

Article

Research on Carbon Footprint Calculation for the Materialisation Phase of Prefabricated Housing

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Abstract

Against the backdrop of accelerating global low-carbon transition, the construction sector has emerged as a critical domain for carbon reduction. This paper establishes a carbon footprint calculation model for the materialisation phase of prefabricated residential buildings, grounded in the theory of whole-life-cycle carbon and the carbon emission factor method. It delineates phase boundaries and carbon source composition, while integrating project data to formulate computational expressions. Using Building 1 of YT Apartments as a case study for phased assessment, results indicate that the building material production phase accounts for the highest proportion of emissions (90.76%), followed by on-site construction (3.83%), material transportation (2.92%), on-site assembly (1.27%), component manufacturing (0.86%), and component transportation (0.36%). This demonstrates that the building material production phase holds the greatest potential for emissions reduction, providing theoretical support for low-carbon strategies in prefabricated housing.

Keywords: prefabricated housing; materialisation phase; carbon footprint; carbon emission factor method



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1. Introduction

During the 20th century, the greenhouse effect emerged as a critical issue amid relentless global industrial and technological advancement. Between 1972 and 2011, global carbon emissions (CEs) rose sharply, from 1.48 billion t to 3.13 billion t, significantly influencing climate change [1]; concurrently, the construction sector's rapid expansion has intensified its environmental pressures, as it is recognised as one of the three largest global energy consumption and greenhouse gas emission sources, with the other two being industry and transport. In China, buildings alone contribute roughly 40–50% of total national emissions [2], but the IPCC Sixth Assessment Report indicates that the building sector has the potential to achieve net-zero emissions by 2050 through measures such as improving energy efficiency, strengthening demand-side management, and expanding the use of renewable energy [3]. To align with the Paris Agreement's temperature targets and promote the realisation of the United Nations Sustainable Development Goals (SDGs), it is crucial to prioritise emission reduction within the construction sector.

In response, China has prioritised green building development at the policy level. Within the 14th Five-Year Plan for the Construction Industry, clear emphasis is placed on speeding up the adoption of prefabricated construction and encouraging environmentally friendly building practices, with the aim of driving the sector towards a low-carbon transformation [4]. Existing research indicates that prefabricated construction, owing to

its industrialised and standardised advantages, possesses significant energy conservation and emission reduction potential [5,6]. Within the field of carbon footprint assessment for prefabricated buildings, while some scholars have explored the topic from various angles, most of their studies suffer from weak data foundations, as a substantial number rely heavily on industry databases (such as Ecoinvent and the China LCA Database), making it difficult to reflect regional variations in energy structures, transport modes, and component manufacturing processes [7]. In some studies, researchers consider only the component production phase, while others incorporate the transportation and construction assembly phases, leading to inconsistent boundaries in carbon footprint calculations [8,9]. Furthermore, existing research predominantly focuses on the construction or operational phases of prefabricated buildings, lacking systematic quantification and factor analysis for embodied phase carbon footprints. Given that residential buildings constitute the largest share of completed floor area (approximately 66%), research into carbon footprint accounting and reduction pathways for prefabricated housing holds significant practical relevance.

Drawing on life cycle carbon theory and the carbon emission factor approach, we conducted this study to develop a calculation model through which to assess the carbon footprint during the embodied stage of prefabricated residential buildings. Our model can be used to specify the boundaries and scope of embodied phase measurement and systematically examine the carbon source composition across different processes; on this basis, a database of carbon emission factors was combined with project-specific baseline data to formulate corresponding calculation expressions for each stage of the materialisation process. In order to verify the model's applicability, Building 1 of the YT prefabricated apartment project was selected as a case example, and a staged carbon footprint evaluation was carried out for its materialisation phase.

2. Literature Review

2.1. Carbon Footprint Accounting Boundaries

In recent years, many scholars have used the life cycle assessment (LCA) method to analyse carbon footprint sources for buildings throughout their entire life cycles, or at specific stages; by applying quantitative analysis, this method is used to estimate the overall carbon footprint of a building and evaluate its environmental impacts. Regarding the full life cycle, Mei et al. [10] took a single urban building as an example and divided its life cycle into five stages—planning, material preparation, construction, operation and maintenance, and demolition—based on which they constructed a carbon emission calculation model through which to achieve accurate quantification of emissions at each stage. Valeria et al. [11] conducted a full life cycle comparative study of recycled and otherwise prefabricated wall panels, the results of which showed that the use of bio-based materials helps to reduce carbon emissions in circular buildings. Zhang et al. [12] proposed an integrated method, combining building life cycle carbon emissions with cost analysis, leveraging BIM technology to assess carbon intensity throughout a building's entire life cycle. Xing et al. [13] established a dynamic life cycle assessment model through which to optimise a building's thermal insulation performance through time series verification of upstream parameters, thereby predicting carbon emissions. Borja et al. [14] established a full life cycle carbon emission baseline for typical Spanish residential buildings, encompassing specific, operational, and total emissions across their entire life cycles. Tavares and Freire [15] conducted a full life cycle assessment for steel-framed lightweight prefabricated single-bedroom dwellings, comparing carbon footprints and environmental impacts across different climate zones, insulation levels, and energy system configurations. Gao et al. [16] proposed an integrated LCA and BIM simulation model for calculating the carbon emissions of prefabricated buildings (PBs) and timber buildings (TBs) throughout their life

cycles, systematically evaluating these technologies' carbon performances through case studies. Regarding the physical–chemical phase, Ma et al. [17] examined the impacts of factory production, logistics transport, and assembly construction on prefabricated building carbon emissions, and comparative results indicated lower overall energy consumption for prefabricated buildings compared to conventional constructions. Luo et al. [18] focused on carbon emission environmental impacts in the building operation stage and predicted and evaluated the carbon footprint through a multi-scenario model. Zhan et al. [19] studied the carbon emissions of residential prefabricated buildings in the materialisation stage, based on the LCA-BIM platform, and used a structural equation model to analyse the impacts of material selection, energy consumption, and material storage on emissions. Li et al. [20] utilised Dynamo parametric modelling and coding, integrated with BIM systems and IoT technology, in order to achieve carbon emission data integration, precise assessment, and real-time tracking during the materialisation phase. Liu et al. [21] used the data quantification DEMATEL-ISM-MICMAC method to conduct an in-depth analysis of the carbon footprint and key influencing factors of the materialisation stage of prefabricated houses, providing theoretical guidance for low-carbon emission reduction strategy formulation.

In recent years, with the rapid development of China's prefabricated construction industry, academic interest in residential carbon footprint research has significantly increased. When scoping carbon footprint calculations, the authors of most studies still use life cycle assessment (LCA) methods to assess the carbon emissions of prefabricated homes from construction to demolition; however, the results of such methods often underappreciate the representative role of the materialisation phase in overall carbon emissions, as the materialisation phase can largely reflect the total carbon emission level of a building, while significantly reducing computational complexity. Further literature analysis shows that the materialisation phase can be broken down into the following five key components: building material production, building material transportation, component manufacturing, component transportation, and on-site construction operations.

2.2. Carbon Footprint Accounting Methods

Against the backdrop of deepening global urbanisation, traditional construction models render urban development a persistent and substantial carbon source; notably, in most mature cities, new buildings account for merely 1–2% of the existing stock annually, implying that, over the coming decades, more than 95% of carbon emissions will originate from existing structures. Promoting low-carbon new developments and green retrofits of existing buildings has thus become a critical pathway to carbon reduction. Carbon footprint accounting plays a pivotal role in this process, yet currently faces challenges, including inconsistent standards and ambiguous system boundaries. Cang et al. [22] proposed a building embodied carbon accounting method applicable to the schematic design phase, which extracts quantities from BIM models through coding and combines them with pre-constructed BE-level emission factors for rapid calculation. Ouellet et al. [23] analysed discrepancies in biogenic carbon accounting across 16 countries using three LCA methodologies for identical timber structures, revealing significant variations in outcomes based on differing biogenic carbon treatment approaches, despite identical methodologies. Tsay et al. [24] developed a digital carbon footprint calculation tool integrating Building Information Modelling (BIM) with parametric analysis; employing a dynamic life cycle assessment approach, it enables real-time calculation of embodied and operational carbon by inputting building geometric parameters (window-to-wall ratio, shading depth, etc.). Muheeb et al. [25] employed a parametric LCA methodology, utilising One Click LCA software and an Excel platform to conduct 630 iterative calculations across four structural systems (timber, steel, concrete, and composite structures), strictly adhering to ISO 14040

standards for carbon footprint assessment. Sun and Huang [26] employed stochastic frontier analysis to identify key influencing factors, constructing a predictive model integrating factor analysis and extreme learning machines (ELMs) for assessing and forecasting carbon emission intensity. Lu et al. [27] proposed a design process-oriented carbon footprint calculation method enabling rapid emission estimation under incomplete information conditions. Wang et al. [28] constructed a Multi-Region Input–Output (MRIO) model based on 2007 and 2012 input–output data, comparing carbon footprints and inter-regional implicit carbon flows across 30 Chinese provinces under production and consumption accounting principles. Gao et al. [29] systematically analysed building carbon footprint accounting and prediction models. Accounting primarily employs two methodologies, top-down (e.g., economic input–output models) and bottom-up (e.g., physical models), with the former predominantly used at the urban scale, while the latter applies to individual buildings. Liu et al. [30] systematically reviewed the evolution of carbon accounting methodologies; traditional approaches rely mainly on the IPCC emission factor method (bottom-up) and atmospheric concentration inversion (top-down), yielding annual emission inventories; on the other hand, emerging real-time carbon monitoring technologies have successfully reduced the accounting scale to daily, or even hourly, intervals by integrating multi-source high-frequency big data from the electricity, transport, and industry sectors.

Currently, diverse methods exist for calculating building carbon footprints, with field surveys, structural balance approaches, and carbon emission factor methods being the most widely applied and representing the mainstream research methodologies within this field.

3. Model and Methods

3.1. System Boundaries and Methodology for Prefabricated Housing Carbon Footprint Calculation During the Materialisation Phase

(1) Time Boundaries

As illustrated in Figure 1, the prefabricated housing materialisation stage is divided into four sequential phases for this research. The first phase is building material production and transportation, which accounts for carbon emissions arising from raw material consumption during production, as well as energy used for logistics. The second phase is the factory production stage, during which carbon emissions result from energy consumed by machinery during prefabricated component processing and internal transport. The third phase covers prefabricated component transportation, including the fuel consumption associated with different transport modes. Finally, the on-site assembly stage incorporates carbon emissions from both material usage and mechanical energy during on-site operations such as pouring, hoisting, and installation [31].

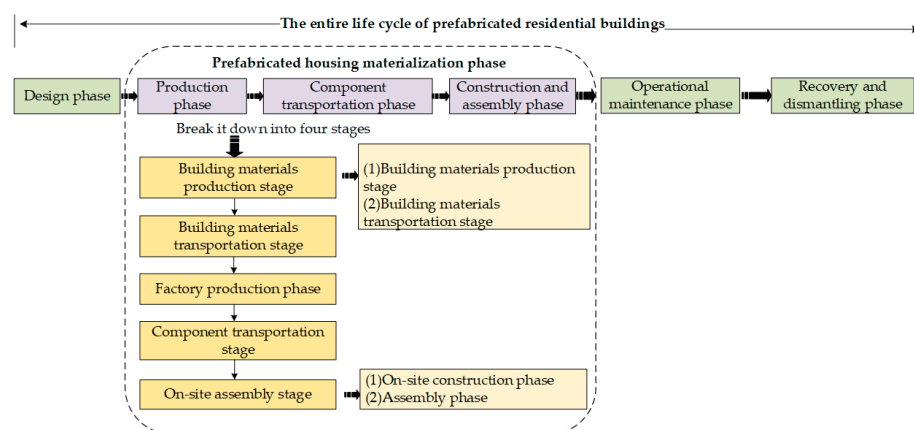


Figure 1. Division of the materialisation stage of prefabricated housing.

(2) Study Scope

During the building project construction, large quantities of various materials, construction machinery, and equipment are utilised. From raw material production to machinery operation and material and component transportation, each stage involves significant energy use and corresponding CO₂ emissions. In this study, we consider carbon footprint contributions from major phases: building material production, energy consumption from mechanical operations, transportation emissions, and manual on-site activities. Minor operations and low-impact consumables are excluded. Since key building materials contribute most significantly to overall emissions, our analysis is focused on concrete, steel, cement, mortar, lime, timber, and water, while materials with smaller usage volumes are omitted due to their limited impacts.

(3) Carbon Emission Factor Method

The carbon emission factor methodology was first introduced by the United Nations Intergovernmental Panel on Climate Change (IPCC) in 1996, as part of a standardised approach for calculating carbon emissions; since then, the methodology has undergone several updates, and the version currently in use originates from the 2006 IPCC guideline revision, in which carbon emissions are calculated by multiplying activity data from emission sources by standardised carbon emission factors [32].

The above method has a well-established methodological framework and good authority, making it suitable for various carbon emission calculation scenarios related to energy consumption and providing a reliable tool for assessing greenhouse gas emissions. Carbon emission coefficient method application examples include those by Quan [33], Yu [34], and Zhang [35], who used carbon emission coefficients to calculate and analyse the greenhouse gas emissions generated during the prefabricated building materialisation process. The calculation formula is as follows: “Carbon footprint = Carbon footprint factor × Activity data.” The carbon emission coefficient method can be further divided into the three following calculation methods.

The inventory method integrates diverse data resources and combines actual operating parameters from various fields to establish a systematic calculation model. While enabling dynamic carbon emission monitoring, it ensures the temporal and spatial comparability of inventory data, providing a reliable basis for formulating emission reduction strategies; this standardised calculation system covers the entire process from production to consumption, effectively linking emission data across different sectors, and it can meet regional-level greenhouse gas inventory requirements and support carbon footprint tracing in key industries, highlighting the foundational role of inventory compilation technology in environmental management.

The information modelling method is a quantitative assessment model for energy consumption and material flow, integrating multi-dimensional parameters from the design, construction, operation, and demolition stages; this model leverages BIM platforms to integrate multi-source data, forming a carbon footprint monitoring framework covering the entire building life cycle, and its parameterised database provides precise data support for carbon footprint calculations.

The mathematical modelling method uses building material production, transportation, and installation data as input variables for the formula “carbon footprint = carbon footprint factor × activity data”. It relies on engineering construction process inventory data to obtain key indicators, such as fuel consumption and process parameters, at each stage; selects corresponding carbon footprint factors based on industry characteristics; and uses the calculation formula to achieve precise carbon footprint tracing. The resulting scientific calculation system enables both enterprise-level carbon footprint management

and regional greenhouse gas inventory compilation, providing a quantitative basis for developing differentiated emission reduction plans.

Based on these considerations, we adopted the carbon emission factor method and implemented mathematical modelling to develop a detailed carbon footprint calculation model for prefabricated housing in this study, enabling precise emission quantification throughout the materialisation stage.

3.2. Carbon Footprint Factor Determination

When determining carbon footprint factors, data selection should follow the principle of hierarchical matching, as follows: prioritise the use of carbon footprint factors provided by domestic data platforms, such as China's Life Cycle Database (CLCD); if existing domestic data is outdated due to its statistical year being too early, supplementary data should be collected from recent domestic research on carbon footprints in the construction sector over the past five years, or carbon footprint factors should be reconstructed based on current industrial technology levels; when the above conditions cannot be met, international authoritative databases (such as Ecoinvent, ELCD) or peer-reviewed overseas research results may be used as alternative carbon footprint factors across regions, but the applicability of the data sources must simultaneously be explained, and regional adjustments must be made. Following this approach ensures that carbon footprint accounting throughout the building life cycle is based on reliable and regionally relevant data. The carbon footprint factors are detailed in Appendices A.1–A.4.

3.3. Carbon Footprint Calculation Model for Prefabricated Housing During the Materialisation Phase

A carbon footprint calculation framework for the prefabricated housing materialisation phase was developed in this study, employing the carbon emission factor method and defining the system boundary to clarify the calculation scope. As expressed in Equation (1), the total carbon footprint is obtained by summing the carbon emissions across all relevant phases.

$$C = C_1 + C_2 + C_3 + C_4 \quad (1)$$

In the formula, C denotes the total carbon footprint of the prefabricated residential building during the materialisation stage (kgCO_2e), and C_1 – C_4 are the carbon footprint values for building material production and transportation, factory production, prefabricated component transportation, and on-site assembly stages, respectively.

The unified functional unit for result analysis is detailed in Equation (2).

$$C_{x/s} = \frac{C_x}{s} \quad (2)$$

In the formula, $C_{x/s}$ denotes the carbon footprint value per unit area ($\text{kgCO}_2\text{e}/\text{m}^2$); S represents the building area (m^2).

3.3.1. Carbon Footprint Calculation for Building Material Production and Transportation

The carbon footprint assessment for the production and transportation stages covers the complete life cycle flow of primary building materials, including the full manufacturing process, from raw material extraction and industrial processing to finished product dispatch, as well as greenhouse gas emissions arising from the energy consumed during transportation to precast plants and construction sites; this process is formalised in Equation (3).

$$C_1 = C_{ZS} + C_{ZY} \quad (3)$$

In the formula, C_{ZS} indicates the carbon footprint from building material production; and C_{ZY} is the carbon footprint from material transportation.

(1) Building Material Production Stage

The carbon footprint for the building material production stage is calculated according to Equation (4).

$$C_{ZS} = \sum_{i=1}^n Q_i \times E_{c,i} \quad (4)$$

In the formula, Q_i denotes the quantity of consumption for the i -th primary building material; and $E_{c,i}$ represents the i -th major building material carbon footprint factor ($\text{kgCO}_2\text{e}/\text{building material unit}$).

(2) Building Material Transportation Phase

The carbon footprint for the building material transportation phase is calculated according to Equation (5).

$$C_{ZY} = \sum_{i=1}^n Q_i \times D_i \times E_{ys,i} + \sum_{m=1}^m Q_m \times D_m \times E_{ys,m} \quad (5)$$

In the formula, Q_i and Q_m represent material consumption for transportation to the prefabrication plant and material consumption for transportation to the site, respectively; D_i and D_m denotes the transport distances for materials delivered to the factory and site; and E_{ys} indicates the carbon footprint factor per unit distance for each transportation mode ($\text{kgCO}_2\text{e}/\text{Unit} \cdot \text{km}$).

3.3.2. Carbon Footprint Calculation Model for the Factory Production Stage

As a distinctive process unit within the prefabricated construction model, the factory production stage fundamentally transforms the on-site operations characteristic of traditional in situ casting into standardised manufacturing within industrial workshops; this stage focuses on the comprehensive processing system for prefabricated components, specifically encompassing the use of standardised products to manufacture building elements of varying integration levels, alongside the carbon footprint generated by energy consumption during the internal transport of factory-produced goods within the premises.

Since the impacts of raw materials are already accounted for in the material production stage, the factory production stage focuses primarily on the energy usage from equipment operation, and the resulting carbon footprint is influenced by the production line layout, component complexity, and processing technology. Equations (6)–(8) are used for calculating in this stage.

$$C_2 = C_{SC} + C_{YS} \quad (6)$$

In the formula, C_{SC} denotes the carbon footprint value during the factory production stage (kgCO_2e); and C_{YS} indicates the carbon footprint calculation for on-site transportation processes (kgCO_2e).

$$C_{SC} = \sum_{i=1}^n \frac{Q_{y,i}}{q_{y,i}} \times P_{s,i} \times E_e \quad (7)$$

In the formula, $Q_{y,i}$ is the quantity of the i -th type of prefabricated component (ALC precast wall panel, m^2 ; other components, m^3); $q_{y,i}$ denotes the production capacity per shift for each line of the i -th type of prefabricated component; and $P_{s,i}$ represents the shift output for the i -th type of factory-produced product (kWh/shift).

$$C_{YS} = \sum_{j=1}^n (Q_{y,i} \times T_{yi,j} \times R_{yc,j}) \times E_j \quad (8)$$

In the formula, $Q_{y,i}$ is the total volume of prefabricated components of the i -th type; $T_{yi,j}$ denotes the number of machine hours consumed by the j -th type of transport machinery for delivering the i -th type of prefabricated component on site (machine hours); and $R_{y,j}$ represents the energy consumption per unit shift for the j -th type of conveying machinery (energy consumption per shift).

3.3.3. Carbon Footprint Calculation Model for Prefabricated Component Transportation

Within the industrialised construction system transportation phase, the component transfer process may be analogous to manufacturing supply chain operations, comprising three sub-stages, as follows: firstly, vertical hoisting operations, during which factory crane equipment transfers components onto transport vehicles; secondly, horizontal conveyance processes, matching component characteristics and functional requirements to appropriate transport modes (vertical transport, horizontal transport, or bulk transport); finally, reverse hoisting operations at the construction site, used to achieve precise component stacking. Taking composite slab transportation as an example, the initial vertical hoisting requires a bridge crane for positioning and loading; horizontal transport employs low-loader trailers for long-distance conveyance; and, upon site arrival, truck-mounted cranes complete unloading and stacking, as illustrated in the following equation:

$$C_3 = C_{CZ1} + C_{SP} + C_{CD} = C_{Z4} \quad (9)$$

In the formula, C_3 denotes the carbon footprint value during the transport phase (kgCO_2e); C_{CZ1} and C_{CZ2} indicate carbon footprint values for the two vertical hoisting processes (kgCO_2e); and C_{SP} represents the carbon footprint value of the horizontal transport process (kgCO_2e).

(1) Vertical Transport Process

In prefabricated construction, secondary vertical hoisting operations are reciprocal in nature, allowing the calculation process to be streamlined and simplified. The vertical lifting machinery operating duration is determined according to the quantity of each type of prefabricated component, which enables an accurate energy use assessment. The carbon footprint associated with vertical transport is computed using Equation (10).

$$C_{CZ1} + C_{CZ2} = 2 \times \sum_{i=1}^n (Q_{y,i} \times T_{yci,j} \times R_{yc,j}) \times E_j \quad (10)$$

In the formula, $Q_{y,i}$ denotes the quantity of the i -th type of prefabricated component; $T_{yi,j}$ represents the machine hours required by the j -th type of lifting equipment to handle; and $R_{y,j}$ indicates the energy consumption per shift for the j -th lifting machine (kWh/shift).

(2) Horizontal Transport Process

Horizontal transport energy consumption is influenced by the type of vehicle assigned to the prefabricated components, the load capacity, and the transport distance, and it is directly related to the energy consumption of the transport vehicle. The carbon footprint of the horizontal transport process is calculated according to Equation (11).

$$C_{SP} = \sum_{i=1}^n QM_{y,i} \times D_{y,i} \times E_{ys,i} \quad (11)$$

In the formula, $QM_{y,i}$ denotes the weight (in t) of the i -th type of prefabricated component being transported; $D_{y,i}$ indicates the transportation distance between the factory and the construction site (km); and $E_{ys,i}$ is the carbon footprint factor for the i -th type of prefabricated component transport method ($\text{kgCO}_2\text{e/Unit}\cdot\text{km}$).

3.3.4. Carbon Footprint Calculation Model for the On-Site Assembly Phase

The ‘semi-prefabricated, semi-cast-in-place’ construction method employed in this study for prefabricated housing involves factory-prefabricating certain components, while assembling and finishing the remainder on-site. The assembly rate determines each method’s proportion, allowing flexible adjustment to achieve efficient construction, as illustrated in the following formula:

$$C_4 = C_{XS} + C_{ZP} \quad (12)$$

(1) On-site Construction Phase

The carbon emissions associated with on-site construction mainly arise from two sources: (i) the energy consumed by construction machinery and equipment during operation, and (ii) the energy expenditure resulting from human labour involved in the assembly processes. Together, these two aspects represent the principal contributors to the carbon footprint during on-site construction.

$$C_{XS} = C_{SG} + C_{RG} \quad (13)$$

In the formula, C_{SG} indicates the carbon footprint values of machinery and equipment during on-site construction processes (kgCO_2e); and C_{RG} denotes the carbon footprint value from human involvement (kgCO_2e).

The emissions produced by construction machinery are further quantified using Equations (14) and (15).

$$C_{SG} = \sum_k \sum_h Q_{s,h} \times EQ_{h,k} \times E_{e,k} \quad (14)$$

$$C_{RG} = Q_r \times E_{e,r} \quad (15)$$

In the formula, $Q_{s,h}$ is the total number of shifts performed by the h -th type of construction equipment; $EQ_{h,k}$ represents the energy consumption of the h -th type of construction machinery per k units of energy (energy consumption per unit shift); and $E_{e,k}$ denotes the carbon footprint factor for energy k ($\text{kgCO}_2\text{e}/\text{kg}$).

(2) Assembly Phase

On-site precision positioning of building components requires specialised equipment. Field operations primarily comprise three modules: horizontal prefabricated component assembly, vertical cast-in-place joint construction, and enclosure system installation. Carbon measurement during construction focuses on two core processes: component hoisting and positioning (lifting), and joint connection and fixation (installation).

Lifting refers to the process of transferring prefabricated components from storage yards to the construction site using specialised equipment, requiring tower cranes and lifting apparatuses; its carbon footprint primarily stems from lifting machinery diesel or electricity consumption. Installation connections are categorised into two types: removable mechanical connections, and cast-in-place fixed connections. The former encompasses dry construction techniques, such as high-strength bolt anchoring and robotic welding; the latter, involving minimal cast-in-place material usage and emissions already accounted for in the preceding building material production phase, is excluded from the construction phase carbon footprint. The carbon footprint of the assembly process is calculated using Equations (16)–(19).

$$C_{ZP} = C_{DZ} + C_{AZ} + C_{RG} \quad (16)$$

$$C_{DZ} = \left(\sum_n^{i=1} P_i \times T_i \times E_e \right) \times N_i \quad (17)$$

$$C_{AZ} = \sum_j (R_{gs,j} \times T_{gs,j} \times E_j) \times Q_{gs,i} \quad (18)$$

$$C_{RG} = Q_r \times E_{e,r} \quad (19)$$

In the formulae, C_{DZ} represents the carbon footprint value of hoisting machinery and equipment (kgCO_2e); C_{ZP} is the carbon footprint value of mechanical equipment installation (kgCO_2e); C_{RG} indicates the carbon footprint value of manual operations (kgCO_2e); P_i denotes the rated power (kw) of the i -th type of lifting machinery; T_i is the time required for hoisting the i -th type of precast component (hours); N_i represents the quantity of the i -th type of prefabricated component (units); $R_{gs,j}$ denotes the per-shift energy consumption of the j -th construction machine; $T_{gs,j}$ indicates the hourly consumption of the j -th machine under the i -th prefabricated component connection method (hours); and $Q_{gs,i}$ is the quantity of work for the i -th type of prefabricated component to be assembled.

4. Case Study

4.1. Project Overview

In this study, we took the YT Prefabricated Apartment Project in Ganzhou, Jiangxi Province, as our research object. The construction site is rectangular in shape, with a total floor area of $39,314.05 \text{ m}^2$, approximately $27,282.7 \text{ m}^2$ above ground and $12,031.35 \text{ m}^2$ below ground. The primary components comprise one new eight-storey and two nine-storey high-rise residential public buildings, alongside a single-storey public building serving as a duty office. Specifically, Building 1 is an eight-storey residential block with a height of 29.1 m and a gross floor area of 8484.11 m^2 ; Building 3 is a nine-storey block reaching 32.7 m in height and 8935.96 m^2 in floor area; and Building 5 is also nine storeys high, with a total height of 33.45 m and a floor area of 9740.32 m^2 . The project also includes an underground car park and associated outdoor works. The prefabricated building area totals $23,532.16 \text{ m}^2$, comprising Buildings 1, 3, and 5, and accounting for 37% of the gross floor area. For this research, we analysed Building 1 as a case study; this prefabricated concrete structure comprises one basement level and seven above-ground storeys, with a total floor area of 8484.11 m^2 .

For this research, a residential building project was taken as the case study, and our analysis places emphasis on examining the embodied carbon profile of prefabricated housing throughout the materialisation stage. Multiple building materials are utilised during the materialisation stage, some of which have minimal impacts on the overall carbon footprint due to low consumption volumes and the absence of established carbon footprint factors; consequently, calculations primarily focused on materials with substantial cumulative usage, high construction costs, and significant energy consumption, alongside mechanical equipment shifts. Lightweight materials and sporadically used tools were excluded from the assessment.

This residential development incorporated prefabricated staircases, composite slabs, and ALC wall panels, resulting in an assembly ratio of 35.75%, the specific component usage for which is detailed in Table 1.

Data collection for this study was conducted in three phases: Firstly, discussions were held with project partners to systematically gather foundational materials, including structural design drawings, construction bills of quantities, and raw material supply chain data. Building upon this step, field investigations were undertaken at prefabricated component production bases to meticulously record process parameters, equipment energy consumption rates, and on-site component logistics solutions. Finally, through regular thematic interviews, we focused on key carbon footprint nodes within the assembly workflow to

systematically identify optimisation opportunities for emission reduction during technical implementation.

Table 1. Use of prefabricated components in prefabricated buildings.

Prefabricated Component Type	Component Location	Number of Components (pcs)	Component Volume (m ³)
Prefabricated Stairs	Above 2nd Floor	56	32.771
Prefabricated Composite Slabs	Above 2nd Floor	759	248.321
ALC Prefabricated Wall Panels (100 mm thick)	Internal Partition Walls	46,146	876.142
ALC Prefabricated Wall Panels (200 mm thick)			115.6839

4.2. Prefabricated Building Carbon Footprint Assessment

4.2.1. Carbon Emissions from Material Production and Transportation

(1) Material Production Stage

The dataset on material consumption used in this research was derived from the bill of quantities supplied by the construction enterprise. To address material diversity, a functional attribute classification method was employed for systematic integration. The building material production stage was divided into two distinct components for independent calculation: in situ construction and prefabricated processing. The respective results are presented in Tables 2 and 3.

Table 2. Inventory of embodied carbon emissions by material type during the materialization stage.

Category	Material Type	Measurement Unit	Quantity Used	Emission Factor (kgCO _{2e} /t) or (kgCO _{2e} /m ³)	Carbon Emissions (kgCO _{2e})
Raw Materials	Water	t	3111.70	0.168	522.77
	Gravel	t	601.95	2.18	1312.24
	Sand	t	213.70	2.51	536.39
	Timber	m ³	62.02	178	11,039.20
Cement	Cement (32.5)	t	105.21	820	86,272.20
Mortar	Masonry Mortar	m ³	359.63	220	79,118.60
	Plastering Mortar	m ³	387.29	277	107,279.33
Concrete	C20	m ³	265.71	250	66,426.25
	C25	m ³	483.10	267.7	129,326.14
	C30	m ³	1801.00	287.7	518,147.70
	C35	m ³	256.55	307.7	78,940.44
	C40	m ³	534.87	327.7	175,276.24
	C50	m ³	161.30	367.7	59,311.48
Steel	Hot-rolled small section	t	35.90	2310	82,919.76
	Hot-rolled medium section	t	20.92	2365	49,463.98
	Hot-rolled high-wire	t	34.84	2375	82,745.00
	Hot-rolled rebar	t	215.85	2340	505,089.00

Table 2. Cont.

Category	Material Type	Measurement Unit	Quantity Used	Emission Factor (kgCO _{2e} /t) or (kgCO _{2e} /m ³)	Carbon Emissions (kgCO _{2e})
Other Metals	Aluminum Composite	t	16.74	15,450	258,633.00
	Iron Products	t	12.86	2000	25,714.00
Bricks and Blocks	Shale Solid Bricks	m ³	449.97	292	131,391.24
	Sintered Perforated Bricks	m ³	462.30	215	99,394.50
	Concrete Bricks	m ³	456.10	336	153,249.60
	Clay Hollow Bricks	m ³	396.26	250	99,065.00
	Sintered Gangue Solid Bricks	m ³	816.99	22.8	18,627.37
Bricks and Blocks	Autoclaved Aerated Concrete Blocks	m ³	104.18	270	28,128.60
Glass	Tempered Glass	t	14.33	1790	25,643.54
	General Glass	t	25.82	1190	30,725.80
Waterproof	Polymer-Modified Asphalt Self-Adhesive Membrane	m ²	2827.39	0.72	2035.72
Thermal Insulation	Rock Wool Board	t	10.50	1980	20,790.00
Coatings and Paints	Paints and Coatings	t	21.44	3500	75,040.00
Total carbon footprint value: 3,002,165.08 kgCO _{2e}					

Table 3. Carbon footprint in the production stage of prefabricated building materials.

Category	Material	Unit	Consumption	Emission Factor (kgCO _{2e} /t) or (kgCO _{2e} /m ³)	Carbon Emissions (kgCO _{2e})
Prefabricated staircase	Precast concrete C30	m ³	32.77	287.7	9427.93
	Reinforcing steel	t	4.91	2340	11,489.40
Precast composite slab	Precast concrete C30	m ³	248.32	287.7	71,441.66
	Reinforcing steel	t	37.25	2340	87,165.00
ALC Precast Wall Panel, 100 mm Thick	Autoclaved aerated concrete	m ³	876.14	166.02	164,662.60
ALC Precast Wall Panel, 200 mm Thick			115.68		
Steel formwork	Steel formwork	t	0.0614	2310	141.83
Total carbon footprint value: 344,328.42 kgCO _{2e}					

(a) Carbon Emissions from Material Production in Cast-in-Place Construction

Based on the aforementioned calculations, an analysis of the carbon footprint distribution among primary building materials during the production phase for in situ construction is presented in Figures 2 and 3.

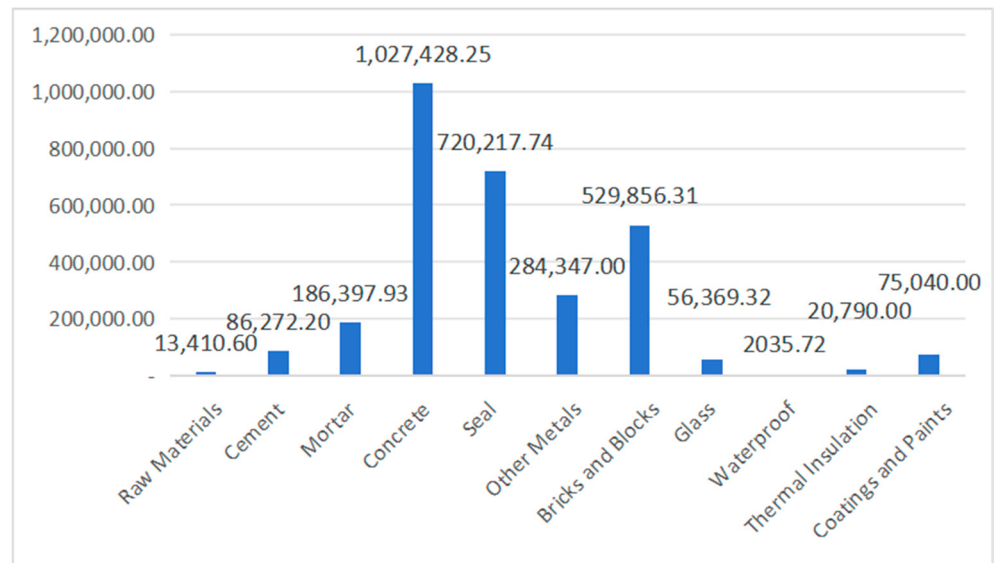


Figure 2. Carbon emissions from key construction materials applied in cast-in-place structures (kgCO_{2e}).

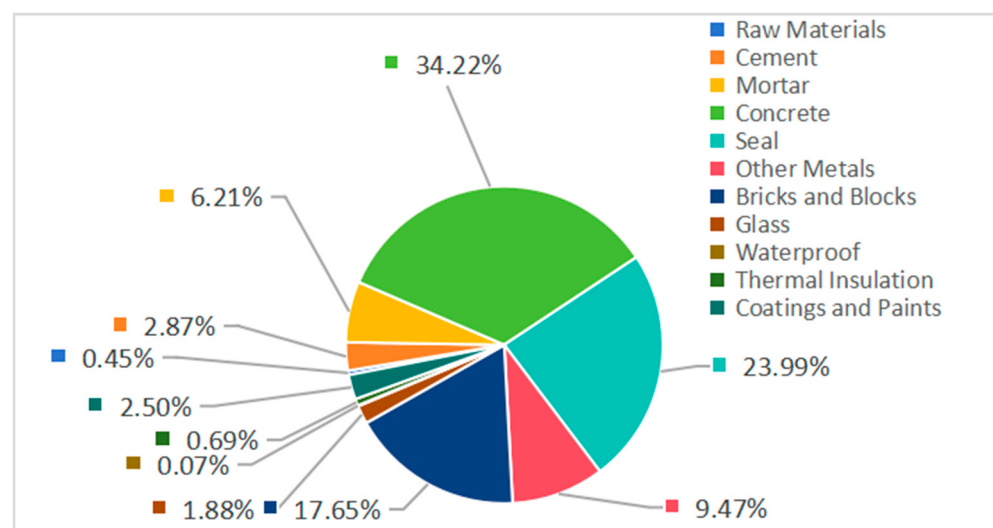


Figure 3. Share of carbon emissions attributed to primary construction materials in cast-in-place components (%).

Data analysis shows that, during the manufacturing stage, the carbon emissions of materials used in cast-in-place construction are largely concentrated in concrete (34.22%), steel (23.99%), and bricks and blocks (17.65%); this distribution pattern exhibits a significant positive correlation with the proportion of material usage in the project. For these high-carbon-footprint materials, environmental benefits should be maximised by optimising material mix ratios and usage based on physical and mechanical properties while ensuring structural integrity; refining aggregate grading design; enhancing steel recycling rates; and optimising masonry construction methods.

(b) Carbon Emissions Associated with Prefabricated Materials Throughout The Manufacturing Stage

According to the data presented in Table 3, concrete components and steel reinforcement products generate the most significant greenhouse gas emissions throughout their entire life cycles, while steel moulds produce the lowest emissions. Within standardised

construction systems, metal moulds function as reusable components, and the standardised specifications of these moulds significantly reduce the overall demand for moulding equipment; specifically, the area of standardised metal moulds used for prefabricated staircases is 57.1 m², while the lateral surface area utilised for composite slab production is 30.8 m².

Based on the aforementioned calculations, an analysis of the carbon footprint distribution across various materials for prefabricated components (precast composite slabs, precast staircases, ALC precast wall panels) is presented in Figures 4 and 5.

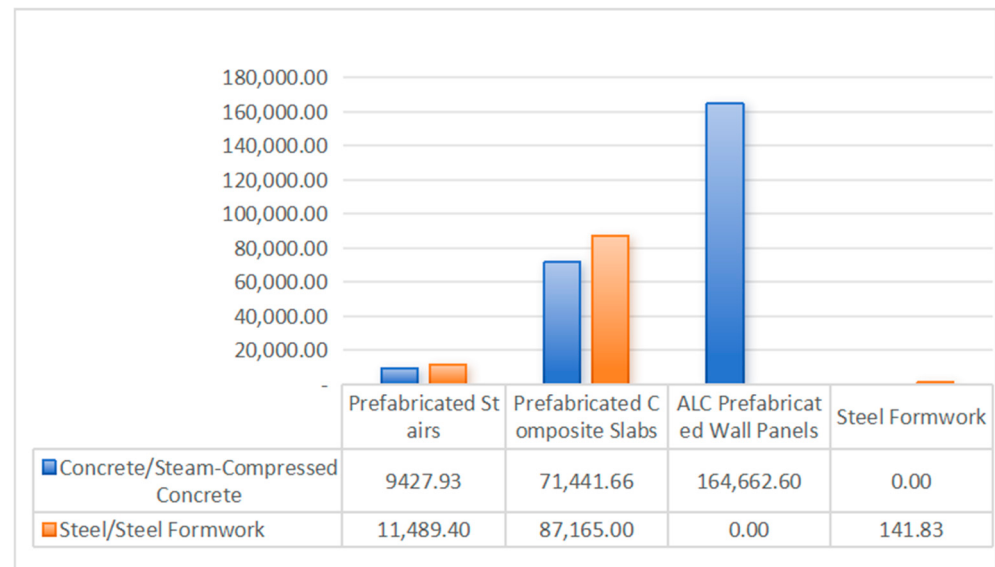


Figure 4. The quantified carbon footprint of prefabricated elements within the production stage of construction materials.

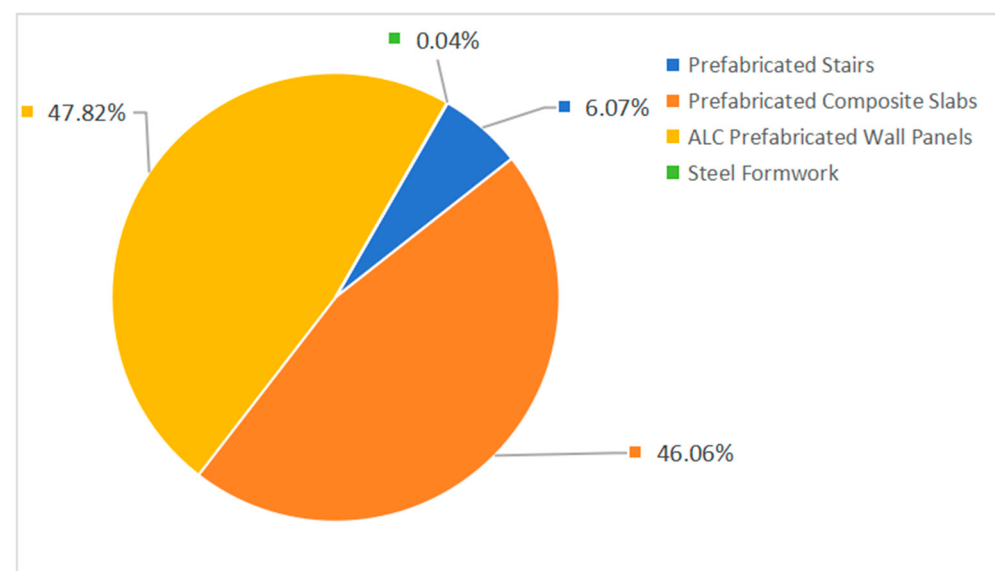


Figure 5. The relative contribution of carbon emissions during the material production stage of prefabricated buildings.

It is estimated that the total greenhouse gas emissions produced in the raw material preparation stage of prefabricated components amount to 344,328.42 kgCO_{2e}. Analysing emission composition revealed that ALC partition walls contribute the largest carbon footprint, at 164,662.6 kgCO_{2e} (47.82% share) (in this case study, all internal partition walls were prefabricated wall panels); composite floor slabs followed, with a carbon

footprint of 158,606.66 kgCO_{2e} (46.06%); stair components had the lowest footprint, at 20,917.33 kgCO_{2e} (6.07%); steel formwork, possessing reusable properties, was calculated separately, at 144.83 kgCO_{2e}.

(2) Building Material Transport Phase

The distance required for transporting building materials was calculated through electronic map tools, selecting the most suitable route from the supplier's location to either the construction site or the prefabrication plant. Road freight was employed as the exclusive transport mode, with trucks delivering goods at full capacity, and then returning without load. To better capture the imbalance between outbound and return trips, we made adjustments to the emission factors assigned to transport vehicles, and the corresponding outcomes are illustrated in Tables 4 and 5, as well as Figures 6 and 7.

(a) Carbon Emissions from Transporting Major Building Materials to the Construction Site

Table 4. Carbon emissions of building materials from the transportation stage to the construction site.

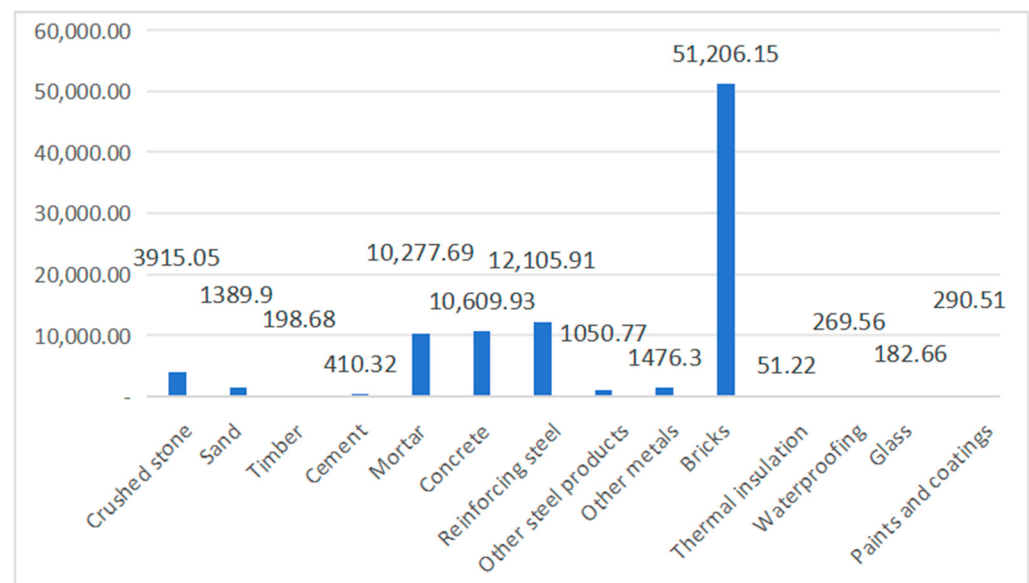
Process	Material Type	Weight (t)	Distance (km)	Transport Vehicle	Emission Factor (kgCO _{2e} /t·km)	Carbon Emissions (kgCO _{2e})
Delivery of building materials	Crushed stone	601.95	24	Diesel lorry (heavy-duty 10 t)	0.271	3915.05
	Sand	213.70	24	Diesel lorry (heavy-duty 10 t)	0.271	1389.90
	Timber	62.02	14.9	Diesel lorry (heavy-duty 18 t)	0.215	198.68
	Cement	105.21	30	Diesel lorry (heavy-duty 30 t)	0.13	410.32
	Mortar	1493.85	32.4	Diesel lorry (heavy-duty 18 t)	0.215	10,277.69
	Concrete	8224.75	5.6	Diesel lorry (heavy-duty 18 t)	0.215	10,609.93
	Reinforcing steel	230.50	404	Diesel lorry (heavy-duty 30 t)	0.13	12,105.91
	Other steel products	34.84	232	Diesel lorry (heavy-duty 30 t)	0.13	1050.77
	Other metals	29.60	232	Diesel lorry (heavy-duty 18 t)	0.215	1476.30
	Bricks	6298.42	30	Diesel lorry (heavy-duty 10 t)	0.271	51,206.15
	Thermal insulation	10.50	18	Diesel lorry (heavy-duty 10 t)	0.271	51.22
	Waterproofing	41.45	24	Diesel lorry (heavy-duty 10 t)	0.271	269.56
	Glass	40.15	35	Diesel lorry (heavy-duty 30 t)	0.13	182.66
	Paints and coatings	21.44	50	Diesel lorry (heavy-duty 10 t)	0.271	290.51

(b) Transportation of construction materials to the prefabrication plant

Table 5. Carbon emissions generated during the delivery of building materials to the prefabrication site.

Transport process	Material Type	Weight (t)	Distance (km)	Vehicle Category	Emission Factor (kgCO _{2e} /t·km)	Carbon Emissions (kgCO _{2e})
Delivery of raw materials	Concrete	674.63	60	Diesel lorry (heavy-duty 18 t)	0.215	8702.73
	Reinforcing steel	42.16	380	Diesel lorry (heavy-duty 30 t)	0.13	2082.70
	Autoclaved aerated concrete	495.91	54	Diesel lorry (heavy-duty 30 t)	0.13	3481.29

Our analysis showed that the total transportation-related carbon emissions for major construction materials and prefabricated elements reached 107,701.38 kgCO_{2e}; among them, masonry blocks accounted for the largest proportion, at 47.54%, with a carbon footprint of 51,206.15 kgCO_{2e}, making them the primary carbon emission source. Concrete followed, at 22,793.95 kgCO_{2e}; then steel, at 15,239.38 kgCO_{2e}; and mortar, at 10,277.69 kgCO_{2e}, accounting for 21.16%, 14.15%, and 9.54% respectively. By contrast, the emissions associated with the transportation of other materials were relatively insignificant.

**Figure 6.** Carbon footprint values of major construction materials and prefabricated components during the transport phase (kgCO_{2e}).

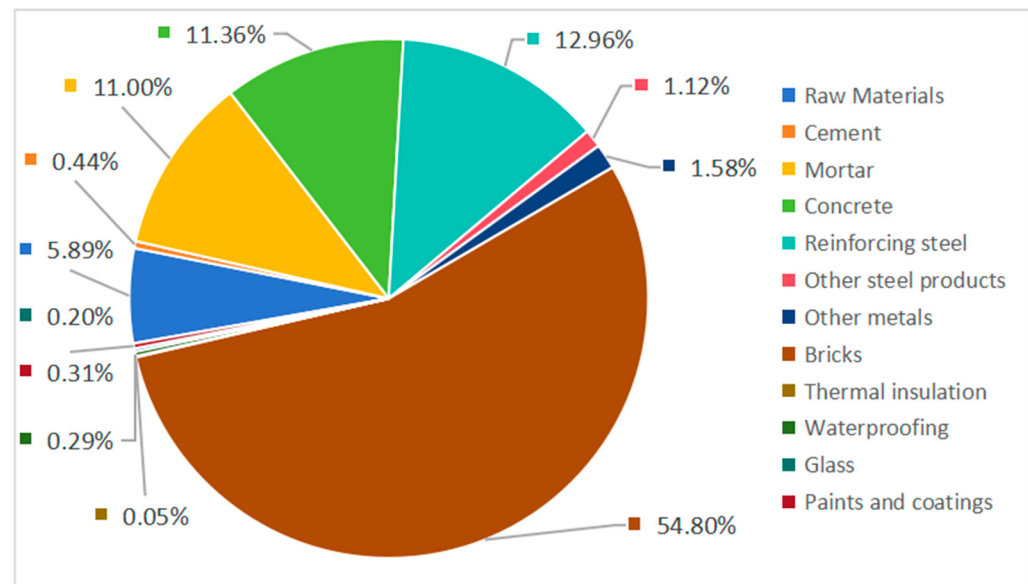


Figure 7. Share of carbon emissions during the transportation of key building materials and prefabricated components (%).

4.2.2. Emissions from the Factory Production Stage

In this study, we examined three categories of prefabricated components—precast staircases, precast composite floor slabs, and ALC precast wall panels—among which staircases and precast composite slab components were manufactured via semi-automated production lines within the factory. Their standardised production sequence was as follows: form work surface preparation → mould assembly → embedded component positioning → reinforcement mesh fabrication → concrete placement → compaction → surface texturing → temperature-controlled curing. During prefabrication, concrete placement, compaction, and on-site transportation, automated equipment was utilised; meanwhile, mould assembly, embedded component positioning, and reinforcement tying required manual intervention. ALC panels were formed using specialised moulds on fully automated production lines, with process parameters and product performance meeting industrialised construction standards.

Through on-site inspection of the prefabricated component production base, capacity data for various component production lines and equipment energy consumption parameters were obtained. Research indicates that, after production and curing, components must be transported to temporary storage yards before being delivered to construction sites via specialised transport; this series of transport operations generates corresponding greenhouse gas emissions. The methodology for calculating emissions and the corresponding results are summarised in Table 6.

Table 6. Estimated greenhouse gas emissions from the production and on-site transport of prefabricated components.

Process	Prefabricated Component Category	Production Method	Total Machine-Shift Consumption (Shifts)	Total Machine-Shift Consumption (kWh/Shift)	Emission Factor (kgCO _{2e} /kWh)	Carbon Emissions (kgCO _{2e})
Production of Precast Components	Prefabricated staircases	Semi-automated production line	1.506	288	0.8587	372.44
	Prefabricated composite slabs	Semi-automated production line	15.18	608	0.8587	7925.32
	ALC prefabricated wall panels	Automated production line	29.91	640	0.8587	16,438.13

Table 6. Cont.

Process	Prefabricated Component Category	Production Method	Total Machine-Shift Consumption (Shifts)	Total Machine-Shift Consumption (kWh/Shift)	Emission Factor (kgCO _{2e} /kWh)	Carbon Emissions (kgCO _{2e})
Intra-site transport	Prefabricated staircases	Flatbed trailer set	1.507	45.39	3.11	212.73
	Composite slab balconies	Flatbed trailer set	11.42	45.39	3.11	1612.08
	ALC prefabricated wall panels	8-tonne lorry	45.62	35.49	3.11	5035.37
Total carbon footprint value: 31,596.07 kgCO _{2e}						

4.2.3. Carbon Footprint During Precast Component Transportation

During component transportation, both vertical and horizontal transport methods must be considered.

(1) Vertical Transport

Vertical transport is employed to prevent damage and reduce subsequent construction difficulties. Prior to loading, hoisting frames should be assembled, components properly positioned and secured within the frames, and stabilised using flexible cushioning materials to ensure components remain undamaged during transit, when vehicles must start smoothly and maintain a steady speed. Particular care is required when manoeuvring turns or changing lanes, necessitating a reduction in speed well in advance and adopting a slow-speed approach to ensure the stability of precast elements, such as wall panels, and prevent overturning incidents. The carbon footprint results of the vertical transportation process are shown in Table 7.

Table 7. Carbon footprint of vertical transportation of prefabricated components.

Process	Prefabricated Component Category	Transport Machinery	Unit Shift Consumption (kWh/Shift)	Total Shift Consumption (Shifts)	Emission Factor (kgCO _{2e} /kWh)	Carbon Emissions (kgCO _{2e})
Vertical Transport	ALC Precast Wall Panels	Truck-mounted crane 12 t	30.55	55.52	3.11	5274.99
	Precast Composite Slabs	Truck-mounted crane 30 t	42.14	17.38	3.11	2277.74
	Precast Staircases	Truck-mounted crane 30 t	42.14	2.28	3.11	298.81

(2) Horizontal Transport

The prefabricated staircases and composite slabs were supplied locally by the same manufacturer, with a reasonable transport distance. The resulting emissions for the horizontal transportation stage are summarised in Tables 8 and 9.

Table 8. Emissions associated with horizontal transport of prefabricated components.

Process	Component Type	Transport Method	Distance (km)	Weight (t)	Emission Factor (kgCO _{2e} /t-km)	Carbon Emissions (kgCO _{2e})
Horizontal transport	Prefabricated ALC wall panels	Diesel lorry (heavy-duty 10 t)	18	495.91	0.271	2419.05
	Prefabricated composite slabs	Diesel lorry (heavy-duty 30 t)	32	633.22	0.13	2634.20
	Prefabricated staircases	Diesel lorry (heavy-duty 30 t)	32	83.57	0.13	347.65

Table 9. Carbon footprint during the cast-in-place construction stage Carbon footprint during the cast-in-place construction stage.

Serial Number	Type of Construction Equipment	Total Operating Shifts (shifts)	Energy Consumption per Shift (kWh/Shift)	Emission Factor (kgCO _{2e} /kWh)	Carbon Emissions (kgCO _{2e})
1	Rebar straightening machine 40 mm	36.77	56.5	3.11	6461.04
2	Diesel	3103.187	1	3.11	6584.06
3	Electric compactor 250 N·m	0.562	16.6	0.8587	8.01
4	Electric	13,176.262	1	0.8587	10,455.76
5	Truck-mounted crane 8 t	5.243	28.4	3.11	463.08
6	Truck-mounted crane 16 t	4.369	35.85	3.11	487.12
7	Truck-mounted crane 20 t	8.897	38.41	3.11	1062.79
8	Truck-mounted crane 40 t	4.3	48.52	3.11	648.86
9	Self-erecting tower crane 400 kN·m	177.254	164.31	0.8587	25,009.30
10	Self-erecting tower crane 2500 kN·m	0.43	266.04	0.8587	98.23
11	Gantry crane 10 t	0.053	88.29	0.8587	4.02
12	Motorised tipper truck 1 t	0.371	6.03	3.11	6.96
13	Mortar mixer 200 L	11.351	8.61	0.8587	83.92
14	Dry-mix mortar drum mixer	11.796	28.51	0.8587	288.78
15	Concrete screed machine 5.5 kW	4.641	23.14	0.8587	844.29
16	Rebar straightening machine 40 mm	0.15	41.6	0.8587	1250.34
17	Rebar cutting machine 40 mm	30.63	32.1	0.8587	92.49
18	Rebar bending machine 40 mm	113.757	12.8	0.8587	0.21
19	Circular saw for timber 500 mm	4.488	24	0.8587	0.33
20	Sheet metal levelling machine 16 mm × 2000 mm	0.002	120.6	0.8587	4688.90
21	Edge planer 12,000 mm	0.005	75.9	0.8587	0.87
22	Semi-automatic cutting machine 100 mm	55.719	98	0.8587	1.05
23	Shape steel shears 500 mm	0.019	53.2	0.8587	26.81
24	Shape Steel Straightener 60 mm × 800 mm	0.019	64.2	0.8587	5224.74
25	AC Arc Welder 21 kVA	0.518	60.27	0.8587	85.73
26	AC Arc Welder 32 kVA	63.032	96.53	0.8587	906.29
27	AC Arc Welder 42 kVA	0.755	132.23	0.8587	1781.34
28	Butt Welder 75 kVA	8.651	122	0.8587	16.34
29	Electroslag Welder 1000 A	14.112	147	0.8587	651.39
30	Electric Air Compressor 3 m ³ /min	0.177	107.5	0.8587	6632.63
31	Electric Multi-Stage Centrifugal Clean Water Pump 100 mm	4.205	180.4	0.8587	989.39
32	Lorry 6 t	64.193	33.24	3.11	14.39
33	8-tonne lorry	8.964	35.49	3.11	922.72
34	12-tonne lorry	0.1	46.27	3.11	0.97
35	15-tonne lorry	5.229	56.74	3.11	210.90
36	20-tonne lorry	0.005	62.56	3.11	1.52
37	20-tonne flatbed trailer unit	1.494	45.39	3.11	5401.06
38	10-tonne rail flatcar	0.048	36.8	0.8587	0.18
39	Single-cage construction hoist 1 tonne 75 m	148.625	42.32	0.8587	0.20
40	Woodworking three-sided planer 400 mm	0.004	52.4	0.8587	29.20
41	Radial drill press 50 mm	0.024	9.87	0.8587	6461.04
42	Welding rod drying oven 45 × 35 × 45 (cm ³)	5.076	6.7	0.8587	6584.06
Total carbon footprint value: 81,436.21 kgCO _{2e}					

As shown in Figure 8, during prefabricated component transport, vertical lifting generated the largest emissions, totalling 7851.53 kgCO_{2e}, whereas horizontal transport contributed 5400.90 kgCO_{2e}. Examining component types, ALC precast wall panels exhibited the highest carbon footprint, at 7694.04 kgCO_{2e}, primarily due to the exclusive use of ALC panels for all internal walls in this case study, as their high material density necessitated greater energy consumption during transport, while their fragility required specialised packaging and handling methods. Furthermore, the vertical hoisting operations involved were particularly demanding.

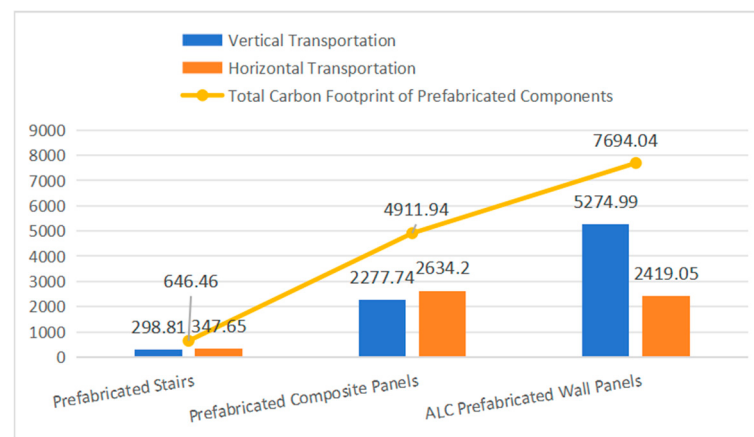


Figure 8. Carbon footprint during the transportation stage of prefabricated components (kgCO_{2e}).

4.2.4. Emissions During the On-Site Assembly Phase

(1) Cast-in-Place Construction Section

The carbon emissions associated with cast-in-place construction are mainly derived from construction machinery operation and manual labour. By analysing energy consumption data, the energy use for equipment and labour for each task can be calculated, with the results summarised in Table 9.

(2) Precast Component Assembly Process

The assembly procedure for precast components comprises two stages: hoisting and positioning. Hoisting operations are executed using tower cranes and specialised lifting equipment, with lifting durations determined based on the contractor's prior operational experience. The method for calculating associated emissions and the corresponding results are presented in Table 10.

Table 10. Carbon emission during the assembly of prefabricated components.

Serial No.	Construction Machinery	Quantity (Units)	Lifting Duration (h)	Lifting Machinery Power (kw)	Emission Factor (kgCO _{2e} /kWh)	Carbon Emissions (kgCO _{2e})
1	Prefabricated staircases	56	0.2	35	0.8587	336.61
2	Prefabricated composite slabs	759	0.2	35	0.8587	4562.27
3	ALC precast wall panels, 100 mm thick	9640	0.15	35	0.8587	4345.88
4	ALC precast wall panels, 200 mm thick	36,506	0.15	35	0.8587	32,915.09

Following the principle of clearly defining system boundaries, we examined the energy consumption associated with mechanical connection processes during prefabricated component installation. Fully threaded sleeve connections were used for stair elements and composite floor slabs, whereas clamp-type dry connection techniques were utilised for lightweight enclosure panels. The corresponding carbon emission results are summarised in Table 11.

Table 11. Carbon emission of ALC lightweight wall panels during the assembly phase.

Serial No.	Prefabricated Component	Construction Machinery	Total Shift Consumption (Shifts)	Unit Shift Consumption (kWh/shift)	Emission Factor (kgCO _{2e} /kWh)	Carbon Emissions (kgCO _{2e})
1	Prefabricated staircases	Straight thread connections are not included				
2	Prefabricated composite slabs					
3	ALC prefabricated wall panels	Sheet metal cutting machine	17.6	53.81	0.8587	813.24
		Hammer drill	4	18.88	0.8587	64.85
		Reaming drill	6	12.59	0.8587	64.87
		AC arc welder 40 kv·A	132.23	3.93	0.8587	446.24

4.2.5. Calculation Result Analysis for Prefabricated Housing Projects

Calculations based on the carbon footprint assessment model indicate that the total materialisation phase carbon footprint for this case study amounted to 3,687,123.13 kgCO_{2e}, with a unit carbon footprint of 434.28 kgCO_{2e}/m². The carbon emission results corresponding to each stage are presented in Table 12.

Table 12. Overview of carbon footprints across sub-processes in the materialisation phase of prefabricated residential buildings.

Materialisation Stage	Subprocess	Emission Factor (kgCO _{2e})	Emission Factor per Unit (kgCO _{2e} /m ²)	Proportion
Building material supply stage	Material production	3,346,493.51	394.44	90.76%
	Material transportation	107,701.38	12.69	2.92%
Factory stage	Component manufacturing	31,596.07	3.72	0.86%
Logistics stage	Component transport	13,252.43	1.56	0.36%
On-site stage	Site construction	141,097.11	16.63	3.83%
	Assembly activities	46,982.63	5.54	1.27%
	Total	3,687,123.13	434.59	100%

To comprehensively examine the carbon emission characteristics, we compared the materialisation stage carbon footprint data within the overall life cycle of the case building. The carbon footprint distribution across different phases is displayed in Figure 9.

During the physical–chemical stage, the total carbon footprint was 3,687,123.13 kgCO_{2e}, corresponding to 434.59 kgCO_{2e}/m² per unit building area; the emissions from the building material production process were the highest, reaching 3,346,493.51 kg of CO_{2e} and accounting for 90.76% of the total. Building material transportation contributed 107,701.38 kgCO_{2e} (2.92%). Prefabricated component production at the factory stage emitted 31,596.07 kgCO_{2e} (0.86%), while component transportation at the logistics stage emitted 13,252.43 kgCO_{2e} (0.36%). During the on-site construction phase, construction activities generated 141,097.11 kgCO_{2e} (3.83%), and assembly activities generated 46,982.63 kgCO_{2e} (1.27%). The results show that building material production was the dominant carbon emission source in the physical–chemical stage, while the contributions of other links were relatively limited.

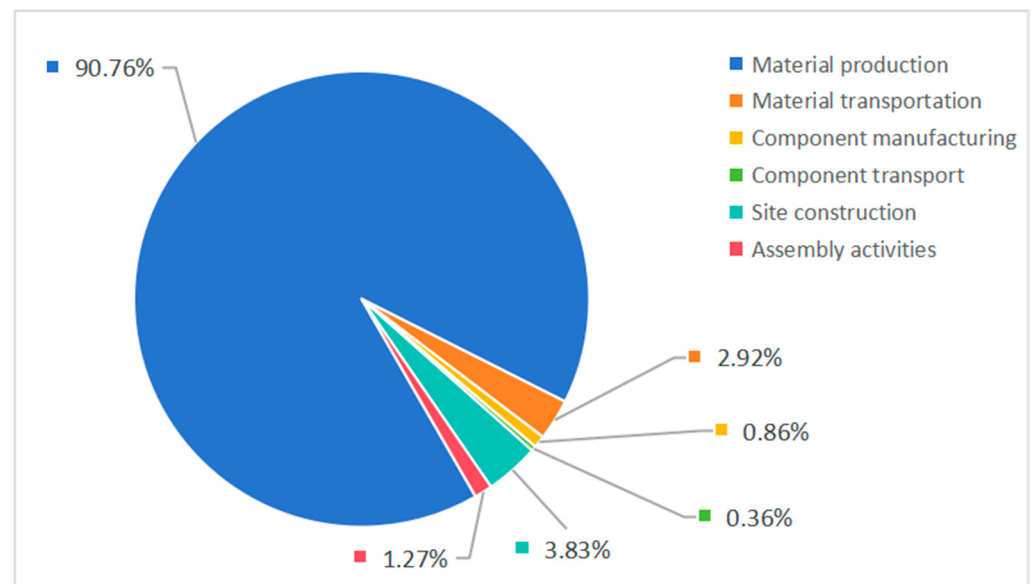


Figure 9. The proportion of carbon footprint in each stage of the physical and chemical phase of prefabricated buildings.

Table 13 illustrates the carbon emission distribution across different sub-processes within the prefabricated subsystem. At the sub-project level of this study, we employed a breakdown by construction package to clearly distinguish construction activities for prefabricated components versus cast-in-place components. Detailed construction contents for each sub-project and sub-process are provided in Appendix A.5 (Table A8). Results indicate that prefabricated component production accounted for the highest proportion of total emissions (78.03%), followed by on-site assembly (9.32%) and factory manufacturing (6.77%). Material production and transportation contributed relatively minor shares, at 3.05% and 2.84%, respectively. The above granular classification enhances transparency and highlights differences between prefabricated and conventional construction models.

Table 13. The proportion of carbon emissions in each stage of the physical and chemical phase of the prefabricated part.

Phase	Emission Factor (kgCO _{2e})	Proportion
Material Production	364,477.70	78.03%
Material Transportation	14,266.72	3.05%
Factory Production	31,596.07	6.77%
Component Transportation	13,252.43	2.84%
On-site Installation	43,549.05	9.32%
Total for Prefabricated Components	467,141.97	100%

Table 14 presents corresponding results for cast-in-place subsystems, wherein material production became the dominant factor (94.48%), followed by building material transportation (2.96%), while on-site construction accounted for only 2.58%. The above distribution underscores the critical role of material production in determining the overall carbon footprint of cast-in-place structures.

Table 14. Carbon footprint distribution across physical and chemical stages of cast-in-place components.

Phase	Emission Factor (kgCO _{2e})	Proportion
Material Production	2,982,015.81	94.48%
Material Transportation	93,434.66	2.96%
On-site Construction	81,436.21	2.58%
Total Cast-in-Place Portion	3,156,886.68	100%

As shown in Table 15, the majority of this building’s carbon footprint—97.62%—stems from the cast-in-place concrete frame and floor slabs. Although the prefabricated components (primarily lightweight partition walls and staircases) are numerous, their contribution to the project’s total carbon emissions is only 2.38%, because their material carbon intensity is inherently lower, and they do not constitute the primary structural elements.

Table 15. Carbon emissions composition by physical form denote comparison between precast and cast-in-place components.

Project	Emission Factor (kgCO _{2e})	Proportion
Total Carbon Emissions During the Entire Building Construction Phase	3,687,123.13	100%
Of which Denote Emissions Related to Prefabricated Components	467,141.97	12.67%
Of which Denote Emissions Related to Cast-in-Place Components	3,156,886.68	85.62%

It is important to note that, to clearly contrast the carbon emission difference between prefabrication and traditional cast-in-place methods, the carbon emissions for the cast-in-place portion (3,156,886.68 kgCO_{2e}) specifically refer to emissions generated under the assumption that the entire project employs traditional cast-in-place techniques; therefore, the emissions share corresponding to materials used for prefabricated components was excluded from this calculation. The carbon emissions for the prefabricated portion (467,141.97 kgCO_{2e}) independently account for the incremental emissions across the entire process resulting from the use of prefabrication technology, including the production and transportation of materials contained in prefabricated components, factory manufacturing, component logistics, and on-site installation. Therefore, the sum of these two carbon footprints does not equal the total materialisation phase carbon footprint; this discrepancy arises because the emissions from the materials in the prefabricated components were already deducted from the cast-in-place section and are subsequently counted again within the prefabricated section.

4.3. Uncertainty and Sensitivity Analysis

In order to enhance the credibility of this study’s results, we conducted uncertainty and sensitivity analyses on the key input parameters of carbon footprint accounting in the physical–chemical stage. Considering the differences in material production factors, as well as in energy emission factors and engineering quantity parameters among different databases and measured data, we set reasonable fluctuation ranges based on a triangular distribution. For instance, the emission factors of major building materials (such as cement and steel) were set at $\pm 15\%$, and those of concrete materials were set at $\pm 10\%$; the power emission factor was set at $\pm 15\%$, and the diesel factor is set at $\pm 10\%$; the fluctuation range of key material usage was $\pm 5\%$ to 15% (depending on the accuracy of the list); and the energy consumption of the factory and on-site machinery and the transportation distance were set at $\pm 20\%$.

On this basis, Monte Carlo simulation was adopted to calculate the propagation of parameter uncertainty. After each random sampling, the sub-processes and the overall carbon footprint were recalculated to obtain the probability distribution of the final result. The simulation results are shown in Figure 10, showing an approximately normal distribution, with the peaks concentrated in the range of 420–450 kgCO_{2e}/m², corresponding to a median intensity per unit area of 435.2 kgCO_{2e}/m²; the 95% confidence intervals were 401.9–468.4 kgCO_{2e}/m², indicating that, within a reasonable range of uncertainty, the overall value fluctuates, but the conclusion is robust. In conclusion, the results of this study verified the method's robustness and the reliability of the results through uncertainty and sensitivity analyses. Although the numerical values of some molecular processes were greatly influenced by the assumed conditions, the core finding remains unchanged under different assumed and data conditions.

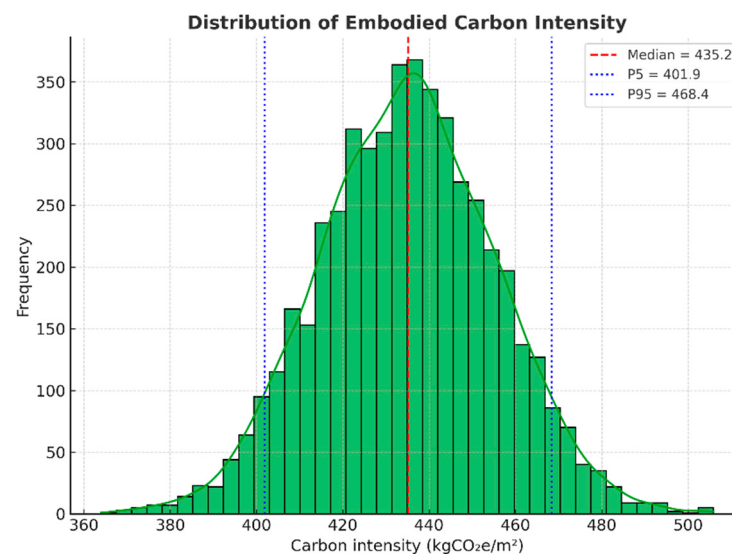


Figure 10. The probability distribution of carbon intensity per unit area in the physical and chemical stage.

5. Discussion

For this research, we conducted an in-depth examination of the carbon emissions generated during the prefabricated housing materialisation stage, with a particular focus on the differences among its sub-processes. The results demonstrate that construction material production represents the principal emission source, contributing more than 90% of the overall footprint, a finding which is consistent with prior studies that highlight the substantial embodied carbon embedded in high-impact materials, such as cement and steel. Unlike many earlier investigations, primarily depending on generic databases (e.g., Ecoinvent, CLCD), and therefore lacking regional specificity, we incorporated project-level data into this study, offering a more context-sensitive evaluation aligned with local building practices, material supply systems, and energy mixes.

From a comparative standpoint, this work advances the literature in two key respects. First, while the authors of existing research often assess the overall carbon footprint of prefabricated buildings, detailed, phased quantification of emission distribution—particularly distinguishing the embodied carbon of prefabricated subsystems versus cast-in-place components—remains rare. While most studies focus on operational carbon or isolated aspects of prefabricated buildings, we used this research to subdivide the materialisation phase into five distinct process categories and provide a detailed emission assessment at each stage; this methodology enables precise identification of high-emission phases, facili-

tating the development of targeted mitigation strategies. Second, the results of this study provide empirical evidence for the debate comparing the environmental performance of prefabricated versus traditional construction. While industrialised production significantly reduces on-site emissions, the overall benefits may be offset if raw material sourcing and transportation retain high carbon footprints.

The above findings emphasise the crucial need to implement emission reduction measures within the upstream supply chain. Practical measures may include adopting low-carbon alternatives to cement, increasing the utilisation of recycled steel, optimising aggregate mix designs, and employing digital tools for logistics management in order to reduce transportation-related emissions. Furthermore, although on-site activities and component manufacturing contribute relatively less to the total footprint, enhancing energy efficiency and integrating renewable energy into prefabrication plants represent promising avenues for further emission reduction.

Compared to traditional cast-in-place construction methods, the prefabricated sections in this case study emitted 467,141.97 kgCO_{2e}, representing a reduction of approximately 73% compared to the cast-in-place sections (3,156,886.68 kgCO_{2e}), demonstrating the significant potential of prefabrication technology for emission reduction; however, it should be noted that its overall carbon benefits are highly dependent on the carbon intensity of raw materials and transportation distances.

Looking ahead, the evaluation framework established in this study can be deeply integrated with cutting-edge digital technologies, significantly enhancing the precision and efficiency of carbon management:

- (1) By embedding the carbon emission factors identified in this study into BIM component libraries, model-based carbon budgets can be automatically generated during the design phase.
- (2) Leveraging machine learning algorithms, carbon emission prediction models trained on historical project data can dynamically simulate and optimise carbon footprints under different design schemes, construction techniques, and supply chain layouts.

6. Conclusions

In alignment with the low-carbon transition objectives in the construction sector, we established a carbon footprint assessment framework for the prefabricated housing materialisation stage by employing the carbon emission factor method. The framework was applied to a representative prefabricated residential project, where its reliability was tested. In addition, a comparative evaluation was carried out between floors constructed with conventional cast-in situ techniques and those using prefabricated components. The major outcomes can be summarised as follows:

- (1) From a project-wide perspective, carbon emissions during the materialisation phase are highly concentrated in the building material production process, accounting for 90.76% of total emissions and representing the dominant emission source. The remaining phases contribute as follows: on-site construction (3.83%), building material transportation (2.92%), on-site assembly (1.27%), component manufacturing (0.86%) and component transportation (0.36%). The above distribution highlights that the building material production process holds the greatest potential for emission reductions.
- (2) From the perspective of the prefabrication subsystem, the prefabricated components accounted for 12.67% (467,141.97 kgCO_{2e}) of the project's total carbon emissions. Within this subsystem, emissions exhibit distinct components, with material production accounting for 78.03%, factory manufacturing 6.77%, component transportation 2.84%, on-site installation 9.32%, and material transportation 3.05%; this structure indicates that, while prefabrication reduces on-site construction emissions, its carbon

benefits remain highly dependent on the carbon intensity of upstream supply chains. Although carbon emissions from prefabricated component transportation account for a relatively small proportion, their absolute value is positively correlated with transport distance; analysis indicates that the overall carbon benefits of prefabrication are highly dependent on the carbon intensity of upstream supply chains and logistics radii. If supply chain layouts are inefficient, leading to excessively long transport distances, the carbon advantages may be partially offset; therefore, promoting low-carbon building materials, optimising regional supply chain layouts, and enhancing factory energy efficiency are key pathways to achieving deep emission reductions in prefabricated construction.

The cast-in-place subsystem's carbon emissions accounted for 85.62% (3,156,886.68 kgCO_{2e}) of the project's total emissions, highly concentrated in material production (94.48%), followed by building material transportation (2.96%) and on-site construction (2.58%); this distribution highlights that carbon emissions from traditional cast-in-place methods are primarily locked in the building material production stage. Reduction efforts should therefore focus on replacing and optimising high-carbon building materials.

- (3) Comprehensive comparisons indicate that, while prefabrication technology reduces on-site construction emissions through industrialised production, the carbon benefits of both construction methods remain highly dependent on the carbon intensity of upstream building material production. Achieving the overall carbon advantage of prefabrication requires multiple measures, including adopting low-carbon building materials, optimising regional supply chain layouts, and enhancing factory energy efficiency. From a theoretical perspective, this research enriches the literature on embodied carbon by clarifying the internal distribution of emissions during the materialisation phase; from a practical standpoint, it provides valuable references for policymakers, developers, and contractors in formulating effective strategies, such as promoting the use of low-carbon building materials, improving recycling systems, and enhancing production and logistics efficiency.

Several study limitations should be acknowledged. First, the exclusion of minor materials and consumables may result in an underestimation of total emissions in certain scenarios. Second, despite regional adjustments, the emission factors derived from national and international databases may not fully capture local technological conditions. Additionally, since the analysis is based on a single project in Jiangxi Province, the findings may have limited representativeness and transferability. To address these gaps, future research should aim to expand both regional and building-type coverage, incorporate dynamic life cycle assessment methods, and leverage advanced digital tools, such as BIM-based carbon monitoring and AI-driven predictive modelling. Such integration would significantly enhance the accuracy and practical utility of carbon footprint accounting. Specifically, future studies should focus on coupling the proposed model with Building Information Modelling (BIM) and AI-enabled analytics to enable real-time carbon emission tracking against predefined targets during construction, automated environmental product declaration (EPD) generation for building components, and dynamic scenario simulations at the design phase to rapidly evaluate the carbon impacts of various material selections and supply chain configurations.

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Appendix A. Summary Table of Carbon Emission Factors

To ensure the traceability of the research calculation results, the carbon emission factors adopted in this study are all sourced from authoritative standards, literature and related databases, covering energy, building materials, electricity and transportation links. The various carbon emission factors are as follows.

Appendix A.1. Carbon Emission Factors from Fossil Energy

Table A1. Main carbon emission factors of fossil energy.

Energy Type	Carbon Oxidation Rate	Lower Calorific Value	Carbon Content	CO ₂ Factor	N ₂ O Factor	CH ₄ Factor	Emission Factor (kgCO _{2e} /Unit)
Fuel oil	0.98	0.000042	21,100	3.17441	0.6	3	3.18
Gasoline	0.98	0.000044	18,900	2.92873	0.6	3	2.94
Diesel	0.98	0.000043	20,200	3.09975	0.6	3	3.11
Raw coal	0.98	0.000021	26,370	1.98363	1.5	1	1.99
Natural gas	0.99	0.000038	15,320	2.16769	0.1	1	2.17
Crude oil	0.98	0.000042	20,080	3.02095	0.6	3	3.03
Coal gangue	0.98	0.000008	25,800	0.77633	1.5	1	0.78
Other coal washing	0.98	0.000010	25,410	0.95451	1.5	1	0.96
Briquettes	0.90	0.000020	33,560	2.31551	1.5	1	2.32
Coke	0.93	0.000021	29,420	2.85617	1.5	1	2.87
Coke oven gas	0.99	0.000018	13,580	0.88746	0.1	1	0.89
Washed clean coal	0.98	0.000026	25,410	2.40839	1.5	1	2.42
Converter gas	0.99	0.000071	49,600	14.3048	0.1	1	14.31
Blast furnace gas	0.99	0.000003	12,200	0.16686	0.1	1	0.17

Appendix A.2. Electricity Carbon Emission Factor

According to the grid regional carbon factor released by the Climate Change Strategy Institute (2019), carbon emission levels vary significantly due to different power source structures.

Table A2. Carbon footprint factors of regional power grids in China in 2019.

Power Grid Area	Covered Provinces	Emission Factor (kgCO ₂ /kWh)
Northeast Power Grid	Liaoning, Heilongjiang, Jilin	1.0826
North China Power Grid	Beijing, Tianjin, Hebei, Shandong, Shanxi, Inner Mongolia	0.9419
Northwest Power Grid	Shaanxi, Gansu, Ningxia, Xinjiang, Qinghai	0.8922
East China Power Grid	Shanghai, Zhejiang, Fujian, Jiangsu, Anhui	0.7921
Central Power Grid	Henan, Hubei, Jiangxi, Hunan, Chongqing, Sichuan	0.8587
China Southern Power Grid	Guangxi, Guangdong, Guizhou, Yunnan, Hainan	0.8042

Appendix A.3. Carbon Emission Factors of Building Materials

Appendix A.3.1. Building Raw Materials

Table A3. Carbon emission factors of building raw materials.

Building Materials Categories	Material Name	Unit	Emission Factor (kgCO _{2e} /Unit)	Note
Building Raw Materials	Tap water	t	0.168	Calculation Standard (Based on CLCD)
	Sand	t	2.51	
	Crushed stone	t	2.18	
	Clay	t	2.69	
	Lime	t	1190	
	Fly ash	t	8.385	Take the mean value from the literature review
	Timber	m ³	178	Literature [36] Recommendation score

Appendix A.3.2. Non-Metallic Materials

Table A4. Carbon emission factors of non-metallic materials.

Materials	Building Materials	Unit	Emission Factor (kgCO _{2e} /Unit)	Note
Cement	Ordinary Portland Cement (PO)	t	1120	Literature [36,37], Calculation standard (based on CLCD) selected by average value
	Slag Portland Cement (PS)	t	820	
	Pozzolanic Portland Cement (PP)	t	631.5	Literature [36], Calculation standard selected by average value
Concrete	C20	m ³	250	Literature [36,37], Calculation standard (based on CLCD) selected by average value
	C25	m ³	267.7	
	C30	m ³	287.7	
	C35	m ³	307.7	
	C40	m ³	327.7	
	C50	m ³	367.7	
Mortar	Masonry mortar	m ³	220	
	Plastering cement mortar	m ³	10	

Appendix A.3.3. Metal Materials

Table A5. Carbon emission factors of metal materials.

Building Materials	Materials	Unit	Emission Factor (kgCO _{2e} /Unit)	Note
Steel	Hot-rolled carbon steel small sections	t	2310	Calculation Standard (Based on CLCD)
	Hot-rolled carbon steel medium sections	t	2365	
	Hot-rolled carbon steel large sections	t	2380	
	Hot-rolled carbon steel reinforcing bars	t	2340	
	Hot-rolled carbon steel high-speed wire rod	t	2375	
Aluminium	Aluminium products	t	15,450	Carbon Emission Calculation Standard for Buildings GB/T 51366-2019
Iron	Iron products (such as iron nails and iron wire)	t	2000	

Appendix A.3.4. Other Building Materials

Table A6. Carbon emission factors of other building materials.

Building Materials	Materials	Unit	Emission Factor (kgCO _{2e} /Unit)	Note
Wall Materials	Concrete bricks	m ³	336	Calculation Standard (based on CLCD)
	Autoclaved fly ash bricks	m ³	341	
	Clay hollow bricks	m ³	250	
	Solid shale bricks	m ³	292	
	Sintered coal gangue solid bricks	m ³	22.8	Carbon Emission Calculation Standard for Buildings GB/T 51366-2019
	Aerated concrete blocks	m ³	270	
	Sintered perforated bricks	m ³	215	
Glass	Toughened glass	t	1790	Carbon Emission Calculation Standard for Buildings GB/T 51366-2019
	General-purpose glass	t	1190	
Thermal insulation materials	Ordinary polystyrene (PS)	t	4620	Calculation standard (based on CLCD)
	Rock wool board	t	1980	
Paints and coatings	Paint coatings	t	3500	Carbon Emission Calculation Standard for Buildings GB/T 51366-2019
Waterproofing membranes	ABS-modified bitumen waterproofing membrane	m ²	0.72	Carbon Emission Calculation Standard for Buildings GB/T 51366-2019

Appendix A.4. Carbon Emission Factors in the Transportation of Building Materials

Table A7. Carbon emission factors for building materials transportation.

Transportation Category	Emission Factor (kgCO _{2e} /t·km)	Emission Factor (*1.67)
Light-duty diesel lorry transport (payload 2 t)	0.286	0.478
Medium-duty petrol lorry transport (payload 8 t)	0.115	0.192
Light-duty petrol lorry transport (payload 2 t)	0.334	0.558
Heavy-duty petrol lorry transport (payload 18 t)	0.104	0.174
Heavy-duty diesel lorry transport (payload 30 t)	0.078	0.130
Medium Diesel Lorry Transport (Payload 8 t)	0.179	0.299
Heavy Petrol Lorry Transport (Payload 10 t)	0.104	0.174
Heavy Diesel Lorry Transport (Payload 18 t)	0.129	0.215
Heavy Diesel Lorry Transport (Payload 10 t)	0.162	0.271
Heavy Diesel Lorry Transport (Payload 46 t)	0.057	0.095

Note: The Emission Factor (*1.67) should be applied in cases of empty return trips to account for the corrected carbon footprint factor.

Appendix A.5. Carbon Footprint Calculation for Traditional Cast-in-Place and Prefabricated Construction Methods

Table A8. Specific construction contents of each sub-item and sub-division.

Sub-Projects and Sub-Items	Traditional Cast-in-Place Method	Assembly Method
Masonry work	Masonry Material Production	ALC Wall Panel Production
	Masonry Material Transportation	ALC Wall Panel Transportation
	On-Site Masonry Construction	ALC Wall Panel Installation

Table A8. Cont.

Sub-Projects and Sub-Items	Traditional Cast-in-Place Method	Assembly Method
Steel bar engineering	Reinforcement Production for Cast-in-Place Sections	Precast Reinforcement Production
	Reinforcement Transportation for Cast-in-Place Sections	Precast Reinforcement Transportation
	Reinforcement Fabrication and Assembly for Cast-in-Place Sections	Precast Reinforcement Fabrication and Installation
Template engineering	Concrete Production for Cast-in-Place Sections	Precast Concrete Production
	Concrete Transportation for Cast-in-Place Sections	Precast Concrete Transportation
	Concrete Placement for Cast-in-Place Sections	Precast Component Transportation and Installation
Concrete engineering	Material Production	Typically, precast formwork can be reused in factories, with its environmental impact already factored into the carbon emission factor for component production. The on-site portion is accounted for in cast-in-place construction
	Material Transportation	
	Formwork Construction	

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