	Diesel trucks (heavy duty 30t)	75	0.13026	8101.70
	Prefabricated laminated panels	573.24	Diesel trucks (heavy duty 30t)	75	0.13026	5600.27
	ALC Lightweight Wall Panel	311.13	Diesel truck (heavy duty 10t)	24	0.21543	1608.66
Total carbon footprint value: 17587.36 kgCO ₂ e, carbon footprint per square meter: 2.60 kgCO ₂ e/m ²						

Table A-7

Carbon footprint of the on-site construction phase

No.	Construction Machinery	Total shift consumption (shifts)	Resources consumption (kwh/shift) or (kg/shift)	Carbon footprint factor (kgCO ₂ e/kg) or kgCO ₂ e/kwh	Carbon footprint (kgCO ₂ e)
1	Crawler bulldozer 75kw	17.52	56.5	3.11	3078.09
2	Crawler type single bucket hydraulic excavator 1.5m ³	8.86	93	3.11	2563.39
3	Electric tamper 250N-m	184.22	16.6	0.432	1321.08
4	Outbound diesel	1593.70	1	3.11	4956.41
5	Electric air compressor 10m ³ /min	8.26	403.2	0.432	1438.22
6	Concrete wet spraying machine 5m ³ /h	8.66	15.4	0.432	57.61
7	Mortar mixer 200 L	23.37	8.61	0.432	86.94
8	Electric grouting machine	21.53	32	0.432	297.68
9	Hydraulic drilling rig for engineering geology	65.63	30.8	3.11	6286.60
10	Dry mortar tank mixer	93.30	28.51	0.432	1149.17
11	Electricity	957.93	1	0.432	413.83
12	Concrete smoothing machine	10.48	23.14	0.432	104.74
13	Rebar straightening machine 40 mm	18.25	41.6	0.432	327.98
14	Steel bar cutting machine 40 mm	19.50	32.1	0.432	270.41
15	Steel bending machine 40 mm	39.94	12.8	0.432	220.85
16	DC arc welding machine 32kVA	47.97	136	0.432	2818.62
17	Butt welding machine 75kVA	8.68	122	0.432	457.32
18	Welding rod drying box 45 × 35*45 cm	4.79	6.7	0.432	13.88
19	Truck-mounted crane 20t	11.56	38.41	3.11	1381.15
20	AC arc welding machine 32kVA	88.92	96.53	0.432	3708.05

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Table A-7 (continued)

No.	Construction Machinery	Total shift consumption (shifts)	Resources consumption (kwh/shift) or (kg/shift)	Carbon footprint factor (kgCO ₂ e/kg) or kgCO ₂ e/kwh	Carbon footprint (kgCO ₂ e)
21	Truck-mounted crane 8t	8.60	28.43	3.11	760.64
22	AC arc welding machine 21kVA	5.06	60.27	0.432	131.73
23	Metal surface polishing machine	21.36	16	0.432	147.61
24	Pipe cutting machine 150 mm	32.20	12.9	0.432	179.44
25	Argon arc welding machine 500 A	13.49	70.7	0.432	411.89
26	Double Cone Reverse Discharge Concrete Mixer 200 L	1.12	55.4	0.432	26.80
27	Load car 6t	23.23	33.24	3.11	2401.10
28	Woodworking circular sawing machine 500 mm	5.25	24	0.432	54.41
29	Electric single drum fast winch 5 KN	203.97	32.9	0.432	2898.92
30	Tower crane QTP125 (6513)	149.95	280	0.432	18137.75
31	Truck-mounted crane 40t	5	48.52	3.11	754.49
32	Truck load 8t	8	35.49	3.11	882.99
33	Load car 15t	4	56.74	3.11	705.85
34	Flatbed trailer set 40t	3	45.39	3.11	423.49
35	Concrete conveying pump 90m ³ /h	15.85	450	0.432	3082.15

Total carbon footprint value: 61951.3 kgCO₂e, carbon footprint per square meter: 9.16 kgCO₂e/m²

Table A-8

Carbon footprint produced by the operation of temporary facilities on site

Temporary Facilities	Area (m ²)	Lighting energy consumption coefficient (kw/m ²)	Lighting time (h)	Heating energy consumption coefficient (kw)	Heating time (h)	Refrigeration energy consumption coefficient (kw)	Cooling time (h)	Total power consumption (kwh)
Office area	80	0.018	2776	4.8	696	4.8	539	9925.44
Dormitory	150	0.006	1635	12	696	12	539	16291.5
Canteen	90	0.013	3470	-	-	-	-	4059.9
Restrooms	10	0.006	1388	-	-	-	-	83.28

Total electricity consumption: 30,360.12kwh, total carbon footprint: 13,115.57 kgCO₂ e, carbon footprint per square meter: 1.94 kgCO₂e/m²

Table A-9

Carbon footprint of the lifting process of prefabricated components

Process	Type of prefabricated components	Quantity (pcs)	Lifting time	Lifting machinery power (kw)	Carbon footprint factor (kgCO ₂ e/kwh)	Carbon footprint (kgCO ₂ e)
Lifting to the designated position	Prefabricated columns	98	0.2 h	35	0.432	296.35
	Prefabricated beams	368	0.25 h	35	0.432	1391.04
	Prefabricated laminated panels	603	0.2 h	35	0.432	1823.47
	ALC Lightweight Wall Panel	486 (3 pieces lifted together)	0.2 h	35	0.432	1468.66

Total carbon footprint value: 4980.53 kgCO₂e, carbon footprint per square meter: 0.74 kgCO₂e/m²

Table A-10

Carbon footprint produced by the installation process of prefabricated components

Process	Type of prefabricated components	Machinery	Head Office Shift	Unit shift consumption (kwh/shift)	Carbon footprint factor (kgCO ₂ e/kwh)	Carbon footprint (kgCO ₂ e)	
Installation process	Prefabricated columns Prefabricated beams Prefabricated laminated panels ALC Lightweight Wall Panel	Initial design: Sleeve grouting Wet connection					
		Plate cutting machine	53.81	17.6	0.432	409.15	
		Impact Drill	18.88	4	0.432	32.63	
		Reaming Drill	12.59	6	0.432	32.63	
		AC arc welding machine 40kv-A	3.93	132.23	0.432	224.71	

Total carbon footprint value: 699.11 kgCO₂e, carbon footprint per square meter: 0.10 kgCO₂e/m²

Table A-11
Carbon footprint produced by transporting building materials waste to the disposal site

Material Category	Dismantling weight (t)	Recycling ratio	Remaining landfill volume (t)	Transportation distance (km)	Carbon footprint factor (kgCO ₂ e/kg)	Carbon footprint (kgCO ₂ e)
Concrete	9178.86	0.55	4130.49	30	0.21543	26694.93
Bricks and Blocks	2063.91	0.55	1000.37	30	0.21543	6465.31
Mortar	1465.63	–	1465.63	30	0.21543	9472.19
Reinforcing Steel	333.51	0.6	133.40	30	0.21543	862.18
Iron	9.89	0.9	0.99	30	0.21543	6.39
Aluminum	3.78	0.85	0.57	30	0.21543	3.66
Glass	26.84	0.1	24.16	30	0.21543	156.12
Wood	28.26	0.4	28.11	30	0.21543	181.66
Other Materials	856.39	–	818.35	30	0.21543	5288.90
Total carbon footprint value: 48842.32 kgCO ₂ e, carbon footprint per square meter: 7.22 kgCO ₂ e/m ²						

Table A-12
Carbon footprint from processing building material waste

Material Category	Recovery weight (t)	Crude oil consumption for processing (kg)	Carbon footprint factor (kgCO ₂ e/kg)	Raw coal consumption for processing (kg)	Carbon footprint factor (kgCO ₂ e/kg)	Carbon footprint (kgCO ₂ e)
Concrete	5048.37	17119.04	3.03	1989.06	1.99	55828.91
Bricks and Blocks	1135.15	3849.3	3.03	447.25	1.99	12553.40
Reinforcing Steel	200.11	678.56	3.03	78.84	1.99	2212.94
Iron	8.90	30.19	3.03	3.51	1.99	98.46
Aluminum	3.21	10.90	3.03	1.27	1.99	35.53
Glass	2.68	9.10	3.03	1.06	1.99	29.68
Wood	11.3	38.33	3.03	4.45	1.99	124.99
Total carbon footprint value: 70883.92 kgCO ₂ e, carbon footprint per square meter: 10.47 kgCO ₂ e/m ²						

Table A-13
Carbon reduction from reusing building materials

Material Category	Recycling weight (t)	Amount in corresponding unit	Recycling methods	Types of materials after recycling	Carbon footprint factor (kgCO ₂ e/unit)	Carbon footprint (kgCO ₂ e)	Carbon reduction share
Concrete	5048.37	2103.49 m ³	Various raw materials for recycled concrete	Recycled aggregates	13	27345.36	6.26 %
Bricks and Blocks	1135.15	667.74 m ³	Crushing as recycled aggregates	Recycled aggregates	13	8680.57	1.99 %
Reinforcing Steel	200.11	200.11t	Recycling of scrap steel into high quality furnace material	Crude steel (converter carbon steel)	1900	380203.68	87.06 %
Iron	8.90	8.90t	Scrap iron products recycled into high quality furnace material	Steelmaking pig iron	1700	15136.29	3.47 %
Aluminum	3.21	3.21t	Re-melting and refining of scrap aluminum	Recycled Aluminum	730	2345.49	0.54 %
Glass	2.68	2.68t	Waste glass combined with bricks and ceramics as decorative materials	Decorative recycled aggregates	13	34.89	0.01 %
Wood	11.30	18.84 m ³	Waste wood is used as raw material for wood-plastic composites, or crushed and processed into artificial boards	Material of man-made board (wood)	158.5	2985.71	0.68 %
Total carbon footprint value saved: 436,732 kgCO ₂ e, unit carbon footprint: 64.57 kgCO ₂ e/m ²							

Appendix B. Correspondence between Data Quality Scores of quantity-take offs and Characteristics Parameters of Log-Normal Distribution

stages	Data	data source	data reliability	representativeness of geography	representativeness of skills	representativeness of timing	CVa ²	CVb ²	Geometric standard deviation (σ _b)
A1- A2	Water (quantity for engineering)	4	3	4	4	5	0.003	0.0006	1.108

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stages	Data	data source	data reliability	representativeness of geography	representativeness of skills	representativeness of timing	CVa ²	CVb ²	Geometric standard deviation (σ_b)
	Crushed stone (quantity for engineering)	4	3	4	4	5	0.003	0.0006	1.108
	Sand (quantity for engineering)	4	3	4	4	5	0.003	0.0006	1.108
	Wood (composite formwork)	2	2	3	3	5	0.018	0.0006	1.275
	Cement (quantity for engineering)	4	3	4	4	5	0.003	0.0006	1.108
	Mortar (quantity for engineering)	4	3	4	4	5	0.003	0.0006	1.108
	Concrete (quantity for engineering)	4	3	4	4	5	0.003	0.0006	1.108
	Rebar (quantity for engineering)	4	3	4	4	5	0.003	0.0006	1.108
	Other steel materials (quantity for engineering) - including scaffolding	4	2	4	4	5	0.009	0.0006	1.188
	Other metals (quantity for engineering)	4	2	4	4	5	0.009	0.0006	1.188
	Bricks (quantity for engineering)	4	3	4	4	5	0.003	0.0006	1.108
	Insulation materials (quantity for engineering)	4	2	4	4	5	0.009	0.0006	1.188
	Waterproofing materials (quantity for engineering)	4	3	4	4	5	0.003	0.0006	1.108
	Glass (quantity for engineering)	4	2	4	4	5	0.009	0.0006	1.188
	Paint and coatings (quantity for engineering)	4	3	4	4	5	0.003	0.0006	1.108
	Concrete	4	3	4	4	5	0.003	0.0006	1.108
	Rebar	4	2	4	4	5	0.009	0.0006	1.188
	Steel (formwork)	2	2	3	3	5	0.018	0.0006	1.275
	Transport distance	4	4	4	0	5	0.001	0.0006	1.067
A3	Precast column production line	4	3	3	3	5	0.010	0.0006	1.203
	Precast beam production line	4	3	3	3	5	0.010	0.0006	1.203
	Precast composite board production line	4	3	3	3	5	0.010	0.0006	1.203
	Equipment consumption for shift (estimated)	3	2	3	3	5	0.017	0.0006	1.264
	Consumption of production machinery	3	3	2	2	5	0.044	0.0006	1.449
	Consumption of production machinery - ALC lightweight wall panels	3	4	3	3	5	0.009	0.0006	1.194
	Electricity consumption for shift - ALC lightweight wall panels	3	4	3	3	5	0.009	0.0006	1.194
	Fuel consumption for shift	3	3	2	3	5	0.011	0.0006	1.214
	On-site transportation machinery consumption - diesel consumption	3	3	2	3	4	0.012	0.0006	1.216
A4	Transport distance	4	4	4	0	5	0.001	0.0006	1.067
	Vertical transportation machinery consumption (electricity consumption)	3	3	2	3	4	0.012	0.0006	1.216
A5	Electricity consumption of on-site construction machinery and equipment (calculated based on quota)	4	3	2	3	5	0.011	0.0006	1.208
	Electricity consumption for shift - national database	3	3	2	3	5	0.011	0.0006	1.214
	Diesel consumption of on-site construction machinery and equipment	4	3	2	3	5	0.011	0.0006	1.208
	Fuel consumption for shift	3	3	2	3	5	0.011	0.0006	1.214
	Time, coefficient	2	2	3	3	4	0.019	0.0006	1.277
	Electricity consumption of temporary facilities (estimated)	3	3	3	3	5	0.011	0.0006	1.208
A6	Number of precast columns	4	3	4	4	5	0.003	0.0006	1.108
	Number of precast beams	4	3	4	4	5	0.003	0.0006	1.108
	Number of precast composite boards	4	3	4	4	5	0.003	0.0006	1.108

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stages	Data	data source	data reliability	representativeness of geography	representativeness of skills	representativeness of timing	CVa ²	CVb ²	Geometric standard deviation (σ_b)
C1	Number of ALC lightweight wall panels	2	2	4	4	5	0.011	0.0006	1.208
	Hoisting time (reference to other projects in Shenzhen)	3	3	2	3	5	0.011	0.0006	1.214
	Installation machinery consumption for ALC lightweight wall panels	4	3	2	3	5	0.011	0.0006	1.208
	Coefficient	3	2	2	2	4	0.051	0.0006	1.487
	Carbon footprint (calculated based on empirical ratios) - construction + assembly	4	2	4	4	5	0.009	0.0006	1.188
C2	Generation of construction waste	4	2	2	3	4	0.017	0.0006	1.265
D	Transport distance	4	4	4	0	5	0.001	0.0006	1.067
	Consumption of crude oil for material recycling and processing	3	3	2	3	5	0.011	0.0006	1.214
	Consumption of raw coal for material recycling and processing	3	3	2	3	5	0.011	0.0006	1.214
	Corresponding recycled materials - recycled aggregates	3	2	2	3	5	0.018	0.0006	1.268
	Corresponding recycled materials - coarse steel	3	2	2	3	5	0.018	0.0006	1.268
	Corresponding recycled materials - pig iron	3	2	2	3	5	0.018	0.0006	1.268
	Corresponding recycled materials - recycled aluminum	3	2	2	3	5	0.018	0.0006	1.268
	Corresponding recycled materials - wood	3	2	2	3	5	0.018	0.0006	1.268

Appendix C. Correspondence between Data Quality Scores of Carbon Footprint Factors and Characteristics Parameters of Log-Normal Distribution

Stages	Carbon Footprint Factors	data source	data reliability	representativeness of geography	representativeness of skills	representativeness of timing	CVa ²	CVb ²	Geometric standard deviation (σ_b)	
A1	Water (based on CLCD)	4	3	2	3	5	0.011	0.0006	1.208	
-A2	Crushed stone (based on CLCD)	4	3	2	3	5	0.011	0.0006	1.208	
	Sand (based on CLCD)	4	3	2	3	5	0.011	0.0006	1.208	
	Wood (literature)	3	2	2	2	4	0.051	0.0006	1.487	
	Cement (literature)	3	2	2	2	4	0.051	0.0006	1.487	
	Mortar (based on quota revision)	4	4	3	4	4	0.002	0.0006	1.088	
	Concrete (based on quota revision)	4	4	3	4	4	0.002	0.0006	1.088	
	Rebar (based on CLCD)	4	3	2	3	5	0.011	0.0006	1.208	
	Other steel materials (based on CLCD)	4	3	2	3	5	0.011	0.0006	1.208	
	Other metals (literature)	3	2	2	2	4	0.051	0.0006	1.487	
	Bricks (based on CLCD)	4	3	2	3	5	0.011	0.0006	1.208	
	Insulation materials (based on CLCD)	4	3	2	3	5	0.011	0.0006	1.208	
	Waterproofing materials (literature)	3	2	2	2	4	0.051	0.0006	1.487	
	Glass (literature)	3	2	2	2	4	0.051	0.0006	1.487	
	Paint and coatings (literature)	3	2	2	2	4	0.051	0.0006	1.487	
	Concrete (based on quota revision)	4	4	3	4	4	0.002	0.0006	1.088	
	Rebar (based on CLCD)	4	3	2	3	5	0.011	0.0006	1.208	
	Steel (based on CLCD)	4	3	2	2	5	0.044	0.0006	1.446	
	Transport mode (based on CLCD revision)	5	4	2	4	4	0.002	0.1275	1.856	
	A3	Electricity consumption of production machinery (revised calculation)	5	4	3	4	5	0.001	0.0006	1.081

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Stages	Carbon Footprint Factors	data source	data reliability	representativeness of geography	representativeness of skills	representativeness of timing	CVa ²	CVB ²	Geometric standard deviation (σ_b)
A4	On-site transportation machinery consumption - diesel consumption (revised calculation)	5	4	2	4	5	0.002	0.0006	1.092
	Transport mode (based on CLCD revision)	5	4	2	4	4	0.002	0.1275	1.856
	Vertical transportation machinery - electricity consumption (revised calculation)	5	4	3	4	5	0.001	0.0006	1.081
A5	Electricity consumption of on-site construction machinery and equipment (revised calculation)	5	4	3	4	5	0.001	0.0006	1.081
	Diesel consumption of on-site construction machinery and equipment (revised calculation)	5	4	2	4	5	0.002	0.0006	1.092
	Electricity consumption of temporary facilities (revised calculation)	5	4	3	4	5	0.001	0.0006	1.081
A6	Electricity consumption	5	4	3	4	5	0.001	0.0006	1.081
C	Transport mode (based on CLCD revision)	5	4	2	4	4	0.002	0.1275	1.856
D	Crude oil consumption for material recycling and processing (revised calculation)	5	4	2	4	5	0.002	0.0006	1.092
	Raw coal consumption for material recycling and processing (revised calculation)	5	4	2	4	5	0.002	0.0006	1.092
	Corresponding recycled materials - recycled aggregates (literature)	3	2	2	2	4	0.051	0.0006	1.487
	Corresponding recycled materials - coarse steel (literature)	3	2	2	2	4	0.051	0.0006	1.487
	Corresponding recycled materials - pig iron (based on CLCD)	4	3	2	3	5	0.011	0.0006	1.208
	Corresponding recycled materials - recycled aluminum (literature)	3	2	2	2	4	0.051	0.0006	1.487
	Corresponding recycled materials - wood (literature)	3	2	2	2	4	0.051	0.0006	1.487

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