

Original Article



Measurement and Analysis of Carbon Emissions during the Operational Phase of Prefabricated Concrete Buildings Based on the Carbon Emission Factor Method

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Abstract:

As one of the major sources of greenhouse gas emissions, buildings have been designated as a key area for carbon reduction initiatives across various countries. Both the Paris Agreement and the United Nations Sustainable Development Goals have explicitly called for the promotion of a low-carbon transition in the construction industry. In response to global climate governance, China has proactively put forward its "Dual Carbon" goals. Although numerous new initiatives have been proposed to mitigate carbon emissions from buildings, there remains a lack of comprehensive investigations into the life-cycle greenhouse gas emissions of buildings, especially in high-density urban areas. Furthermore, without reliable data on building emission levels, it is difficult to identify targeted aspects for reducing greenhouse gas emissions during the operational phase. Therefore, by comparing prefabricated concrete buildings with conventional cast-in-place concrete buildings, this paper aims to investigate the carbon emission characteristics of prefabricated residential buildings during the operational phase, explore the carbon reduction effects of prefabrication technology, and provide specific guidelines and strategies for cutting carbon emissions in the operational stage. The results demonstrate that prefabricated concrete buildings achieve a 16.7% reduction in carbon emissions per unit area compared with traditional buildings. The findings of this study can provide valuable support for stakeholders in pursuing low-carbon and sustainable development in the future.

Keywords: Prefabricated Buildings; Operational Phase; Carbon Emission Calculation

1. Introduction

Against the macro backdrop of global energy transition and green development, the construction industry, as a key sector for energy consumption and greenhouse gas emissions, is facing an increasingly urgent need for low-carbon transformation. Research by Yolcan indicates that renewable energy will play a crucial role in the coming decade, providing fundamental energy support for the green transition of the construction industry[1]. To accurately quantify the environmental impact of buildings, Life Cycle Assessment (LCA) has become a core methodology. Studies by Zhan et al. show that carbon emission calculation at the operational stage of buildings based on the LCA framework

enables a systematic evaluation of the environmental impacts of prefabricated buildings[2]. Furthermore, research by Cheng et al. further verifies the applicability of this method in carbon measurement during the operational phase of buildings[3]. Xiong et al. conducted a comprehensive review and future projection of embodied carbon emissions in residential buildings in China[4].

The research scope is expanding from individual buildings to regional scales. Qing et al. conducted an in-depth exploration of the spatiotemporal patterns and impact mechanisms of carbon emissions in urban agglomerations in China[5]. Zhao et al. adopted the eddy covariance method

to compare and analyze the dynamic changes in urban carbon flux before and after specific regulatory periods[6]. Meanwhile, emerging research fields continue to emerge. Li et al. systematically reviewed studies on the correlation between digital economic development and carbon emissions[7], and Wang et al. proposed coordinated control pathways for carbon emissions and air pollution[8].

In terms of technical application, the study by Hao et al. innovatively applied the integrated BIM-LCA method to evaluate the embodied carbon of wood formwork waste[9], which promoted the refined research on the sustainability of prefabricated buildings. The origin of this methodology can be traced back to the Building LCA Guide issued by the Architectural Institute of Japan in 2006[10]. In subsequent studies, Ding et al. verified the effectiveness of the research method for carbon emissions in the construction process of prefabricated buildings based on BIM and LCA[11], and Zhan et al. systematically analyzed the influencing factors of carbon emissions during the operational phase of prefabricated buildings[12]. In addition, the BIM measurement system developed by Ding et al. provided a complete solution for carbon accounting during the operational phase of prefabricated residential buildings[13]. Ali et al. systematically reviewed the methods and tools for urban building energy modeling[26], and Ang provided detailed guidance for the implementation of the Logarithmic Mean Divisia Index method (LMDI decomposition method)[27].

Regarding the research on influencing factors, Huang and Wang conducted a systematic analysis of carbon emissions from prefabricated structures in China[14], and Cheng et al. focused specifically on the measurement methods for carbon emissions during the operational phase of buildings[15]. Wang assessed the carbon emission reduction potential of prefabricated concrete

structures[16], while Wang et al. extended their research to the measurement and evaluation of carbon emissions during the operational phase of large-scale public buildings[17]. At the urban scale, Jo and Kim examined the spatial effects of urban spatial structure on building carbon emissions at the neighborhood level[18], and W et al. evaluated the impact of urban morphology on carbon emissions from commercial buildings in Beijing at the block scale[19]. In functional research, Yang et al. took Henan Province as an example to explore the influencing factors and peak attainment pathways of carbon emissions from residential buildings[20]. Fan et al. investigated the carbon emission characteristics and reduction potential of new campus building complexes through life cycle assessment[21]. Zhao et al. calculated the full life cycle carbon emissions of inpatient buildings using BIM and LCA methods[23]. Zheng et al. mapped the embodied carbon emissions of building materials in the Beijing-Tianjin-Hebei urban agglomeration[24], and Wang and Pan assessed long-term embodied carbon scenarios for Hong Kong's building sector under uncertainty[25].

Nevertheless, there are still obvious shortcomings in existing research. Most studies on prefabricated concrete buildings only focus on calculating carbon emissions at the single-building level, while comparative analyses of carbon emissions between traditional cast-in-place buildings and prefabricated concrete buildings remain relatively insufficient. Moreover, when calculating carbon emissions during the building material transportation stage, the emissions generated during the delivery of materials to prefabricated component factories are often overlooked. Taking a specific prefabricated concrete building as a case study, this paper employs BIM technology to conduct an in-depth investigation into the calculation of carbon emissions during the operational phase, and carries out a comparative analysis of carbon emissions between

prefabricated concrete buildings and traditional cast-in-place buildings. This study aims to verify whether the adoption of prefabrication can effectively reduce building carbon emissions, and proposes practical measures to cut carbon emissions from prefabricated buildings, so as to provide a robust demonstration for carbon emission calculation of prefabricated concrete buildings.

2. Model Establishment

2.1 Definition of System Boundaries for the Operational Phase

In this paper, the temporal boundary is defined as the embodied phase of prefabricated concrete buildings. The embodied phase mainly covers five stages: building material production, material transportation, component production, component

transportation, and on-site construction. The spatial boundary is defined as the activity sites associated with the entire embodied phase of prefabricated concrete buildings, mainly referring to all main structural components from the building foundation to the highest point of the building, including material production sites, component production plants, construction sites, and transportation routes for machinery and materials.

2.2 Acquisition of Carbon Emission Factors

This paper summarizes and compiles the required carbon emission factor data by referring to China's *Standard for Building Carbon Emission Calculation* (GB/T 51366-2019) and currently published papers, as shown in Table 1.

Table 1 Building Carbon Emission Factors

Factor Type	Name	Carbon Emission Factor	Unit	Source
Energy Type	Gasoline	2.930	kgCO ₂ /kg	(GB/T51366-2019)
	Diesel	3.100	kgCO ₂ /kg	(GB/T51366-2019)
	Electricity	0.527	kgCO ₂ /kWh	(GB/T51366-2019)
Building Material Type	Concrete C20	234.700	kgCO ₂ /m ³	(GB/T51366-2019)
	Concrete C30	295.000	kgCO ₂ /m ³	(GB/T51366-2019)
	Concrete C40	340.000	kgCO ₂ /m ³	(GB/T51366-2019)
	Autoclaved Aerated Concrete Block	341.000	kgCO ₂ /m ²	(GB/T51366-2019)
	Cement	735.000	kgCO ₂ /t	(GB/T51366-2019)
	Medium Sand	2.510	kgCO ₂ /kg	(GB/T51366-2019)
	Crushed Stone	2.180	kgCO ₂ /kg	(GB/T51366-2019)
	Galvanized Iron Wire	2757.000	kgCO ₂ /t	Dong Z, et al[22]
	Hot-Rolled Steel Bar	2340.000	kgCO ₂ /t	Dong Z, et al[22]
Aluminum Formwork	3.400	kgCO ₂ /t	Dong Z, et al[22]	
Latex Paint	6.900	kgCO ₂ /kg	Sun Shan, Niu Jianguang [28]	
Coating	3.600	kgCO ₂ /kg	Sun Shan, Niu Jianguang [28]	
Aluminum Alloy Doors and Windows	194.000	kgCO ₂ /m ²	Sun Shan, Niu Jianguang [28]	

	Architectural Ceramics	1.400	kgCO ₂ / m ²	Sun Shan, Niu Jianguang [28]
	Waterproof Membrane	4.010	kgCO ₂ /(t*km)	Sun Shan, Niu Jianguang [28]
Transportation Type	Light Gasoline Truck (Loading Capacity 2t)	0.334	kgCO ₂ /(t*km)	Li Ziru[29]
	Medium Gasoline Truck (Loading Capacity 8t)	0.115	kgCO ₂ /(t*km)	Li Ziru[29]
	Light Diesel Truck (Loading Capacity 2t)	0.286	kgCO ₂ /(t*km)	Li Ziru[29]
	Medium Diesel Truck (Loading Capacity 8t)	0.179	kgCO ₂ /(t*km)	Li Ziru[29]
	Heavy Diesel Truck (Loading Capacity 10t)	0.162	kgCO ₂ /(t*km)	Li Ziru[29]

2.3 Carbon Emission Calculation Model

In accordance with the temporal boundary division of prefabricated concrete buildings, the embodied phase is mainly categorized into the building material production stage, material transportation stage, component production stage, component transportation stage, and on-site construction stage. This paper analyzes the major carbon emission sources of each segment and establishes corresponding calculation models. The formula for calculating carbon emissions during the embodied phase is as follows:

$$E = E_{X1} + E_{X2} + E_{X3} + E_{X4} + E_{X5} \quad (\text{Formula 1})$$

Where, E represents the total carbon emissions of prefabricated concrete buildings during the embodied phase; E_{X1} represents the carbon emissions of building materials in the production stage; E_{X2} represents the carbon emissions of building materials in the transportation stage; E_{X3} represents the carbon emissions of prefabricated components in the production stage; E_{X4} represents the carbon emissions of prefabricated components in the transportation stage; E_{X5} represents the carbon emissions in the on-site construction stage.

2.3.1 Building Material Production Stage

The production process of building materials in the prefabricated concrete plant is a comprehensive procedure, which mainly involves

two categories: building materials and mechanical equipment. Carbon emissions associated with building materials derive from the input of various construction materials used in prefabricated component manufacturing and cast-in-place sections. For prefabricated residential buildings, component production mainly consists of core materials such as steel bars, concrete, and cement, together with a series of auxiliary materials. Carbon emissions from mechanical equipment mainly come from energy consumption including electricity, diesel, coal, and other fuels during the operation of machinery such as vibrating tables, mixers, and steam curing machines.

Carbon emissions during the building material production stage refer to the greenhouse gas emissions generated in the process of manufacturing building materials, and the calculation formula is as follows:

$$E_{X1} = \sum_{i=1}^n (M_i \times F_i) \quad (\text{Formula 2})$$

Where E_{X1} represents the carbon emissions during the building material production stage; M_i represents the demand for the i -th major building material; F_i represents the carbon emission factor of the i -th major building material.

2.3.2 Building Material Transportation Stage

One of the core customers of building material manufacturers is prefabricated component

manufacturers. Therefore, building materials need to be transported to component manufacturers as well as to the construction site. Such a supply relationship serves as the foundation for the operation of the prefabricated concrete building industrial chain. Due to differences in calculation methods, the transportation stage is divided into concrete transportation and other building material transportation, and the calculation formulas are as follows:

$$E_{X2} = E_{X2H} + E_{X2Q} \quad (\text{Formula 3})$$

$$E_{X2H} = \sum_{j=1}^n \left(\frac{M_j}{R} \times D_j \times F_j \times T_j \right) \quad (\text{Formula 4})$$

Where, E_{X2} represents the carbon emissions of building materials during the transportation stage; E_{X2H} represents the carbon emissions generated by concrete transportation; M_j represents the consumption of the j -th type of concrete; R represents the capacity of the concrete mixer truck; D_j represents the transportation distance of the j -th type of concrete; F_j represents the energy consumption per kilometer of the concrete mixer truck; T_j represents the energy carbon emission factor.

$$E_{X2Q} = \sum_{i=1}^n (M_i \times L_i \times T_i) \quad (\text{Formula 5})$$

Where, E_{X2Q} represents the carbon emissions generated by the transportation of other building materials; M_i represents the demand for the i -th building material; L_i represents the average transportation distance of the i -th building material; T_i represents the carbon emission factor per unit transportation distance of the i -th building material.

2.3.3 Component Production Stage

Prefabricated components are produced through standardized construction with numerous technical processes. Therefore, the research object of carbon emissions is mainly components with independent functions. The calculation formula is as follows:

$$E_{X3} = \sum_{j=1}^n (P_j \times E_{sc,j} \times EF_j) \quad (\text{Formula 6})$$

Where, E_{X3} represents the carbon emissions during component production; P_j represents the machine shift quantity of the j -th type; $E_{sc,j}$ represents the energy consumption of the j -th machine; EF_j represents the carbon emission factor of the energy used by the j -th machine.

2.3.4 Component Transportation Stage

Transportation of prefabricated components can be divided into two main stages: on-site transportation and off-site transportation. This paper mainly focuses on off-site transportation, and the calculation formula is as follows:

$$E_{X4} = \sum_{j=1}^n \sum_{i=1}^m (L_{i,j} \times G_i) \times T_i \quad (\text{Formula 5})$$

Where, C_{X4} represents the carbon emissions during component transportation; G_i represents the weight of the i -th type of component; T_i represents the carbon emission factor per unit weight of the i -th component during transportation; $L_{i,j}$ represents the average transportation distance of the i -th component under the j -th transportation mode.

2.3.5 On-site Construction Stage

During the construction of the cast-in-place part, carbon emissions mainly result from the operation of construction machinery and on-site work by construction workers. The calculation formulas are as follows:

$$E_{X5} = E_{X5J} + E_{X5R} \quad (\text{Formula 6})$$

$$E_{X5J} = \sum_{i=1}^n (E_i \times F_i \times EF_i) \quad (\text{Formula 7})$$

Where, E_{X5} represents the carbon emissions during the on-site construction stage; E_i is the machine shift quantity in the i -th project; F_i represents the energy consumption per unit of the i -th construction machine; EF_i represents the carbon emission factor of the corresponding energy type.

$$E_{X5R} = Q_r \times F_r \quad (\text{Formula 8})$$

Where, Q_r represents labor consumption; F_r represents the labor carbon emission factor.

3. Case Analysis

3.1 Project Overview

This paper selects a prefabricated high-rise residential building in China as the research case. It adopts a reinforced concrete frame structure, with prefabricated composite floor slabs and prefabricated stair flights as the core prefabricated components, and the assembly rate is 54%.

The composite slabs and stair flights from the first-floor roof slab to the top roof are constructed

using prefabricated technology, while the remaining parts are cast-in-place structures. The composite floor slab consists of a precast concrete base slab and an upper cast-in-place layer. Truss reinforcements are arranged in the precast slab to improve the overall stiffness and shear resistance of the horizontal section. In addition, expanded polystyrene boards are used for external walls, foam glass insulation boards for the roof, and plastic profiles for external windows. The detailed project overview is shown in Table 2.

Table 2 Project Overview

Item	Description
Total Building Area	11159.44m ²
Building Height	60m
Standard Floor	3m
Above-Ground Floors	18F
Underground Floors	1F
Above-Ground Building Area	9852.3m ²
Underground Building Area	1307.14m ²
Structure Type	Shear Wall Structure
Types of Prefabricated Components	Composite Slabs, Prefabricated Stairs

3.2 Carbon Emission Calculation

3.2.1 Building Material Production Stage

Building material production is the initial stage in the embodiment of prefabricated residential

buildings. The corresponding concrete quantities are 88.488 m³ of C20 concrete, 190.67 m³ of C25 concrete, 7672.998 m³ of C30 concrete, 1106.822 m³ of C35 concrete, and 1707.512 m³ of C40 concrete.

Carbon Emission Status in the Building Material Production Stage

Material Type	Unit	Project Quantity	Carbon Emission Factor	Carbon Emissions
C20 Concrete	m ³	88.488	234.000	20706.192
C25 Concrete	m ³	190.670	286.630	54651.7421
C30 Concrete	m ³	5672.998	295.000	1673534.41
C35 Concrete	m ³	3106.822	317.500	986415.985
C40 Concrete	m ³	1707.512	340.000	580554.08
Steel	t	4100.000	2050.000	8405000
Masonry	m ³	1122.512	341.000	382776.592
Cement	t	506.794	735.000	372493.59
Sand	t	2057.400	2.510	5164.074
Crushed Stone	t	227.400	2.180	495.732
Aluminum Formwork	t	18.048	3.400	61.3632

Latex Paint	t	4.786	6.900	33.0234
Coating	t	23.106	3.600	83.1816
Aluminum Alloy Windows	m ²	388.000	194.000	75272
Wooden Doors	m ²	3695.000	878.500	3246057.5
Architectural Ceramics	t	6.878	1.400	9.6292
Waterproof Membrane	m ²	1803.960	4.010	7233.8796
Total				4546740.914

3.2.2 Building Material Transportation Stage

Based on field investigation of the project, the transportation distance of concrete to the construction site and prefabricated component factory is calculated as 60 km, while the distance of other materials to the prefabricated component factory and construction site is 120 km. Concrete is transported by concrete mixer trucks with a

capacity of 12 m³, and other materials are transported by 10 t heavy-duty diesel trucks. For concrete mixer trucks, the diesel consumption during concrete transportation is 0.35 L/km, the diesel density is 0.84 kg/L, and the diesel carbon emission factor is 3.10 kgCO₂/kg. After unit conversion, the diesel carbon emission factor is 2.604 kgCO₂/L. The carbon emission factor of heavy-duty diesel trucks is 0.162 kgCO₂e/t·km.

Carbon Emissions during Concrete Transportation

Material Type	Project Quantity	Mixer Truck Volume	Destination	Carbon Emission Factor	Carbon Emissions
C20 Concrete	88.488	12	Construction Site	2.604	1152.113
C25 Concrete	190.670	12	Construction Site	2.604	2482.523
C30 Concrete	4538.398	12	Construction Site	2.604	59089.946
	1134.600	12	Prefabricated Component Factory	2.604	14772.487
C35 Concrete	2174.775	12	Construction Site	2.604	24270.493
	932.047	12	Prefabricated Component Factory	2.604	16180.329
C40 Concrete	1195.258	12	Construction Site	2.604	13339.084
	512.254	12	Prefabricated Component Factory	2.604	8892.722
Total					140179.697

Carbon Emissions during Transportation of Other Building Materials

Material Type	Unit	Project Quantity	Material Unit Weight	Destination	Carbon Emission Factor	Carbon Emissions
Steel	t	1025	1.000	Construction Site	0.162	59778

		3075	1.000	Prefabricated Component Factory	0.162	19926
Masonry	m ³	898.010	0.800	Construction Site	0.162	13965.845
		224.502	0.800	Prefabricated Component Factory	0.162	3491.461
Cement	t	354.756	1.000	Construction Site	0.162	6896.453
		152.038	1.000	Prefabricated Component Factory	0.162	2955.623
Sand	t	1440.180	1.000	Construction Site	0.162	27997.106
		617.220	1.000	Prefabricated Component Factory	0.162	11998.757
Crushed Stone	t	159.180	1.000	Construction Site	0.162	3094.459
		68.220	1.000	Prefabricated Component Factory	0.162	1326.197
Aluminum Formwork	t	18.048	1.000	Construction Site	0.162	1754.265
Latex Paint	t	4.786	1.000	Construction Site	0.162	93.039
Coating	t	23.106	1.000	Construction Site	0.162	449.180
Aluminum Alloy Windows	m ²	388.000	0.534	Construction Site	0.162	4027.812
Wooden Doors	m ²	3695.000	1.000	Construction Site	0.162	71830.8
Architectural Ceramics	t	6.878	0.350	Construction Site	0.162	46.797
Waterproof Membrane	m ²	1803.960	0.006	Construction Site	0.162	210.413
Total						228438.791

3.2.3 Component Production Stage

The component production stage is a critical part in the whole life cycle of a construction project, involving many important procedures and quality control points. Common raw materials for prefabricated component production include

cement, sand, crushed stone, steel bars, etc., and the quality of these materials is directly related to the performance of prefabricated components. The component production stage covers concrete pouring, curing, and final formation of finished components, where the main source of carbon emissions is machinery operation.

Machine Type	Specification	Machine Shift Quantity	Energy Consumption per Shift	Energy Type	Carbon Emission Factor of Energy	Carbon Emission Factor
Concrete Mixer	500L	5.324	107.71	Electricity	0.527	302.207

Concrete Spreader	Belt Type	9.748	143.46	Electricity	0.527	736.982
Steel Bar Cutting Machine	Diameter 40 mm	16.210	32.10	Electricity	0.527	274.219
Steel Bar Straightening Machine	Diameter 40 mm	48.620	57.25	Electricity	0.527	1466.902
Steel Bar Bending Machine	Diameter 40 mm	46.820	12.80	Electricity	0.527	315.828
AC Arc Welding Machine	40kVA	19.810	132.23	Electricity	0.527	1380.464
Butt Welding Machine	Capacity 75 kVA	3.600	122.00	Electricity	0.527	231.458
Total						4708.06

3.2.4 Component Transportation Stage

Different from the transportation of building materials, the transportation of prefabricated components is affected by their shape and stacking requirements. Prefabricated components shall not be stacked higher than six layers. According to the field investigation, one heavy-duty diesel truck can transport 12 composite slabs

or 2 prefabricated stairs. The quantity of various prefabricated components required is counted as 864 prefabricated composite slabs and 96 prefabricated stairs. The distance from the prefabricated component factory to the construction site is about 40 km, which is used to calculate carbon emissions during the component transportation stage.

Component Name	Unit	Actual Quantity	Transportation Machine	Transportation Trips	Transportation Distance	Carbon Emission Factor	Carbon Emissions
Prefabricated Composite Slab	piece	864	Heavy-duty Diesel Truck	72	40	1.62	4031078.4
Prefabricated Stairs	piece	96	Heavy-duty Diesel Truck	48	40	1.62	298598.4
Total							329676.8

3.2.5 On-site Construction Stage

Cast-in-place construction is still adopted for structural columns, beams and other components

in this project. Carbon emissions are calculated according to the project quantity, and the carbon emissions during the on-site construction stage are shown in the table.

Carbon Emission Calculation for Cast-in-place Part in On-site Construction Stage

Machine Type	Specification	Machine Shift Quantity	Energy Consumption per Shift	Energy Type	Carbon Emission Factor of Energy	Carbon Emissions
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Crawler-type Single-bucket Hydraulic Excavator	Bucket Capacity 1m ³	66.004	63.00	Diesel	3.120	12973.746
Truck	6t	146.210	33.24	Diesel	3.120	15163.264
Dump Truck	6t	124.730	31.34	Gasoline	2.930	11453.482
Water Sprinkler	4000L	8.430	30.21	Gasoline	2.930	746.184
Concrete Vibrator	Internal Type	606.480	4.00	Electricity	0.527	1278.460
Concrete Vibrator	External Type	146.220	4.00	Electricity	0.527	308.232
Electric Tamping Machine	Ramming energy 250 Nm	64.420	16.60	Electricity	0.527	563.559
Tower Crane	2500t	71.730	266.04	Electricity	0.527	10056.770
Truck Crane	30t	414.360	42.14	Gasoline	2.930	51161.112
Steel Bar Cutting Machine	Diameter 40 mm	271.900	32.10	Electricity	0.527	4599.651
Steel Bar Bending Machine	Diameter 40 mm	504.600	12.80	Electricity	0.527	3403.830
Butt Welding Machine	Capacity 75 kVA	31.140	122.00	Electricity	0.527	2002.115
Wood Circular Saw	Diameter 500 mm	8.200	24.00	Electricity	0.527	103.714
Crawler Bulldozer	105kW	28.500	60.80	Diesel	3.120	5406.336
AC Arc Welding Machine	40kVA	225.432	132.23	Electricity	0.527	15709.276
Electric Single-Drum High-Speed Winch	30kN	114.370	32.90	Electricity	0.527	1982.981
Concrete Mixer	500L	64.320	107.71	Electricity	0.527	3651.007
Concrete Delivery Pump	45m ³ /h	120.280	243.46	Electricity	0.527	15432.335
Mortar Mixer	200L	54.440	8.61	Electricity	0.527	247.020
Auger Drilling Rig	Hole diameter 600 mm	190.356	181.27	Electricity	0.527	18184.574
Truck	6t	26.95	33.24	Diesel	3.120	2794.952
AC Arc Welding Machine	32kVA	36.67	91.20	Electricity	0.527	1762.448
Mortar Mixer	200L	0.730	8.61	Electricity	0.527	3.312
Total						327976.72

Obviously, the production process of building materials is a core area for carbon emission reduction, with enormous potential for carbon

mitigation.

3.3 Carbon Emission Calculation under Traditional Construction Method

To ensure the accuracy and comparability of the research conclusions, this paper converts all prefabricated components into code-compliant cast-in-place structures using technical methods while keeping all design parameters, material consumption, and structural performance of the original project unchanged. This setting makes

the construction method the only variable affecting carbon emissions, thus achieving an accurate quantification of the emission reduction benefits of prefabricated technology. The carbon emission analysis results at each stage under this benchmark are shown in the table.

Stage	Carbon Emissions	Proportion
Building Material Production Stage	5944226.324	88.9%
Building Material Transportation Stage	339877.272	5.1%
On-site Construction Stage	408855.276	6.0%
Total	6692958.872	

It can be seen from the table that during the embodied phase of traditional buildings, carbon emissions from building material production account for the largest proportion, as high as

88.9%; followed by the on-site construction stage and the building material transportation stage, with proportions of 5.1% and 6.0% respectively.

3.4 Analysis of Calculation Results



Building Material Production Stage	Building Material Transportation Stage	On-site Construction Stage
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Building Material Production Stage	Building Material Transportation Stage	Component Production Stage	Component Transportation Stage	On-site Construction Stage
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Without changing other components and structural details, the prefabricated construction method yields lower carbon emissions. Among them, carbon emissions are reduced by 1392777.35 kgCO₂ in the building material production stage, increased by 358421.016 kgCO₂ in the building material transportation stage, and reduced by 80878.556 kgCO₂ in the on-site construction stage. The total carbon emissions are reduced by 1115237.89 kgCO₂, and the carbon emissions per unit area are reduced by 99.93 kgCO₂. The comparison shows that prefabricated buildings can significantly reduce building carbon emissions.

4. Conclusions and Recommendations

Taking a prefabricated high-rise residential building as a case study, this paper establishes a carbon emission calculation model covering five stages: building material production, material transportation, component production, component transportation and on-site construction. The carbon emission coefficient method is used to quantitatively analyze the carbon emission characteristics of prefabricated buildings in the

embodied phase, and a comparison with the traditional cast-in-place scheme is conducted. The main conclusions are as follows:

(1) The carbon emission per unit floor area of prefabricated concrete buildings is 16.7% lower than that of traditional cast-in-place buildings, showing a significant emission reduction benefit. Carbon emissions in the building material production stage account for more than 80%, making it the core link for emission reduction.

(2) Compared with the traditional method, carbon emissions of prefabricated buildings decrease by 23.5% in the material production stage and 19.8% in the on-site construction stage. However, due to the increased transportation demand of prefabricated components, carbon emissions in the material and component transportation stages increase by 8.5% and 329.7 tCO₂ respectively. The supply chain layout and transportation efficiency have a significant impact on carbon performance.

(3) Carbon emissions in the component production stage mainly come from electrical energy consumption of equipment; although the

proportion is low, there is still room for optimization. Carbon emissions in the on-site construction stage decrease significantly due to the reduction of cast-in-place work, verifying the low-carbon advantage of prefabricated construction in the construction process.

(4) Based on the calculation results, carbon reduction strategies are proposed from five dimensions: building material selection, supply chain location, production technology, transportation organization, and construction management, which can provide a reference for the low-carbon practice of prefabricated concrete buildings.

This study improves the carbon emission calculation framework for the embodied phase of prefabricated buildings, and remedies the shortcomings in carbon accounting for material-component two-stage transportation and comparative studies between prefabricated and cast-in-place structures. The following recommendations are put forward:

(1) Building material production stage: This study shows that carbon emissions in the building material production stage account for the largest proportion of the total embodied emissions, serving as the key link for reduction. It is recommended to prioritize building materials with low carbon emission factors, optimize the concrete mix design in prefabricated component production, reduce the usage of high-carbon materials, and cut carbon emissions at the source.

(2) Building material transportation stage: The calculation reveals that carbon emissions in the transportation stage of prefabricated buildings are higher than those of traditional cast-in-place buildings due to component transportation. It is recommended to rationally plan the locations of material and prefabricated component suppliers in the early project stage to shorten the average transportation distance, optimize transportation plans, and select appropriate vehicle types and

loading methods to improve transportation efficiency.

(3) Prefabricated component production stage: The calculation shows that carbon emissions at this stage mainly come from electricity consumption of production equipment. It is recommended that prefabricated component manufacturers improve the automation of production processes, adopt high-efficiency production equipment, and reduce energy consumption per component by optimizing curing processes and other procedures.

(4) Prefabricated component transportation stage: The study indicates that carbon emissions in the component transportation stage are significantly affected by transportation distance and efficiency. It is recommended to give priority to prefabricated component factories close to the construction site, and improve single-vehicle transportation efficiency by rationally planning transportation routes and loading schemes, so as to reduce empty-load rates and transshipment times.

(5) On-site construction stage: The results demonstrate that prefabricated construction significantly reduces carbon emissions in the on-site construction stage. It is recommended to further optimize the construction organization of cast-in-place parts, improve the efficiency of construction machinery and energy utilization, and reduce the consumption of auxiliary materials and energy through refined construction management.

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