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Original Research

Research on Carbon Emission Intensity and Reduction Potential of Prefabricated Concrete Structure Construction Stage: A Case Study in Shenzhen, China

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Abstract

Large-scale construction of prefabricated concrete structures consumes a large amount of resources and energy and has become a major contributor to the environmental impact of the construction industry. Based on the life cycle assessment method, the carbon emission assessment of prefabricated concrete structures (PCS) in the construction stage was carried out, and the carbon emission intensity and level in the construction process of PCS were quantitatively analyzed. The results show that by the end of 2023, the total carbon emission of prefabricated buildings in Shenzhen has reached 4.3652 million tCO_2e, and the carbon emission intensity per unit area in the construction stage is 5398.31 $kgCO_2e/100\ m^2$. Among them, the contribution of the prefabricated component processing and production stage to carbon emissions per unit area is the largest, and its carbon emissions mainly come from hot-rolled steel bars and concrete. When the consumption of building materials and the change rate of carbon emission factors are the same, the change rate of carbon emissions per unit area is hot-rolled steel bars >concrete. By promoting the use of recycled steel, recycled concrete, and other green building materials, the highest carbon reduction rate in the construction process is 11.12%. According to the optimistic estimate, the carbon reduction intensity in 2025-2035 will be 943.3 million tCO_2e, helping Shenzhen to vigorously develop prefabricated buildings.

Keywords: prefabricated concrete structures (PCS), carbon emission intensity, reduction potential, life cycle assessment, sensitivity analysis

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Introduction

Addressing global warming has become a focal point at home and abroad. The 14th Five-Year Plan and the Long-term Goals for National Economic and Social Development of the People's Republic of China (2021-2035) propose that we strive to achieve a carbon emissions peak by 2030 and carbon neutrality by 2060. Achieving the "carbon peak" and "carbon neutrality" targets has significant strategic significance for promoting China's economic and social development and building a modern society in harmony with nature [1]. In 2019, the global carbon emissions in the construction sector were 12 $GtCO_2e$, accounting for 21% of global carbon emissions [2]. Reducing carbon emissions in the construction industry is an inevitable choice for achieving the "dual carbon" goal. Compared with the on-site construction mode, prefabricated construction can reduce energy consumption by 20%-30%, reduce material waste by 60%, and reduce construction waste by 83% [2]. It has attracted the attention of domestic and foreign scholars due to its advantages of a better construction environment, shorter construction period, and better component quality [3]. Prefabricated buildings can be classified into prefabricated concrete buildings, prefabricated steel structure buildings, prefabricated wooden structure buildings, and prefabricated composite material buildings according to the materials used for the main structure of the building. Among them, prefabricated concrete structures (PCS) refer to prefabricated buildings where the structural system is composed of concrete components or prefabricated components, which have the characteristics of high construction efficiency, easy control of material quality, short construction time, high safety performance, environmental protection during construction, and low labor cost, becoming a common form of prefabricated buildings and widely used in residential, commercial, and public building fields. In addition, the national and local levels have begun to pay attention to the carbon reduction benefits brought by the prefabricated construction mode in recent years. Therefore, it is necessary to quantify the carbon emission level and carbon reduction potential of prefabricated construction in the construction stage, providing a scientific basis for relevant policy formulation and promotion of prefabricated construction mode.

There have been many fruitful studies on the intensity of carbon emission and mitigation potential throughout various life cycles. In the field of urban rail transit, Chen et al. established a carbon emission evaluation method for subway systems based on life cycle assessment (LCA) theory, quantifying the carbon emission intensity and level of subways [4]. Li et al. established a carbon emission evaluation method for the utilization and disposal of tunnel sludge in subways based on LCA, quantifying the carbon emission intensity and mitigation potential of sludge utilization and disposal [5]. Many scholars have studied subway construction and tunnel boring relatively maturely. In the field of prefabricated buildings, Yu et al. established a carbon emission calculation model for prefabricated buildings with a recycling process based on LCA theory, calculating the carbon emissions of the physical stage of high-ductility regenerative micro-powder concrete structures [2]. Han et al. calculated the carbon emissions of prefabricated buildings with different assembly rates using the carbon emission coefficient method [6]. Zheng et al. established a life cycle evaluation model for prefabricated buildings based on LCA and calculated the life cycle carbon emissions of light steel prefabricated buildings [7]. In the field of PCS, scholars have begun to pay attention to the environmental impact of prefabricated concrete components. Research on carbon emissions from PCS has gradually attracted the attention of experts and scholars and can be classified into the following four categories: (i) Factors influencing the carbon emissions of PCS; (ii) Calculation methods for carbon emissions from PCS; (iii) Assessment and reduction of carbon emissions from PCS; (iv) Assessment and reduction of carbon emissions from prefabricated components. For example, Xu et al. established a carbon emission calculation model for prefabricated components in the production and construction stages based on the process inventory analysis method, they selected the precast concrete composite slabs and cast-in-place slabs of two typical residences as cases to conduct a comparative study on their carbon emissions in the production and construction stages [8]. Li et al. established an overall carbon footprint accounting model for the three materialization stages of precast concrete composites, namely component production, transportation logistics, and construction installation, comprehensively evaluated the quantity and distribution of their carbon emissions, and verified the proposed method and empirical results through detailed case studies [9]. Guo et al. established a coupled heat and moisture transfer model to analyze the influence of different connection methods on the heat and moisture performance of the envelope structure of prefabricated concrete buildings, mainly studying two typical connection methods of prefabricated buildings: grouting sleeve connection and bolt connection [10]. Zou et al. proposed a construction technology and carbon emission calculation method for prefabricated inverted arches suitable for drill-and-blast tunnels, calculated the carbon emissions during the construction process of fabricated inverted arches, and optimized the carbon emission model for on-site transportation [11]. In addition, some scholars have carried out carbon emission accounting and mitigation potential assessments in fields such as the steel industry [12], marine fishery [13], and demolition waste [14]. However, the quantitative carbon emission intensity and estimated mitigation potential of precast concrete structures based on the life cycle perspective are relatively lacking. Therefore, this study conducts carbon emission calculation and evaluation work for the PCS construction stage based on LCA theory and predicts the carbon emission level of the PCS construction stage in the future using the scenario analysis method. By implementing appropriate emission reduction pathways, the study estimates the carbon reduction potential of PCS. The research results are expected to provide reference opinions for the green and low-carbon transformation of traditional on-site construction mode, achieving the goals of "carbon peak" and "carbon neutral". Furthermore, the research results will provide a decision-making basis and theoretical support for governments, enterprises, and the construction industry. For example, for the government, they can provide a powerful decision-making basis and management support for relevant work in the PCS industry. Enterprises can base on the research results to analyze the trend of market demand in advance, lay out the research, development, and production of green and low-carbon PCS products in advance, and launch high-quality products that conform to the national strategic development trend, thus establishing a good corporate image in the market and attracting more customers to enhance their competitive advantage in the industry. For the PCS industry, construction units can use the carbon emission calculation model to compare and analyze the carbon emissions generated by the construction projects using prefabricated concrete structures and the current cast-in-place structures, thus better promoting the green and low-carbon development of the construction industry.

Material and Methods

LCA is a quantitative analysis method that can be used to predict the environmental impact of prefabricated buildings throughout their entire life cycle from raw material production to demolition and disposal [15]. LCA is one of the main methods for conducting environmental impact assessment. It can explore the environmental impact of resource and energy consumption throughout the entire life cycle of prefabricated buildings. The implementation steps include four stages: determination of the goal and scope, life cycle data inventory analysis, impact assessment, and result interpretation and analysis [16]. The environmental impact assessment indicator selected in this study is carbon dioxide emission equivalent (CO_2 Equivalent, CO_2e), and the research object is the construction stage of prefabricated concrete structures, namely, the processing and production of prefabricated components, transportation, on-site construction, and assembly, to construct a carbon emission assessment method for prefabricated concrete structures in a quantitative form.

Determination of the Goal and Scope

This article determines that the objective of LCA is to calculate the carbon emissions throughout the entire process of PCS, from the processing and production of prefabricated components to on-site construction and assembly. It follows the regulations of ISO 14040/14044 and selects the carbon dioxide emission equivalent as the environmental impact assessment indicator. The full life cycle of PCS is divided into six stages, namely the planning and design stage, prefabricated component production and processing stage, prefabricated component and building material transportation stage, on-site construction and assembly stage, operation and maintenance stage, and demolition and recycling stage. Since China's PCS industry is still in its initial development stage, the PCS built earlier are just entering the operation and maintenance stage. Therefore, this paper focuses on exploring the carbon emission intensity and level of the PCS construction stage and has not yet covered the planning and design, operation and maintenance, and demolition stages. The system boundary of the PCS construction phase includes three subphases: (i) The processing and production stage of prefabricated components, including the embodied carbon emissions of prefabricated components such as columns, beams, slabs, and stairs, that is, the direct or indirect carbon emissions generated due to the consumption of resources and energy throughout the entire process from the mining, transportation, and processing of raw materials to the final production of prefabricated components such as columns, beams, slabs, and stairs. (ii) The transportation stage of prefabricated components and building materials, including the direct or indirect carbon emissions generated by the transportation of prefabricated components such as columns, beams, slabs, and stairs from the prefabrication plant or processing plant to the construction site and the fuel burning of transportation tools such as automobiles. (iii) The on-site construction and assembly stage, including the direct or indirect carbon emissions generated by the energy consumption during the on-site transportation of construction machinery, construction assembly of prefabricated components, and the use of machinery such as hoisting machinery and ac welder, as shown in Fig. 1. PCS has a wide variety of component types and different sizes. To eliminate the influences of unfavorable factors and facilitate further exploration of the emission reduction potential, this article selects the unit area (calculated as 100 m^2) as the functional unit.

Carbon Emission Accounting Model

Prefabricated Components Processing Production Stage

The carbon emissions during the prefabricated component processing and production stage consist of two parts. One is the carbon emissions generated from the extraction, transportation, and processing of raw materials for component production, which is calculated by multiplying the usage or consumption amount of various building materials by the corresponding carbon emission factor and cumulative summing up.

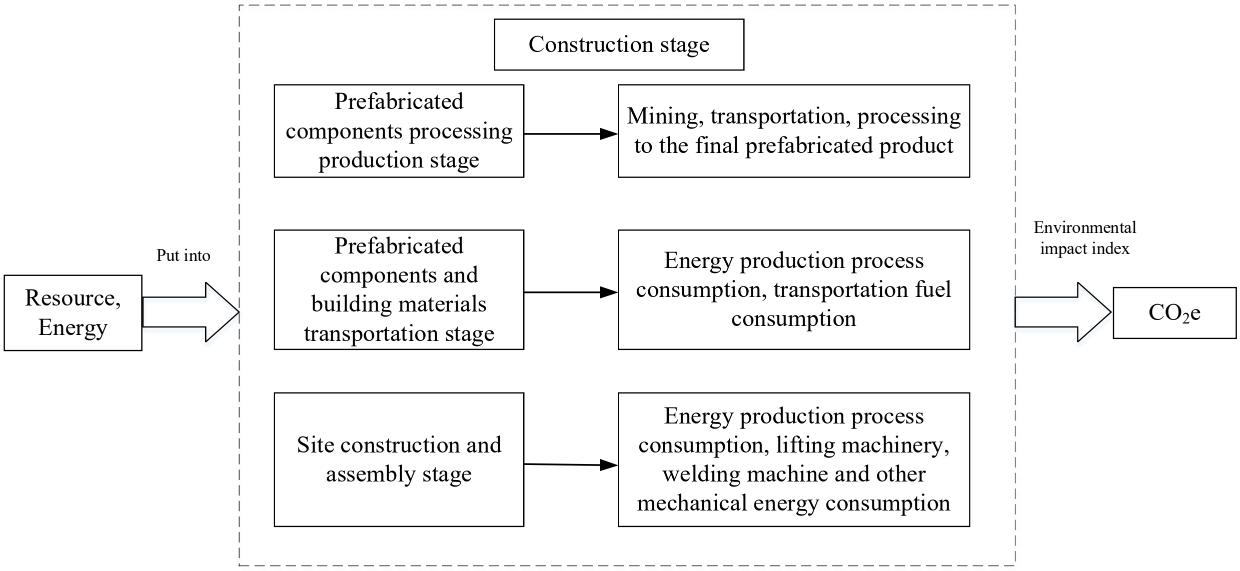


Fig. 1. System boundary of PCS construction stage.

The calculation formula is as shown in (1). The other is the carbon emissions generated by machine tools and processing equipment during the process of processing and producing prefabricated components such as columns, beams, slabs, and stairs into prefabricated products, calculated through formula (2). The total carbon emissions of the prefabricated component processing and production stage, CE_P is the sum of CE_{P1} and CE_{P2}. The carbon emissions generated from the transportation of raw materials for prefabricated component processing and production are included in the transportation stage of prefabricated components and building materials.

$$CE_{P1} = \sum_{i}^{n} C_i \times (1 + \alpha_i) \times E_i \tag{1}$$

Where, CE_{P1} is the carbon emission of prefabricated building materials, the unit is $kgCO_2e$. C_i is the usage amount or consumption of the i kind of building materials, the unit is m^3, kg, m, m^2. α_i is the loss rate of the i type of building materials. E_i is the carbon emission factor of the i type of building materials, the unit is $kgCO_2e/C_i$. n is the quantity of building materials.

$$CE_{P2} = \sum_{j=1,k=1}^{m,a} (C_{j,k} \times E_k + F_j \times E_j) + R_j \times E_t \tag{2}$$

Where CE_{P2} is the carbon emission in the production process of the precast component and the unit is $kgCO_2e$. $C_{j,k}$ is the usage amount or consumption of the k kind of energy in the production of the j kind of precast component, the unit is kg, kW·h, L, m^3. E_k is the carbon emission factor of the k kind of energy, the unit is $kgCO_2e/C_{j,k}$. m is the category of prefabricated components, including balconies, laminated beams, laminated panels, shear walls, stairs, etc. a is the category of energy, including diesel, gasoline, electricity, and water. F_j is the consumption of admixtures and admixtures required for the production of the j-type prefabricated components, the unit is t. E_j is the production carbon emission factor of the additive and admixture required for the i prefabricated components, the unit is $kgCO_2e/t$. R_j refers to the labor days required for the production of the j-type prefabricated components, the unit is d. E_t is the artificial average carbon emission factor in component production stage, the unit is $kgCO_2e/d$.

Prefabricated Components and Building Materials Transportation Stage

The core of the transportation stage is to transport prefabricated components such as columns, beams, slabs, and stairs from the prefabrication plant or processing plant to the construction site. Due to the direct or indirect carbon emissions generated by different modes of transportation, the carbon emissions belong to mobile source emissions and are closely related to the means of transportation and distance. This leads to uncertainty in carbon emissions during the transportation stage. This study assumes that all vehicles are fully loaded when transporting materials to the construction site, without considering the carbon emissions caused by empty return trips of vehicles. The loading of other materials for return trips to prefabrication plants or processing plants is not within the scope of this study. The carbon emissions during the transportation stage of prefabricated components are calculated using formula (3).

$$CE_T = \sum_{j=1,h=1}^{m,b} W_{j,h} \times D_{j,h} \times E_h + R_y \times E_y \tag{3}$$

Where, CE_T is the carbon emission in the transport stage of prefabricated components and building materials, the unit is $kgCO_2e$. $W_{j,h}$ is the mass of the j prefabricated component transported by the h mode, the unit is t. $D_{j,h}$ refers to the distance of the j prefabricated component transported by the h mode, the unit is km. E_h is the carbon emission factor of the h mode of transport, the unit is $kgCO_2e/(t \cdot km)$. b refers to means of transportation, including road, rail, water, etc. R_y is the labor days required for the transportation of the j-type prefabricated components, the unit is d. E_y is the artificial average carbon emission factor in the transportation stage of components, and the unit is $kgCO_2e/d$.

Site Construction and Assembly Stage

The carbon emissions during the on-site construction and assembly stage mainly include indirect carbon emissions generated by the production of energy upstream in the industrial chain and direct carbon emissions generated by the consumption of energy by machinery during the construction and assembly process. The carbon emissions are calculated by multiplying the amount of energy used or consumed by the corresponding carbon emission factors during the production and use of energy, as shown in formula (4).

$$CE_A = \sum_{r=1}^{a} Q_r \times (E_{r1} + E_{r2}) + R_c \times E_c \tag{4}$$

Where, CE_A is the carbon emission during the on-site construction and assembly of prefabricated components, the unit is $kgCO_2e$. Q_r is the total usage or total consumption of the r kind of energy, calculated by the consumption of construction machinery platform by the energy consumption of unit platform, the unit is kg, kW·h, L, m^3. E_{r1} is the carbon emission factor during the upstream production of the r type of energy, the unit is $kgCO_2e/Q_r$. E_{r2} is the carbon emission factor during the construction and assembly consumption of the r type of energy, the unit is $kgCO_2e/Q_r$. R_c refers to the labor days required for the construction of the j-type prefabricated components, the unit is d. E_c is the artificial average carbon emission factor during component construction, the unit is $kgCO_2e/d$.

The carbon emission intensity of PCS is related to its scale and type. The carbon emission calculation model proposed in this paper is only applicable to small and medium-sized PCS in residential categories, and cannot be used for carbon emission intensity calculation of large-scale PCS in residential categories, commercial PCS, etc. For example, large-scale PCS projects can often fully realize scaled production and batch production. In the prefabricated component processing and production stage, the prefabricated component transportation stage, and the on-site construction and assembly stage, the most advanced large-scale production equipment can be used, a special transportation system can be established, and the most advanced intelligent construction machinery can be used for lean construction, thereby greatly reducing carbon emissions in each link.

Life Cycle Data Inventory Analysis

This paper selects a representative prefabricated building project in Shenzhen as the research case. The above-ground building area of this project is 50,000 m^2, and the prefabricated components covered include types such as laminated beams, laminated slabs, stairs, shear walls, and balconies. The prefabrication rate is 50%, which is much higher than the prefabrication rate requirement in Shenzhen. Based on the bill of quantities for the project settlement, the consumption of various building materials for the production of prefabricated components is summarized from the bill of quantities for sub-projects and sub-items, as shown in Table 1. It can be seen from the consumption that steel bars, C30 concrete, steel plates, electricity, etc., are the resources or energies with large consumption in the production process of prefabricated components. Relying on the types of building materials in the bill of quantities, the carbon emission factors of building materials such as steel bars and C30 concrete are sorted out from lifecycle databases, Calculation Standard of Carbon Emission in Buildings (GB/T 51366-2019), publicly published journal papers and other materials, as shown in Table 1. The transportation tools and transportation distances are obtained through project research. The transportation vehicle for raw materials is a medium-sized diesel truck (with a load capacity of 8t and a carbon emission factor of 0.179 $kgCO_2e/(t \cdot km)$), The transportation vehicle for prefabricated components is a heavy-duty diesel truck (with a load capacity of 30t and fuel consumption of 45L/100km). The distance between the construction site and the prefabrication factory is 100km. The carbon emission factors of prefabricated component transportation and transportation methods are shown in Table 2. The consumption of mechanical shifts in the on-site construction and assembly stage refers to the Shenzhen Prefabricated Building Consumption Quota (2016) and Shenzhen Construction Project Construction Machinery Shift Quota (2014), as shown in Table 3. It should be noted that since the data collection phase of the project did not consider the consumption of labor for prefabricated component production, transportation, and on-site construction personnel, the carbon emission intensity calculated in this paper did not take into account the environmental impact of labor.

During the on-site construction and assembly stage, the carbon emission factor for energy production and consumption is comprehensively considered, the data of which are derived from the journal paper published by Su Yuehua et al. in May 2022 in the Journal

Table 1. Bill of materials and carbon emission factors per unit area (100 m^2) in the production stage of prefabricated components.

Name of building materials	Consumption	Carbon emission factor	Transport distance	Type of shipping
Hot-rolled steel bars	1051.07 kg	2.34 $kgCO_2e/kg$	12 km	Highway
C30 concrete	5.96 m^3	295 $kgCO_2e/m^3$	10 km	
Steel plates	259.85 kg	2.40 $kgCO_2e/kg$	12 km	
PVC	2.74 kg	7.3 $kgCO_2e/kg$	15 km	
Polystyrene	1.81 kg	4.62 $kgCO_2e/kg$	15 km	
Aluminum	2.88 kg	20.30 $kgCO_2e/kg$	12 km	
Electricity	97.14 kW·h	0.87 $kgCO_2e/kW·h$	-	-

Note: The data is sourced from Yu Xiaohan [2], Gao Yu [17], Calculation Standard of Carbon Emission in Buildings (GB/T 51366-2019) [18].

Table 2. List data of unit area (100 m^2) in the transport stage of prefabricated components.

Component category	Weight per unit area/t	Type of shipping	Transport distance/km	Conveyance	Carbon emission factor ($kgCO_2e/(t·km)$)
Superimposed beam	0.15	Highway	100	Heavy-duty diesel truck, carrying capacity 30t	0.078
Superimposed plate	2.15				
Shear wall	8.34				
Precast infill wall (outside)	1.08				
Precast fill wall (inside)	0.58				
Staircase	0.53				
Balcony	1.03				
Balcony partition	0.30				

Note: Data from the Calculation Standard of Carbon Emission in Buildings (GB/T 51366-2019)[18].

Table 3. List of construction machinery platform in unit area (100 m^2) during site construction and assembly stage.

Type of construction machinery	Mechanical specification	Machine shift consumption (machine-team/100 m^2)	Diesel oil consumption (kg/100 m^2)	Electric-power consumption (kW·h/100 m^2)
Hoisting machinery	Improved quality 30t	0.16	6.84	90.53
Ac welder	Capacity 32kV·A	0.07	-	6.19

Note: Data from Shenzhen Prefabricated Building Consumption Quota (2016) [19], Shenzhen Construction Project Construction Machinery Shift Quota (2014).

Table 4. Energy carbon emission factors.

Energy type	Carbon emission factor of production process ($kgCO_2e/kg$)	Carbon emission factor of assembly consumption ($kgCO_2e/kg$)	Total carbon emission factor ($kgCO_2e/kg$)
Diesel oil	0.50	3.10	3.60
Electric-power	0.87	0	0.87

of Environmental Engineering [16], as shown in Table 4. Diesel generates carbon emissions both in the production and consumption stages, and the carbon emission factor data for the production stage are derived from the life cycle database. Electricity generates no carbon emissions in the consumption stage, only carbon emissions in the production process, using the benchmark emission factor of the Southern Power Grid of China.

The carbon emission factor data for the prefabricated components production stage, transportation stage, and on-site construction and assembly stage in this paper mainly come from the Calculation Standard for Building Carbon Emissions (GB/T 51366-2019), which is a national standard issued by the Ministry of Housing and Urban-Rural Development. It has authority and authenticity and can ensure the accuracy and reliability of the carbon emission factor. If there is no data in the national standard, it comes from authoritative academic journals and industry reports. If the research results are published in authoritative journals in related fields, the authors are usually experts and scholars in the field, and the data are all professional analysis and calculation results. Therefore, the data has a high degree of credibility.

Results and Discussion

Prefabricated Components Processing Production Stage

Using formulas (1), (2), and the material list and carbon emission factor in Table 1, the carbon emissions for each type of building material in the prefabricated component processing and production stage, calculated per unit area (assuming 100 m^2), are shown in Fig. 2, while the carbon emissions for each type of prefabricated component are shown in Fig. 3. From Fig. 2 and 3, it can be seen that the carbon emission intensity per unit area of the prefabricated component processing and production stage is 5,215.82 kgCO$_2$e/100 m^2. According to the types of building materials, hot-rolled rebar has the highest carbon emission, reaching 2,607.07 kgCO$_2$e/100 m^2, accounting for 49.98%. Followed by C30 concrete, with a carbon emission of 1,775.78 kgCO$_2$e/100 m^2, accounting for 34.05%. Based on the high carbon emission characteristics of hot-rolled rebar and concrete, attention should be focused on the raw material processing processes of materials such as hot-rolled rebar and concrete and the production processes of prefabricated components. Especially for concrete, its constituent materials, such as cement, sand, stone, water, admixtures, and mineral admixtures, all have implicit carbon emissions to varying degrees. Timely attention should be paid to the carbon emissions in the mining and processing links of raw materials, and energy-saving and carbon reduction measures should be taken to solve the carbon emission problems brought about by the processing and production of downstream prefabricated components from the upstream industry.

From the perspective of component types, the carbon emissions of prefabricated shear walls are the highest, reaching 3,102.61 kgCO$_2$e/100 m^2, accounting for 59.48%. Followed by laminated slabs, with carbon

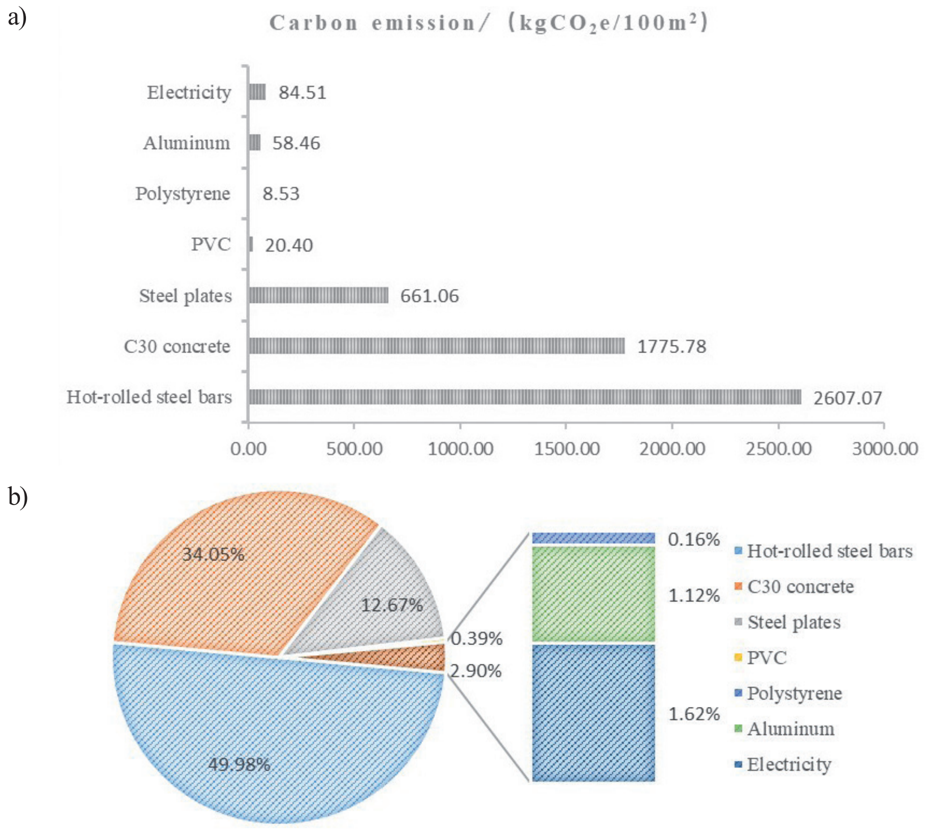
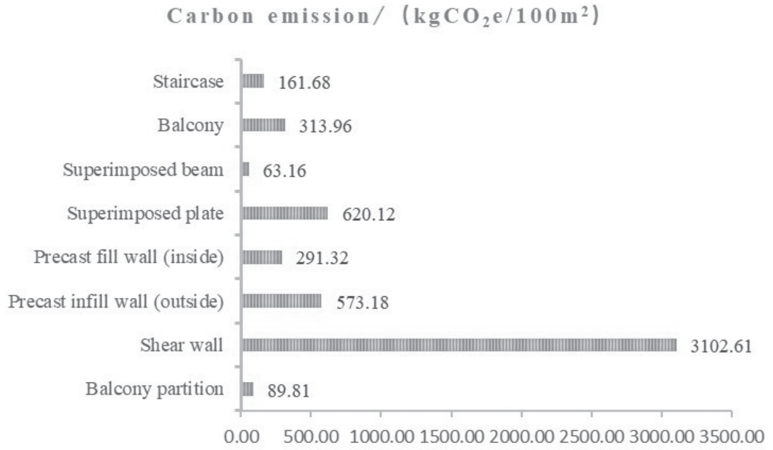


Fig. 2. Carbon emissions in the production stage of prefabricated component processing (by type of building materials). a) Bar chart, b) Pie chart.

a)



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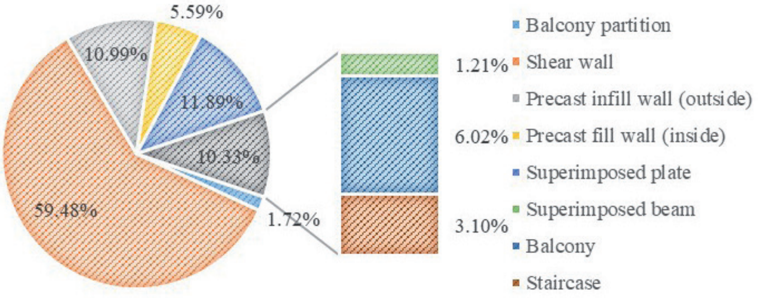

Fig. 3. Carbon emissions in the production stage of precast component processing (by component type). a) Bar chart, b) Pie chart.

emissions of 620.12 kgCO$_2$e/100 m^2, accounting for 11.89%. Based on the high carbon emission characteristics of prefabricated shear walls, through on-site investigations and comparisons of building materials, it is concluded that the processing process of prefabricated shear walls is complex, and the proportion of hot-rolled steel bars and C30 concrete per unit area is much higher than that of other building materials. Therefore, the production process of prefabricated shear walls should be considered for optimization, and the usage of hot-rolled steel bars and concrete per unit area should be reduced while meeting the strength requirements, thereby reducing the environmental impact it brings.

Prefabricated Components and Building Materials Transportation Stage

By applying Formula (3) and the basic data in Table 1-2, the carbon emission results per unit area (calculated at 100 m^2) of the transportation stage of prefabricated components and various building

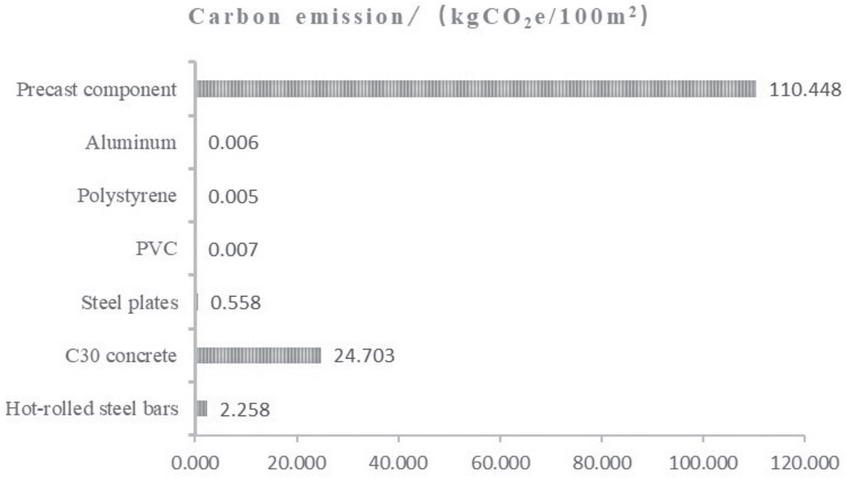

Fig. 4. Carbon emissions of prefabricated components and various building materials during transportation.

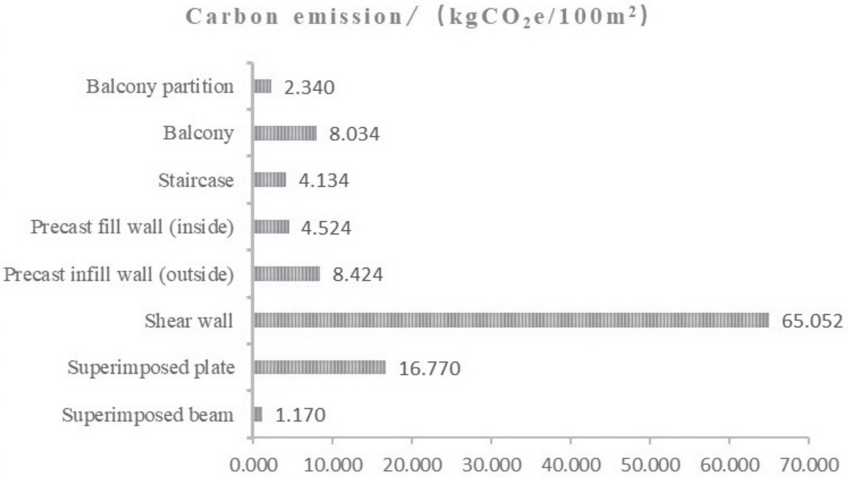

Fig. 5. Carbon emissions of various prefabricated components during transportation.

materials are calculated as shown in Fig. 4. It can be seen from Fig. 4 that the carbon emission intensity of the transportation stage of prefabricated components is 137.985 $kgCO_2e/100\ m^2$. Among them, the carbon emissions of prefabricated components such as prefabricated shear walls and laminated slabs are the highest, reaching 110.448 $kgCO_2e/100\ m^2$, accounting for 80.04%. Followed by C30 concrete, with a carbon emission of 24.703 $kgCO_2e/100\ m^2$, accounting for 17.90%. From the perspective of component types in Fig. 5, prefabricated shear walls have the highest carbon emissions, reaching 65.052 $kgCO_2e/100\ m^2$, accounting for 58.90%. The second is the composite board, with a carbon emission of 16.770 $kgCO_2e/100\ m^2$, accounting for 15.18%. Comparing the calculation results of various prefabricated components with building materials, the carbon emissions of prefabricated shear walls and C30 concrete still rank first and second in the transportation stage, and the carbon emission results in the transportation stage are closely related to transportation methods, transportation distance, etc. Based on the carbon emission levels of prefabricated shear walls and C30 concrete, the environmental impact of prefabricated shear wall components and concrete building materials during transportation should be a key concern.

Site Construction and Assembly Stage

Using the formula (4), the list of mechanical shifts and energy carbon emission factors in Tables 3-4 and the carbon emission results per unit area (calculated at 100 m^2) during the on-site construction and assembly stages are calculated and shown in Fig. 6 and Fig. 7. As shown in Fig. 6, the carbon emission intensity during the on-site construction and assembly phase is 44.50 $kgCO_2e/100\ m^2$. Among them, the carbon emissions of lifting machinery are the highest, reaching 44.12 $kgCO_2e/100\ m^2$. We should focus on the environmental impact of lifting machinery during on-site construction and assembly and further explore equipment that can replace lifting machinery. The carbon emission levels of various types of prefabricated component lifting machinery indicate

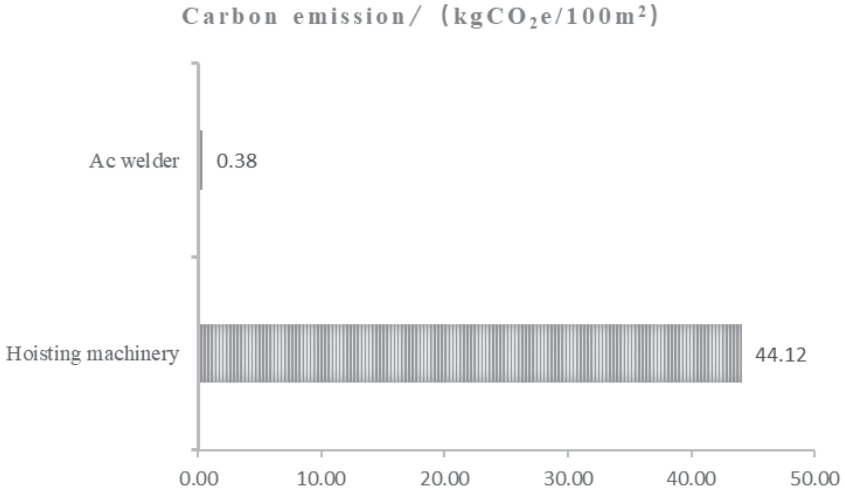

Fig. 6. Carbon emissions during site construction and assembly.

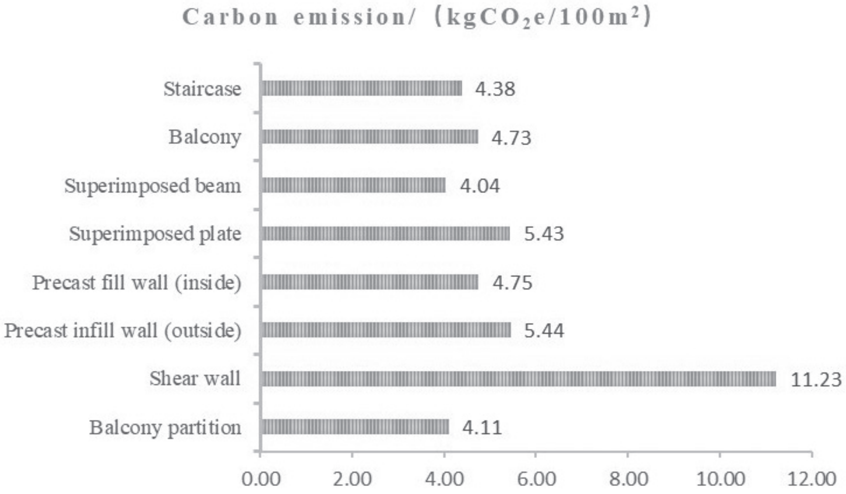

Fig. 7. Carbon emissions of hoisting machinery during the assembly stage of various prefabricated components.

that the prefabricated shear wall has the highest carbon emission, reaching 11.23 $kgCO_2e/100\ m^2$, accounting for 25.45%. The second is prefabricated infilled walls (exterior walls), with a carbon emission of 5.44 $kgCO_2e/100\ m^2$, accounting for 12.34%.

Overall Analysis of the Construction Stage

The construction process of PCS includes three stages, namely the prefabricated component production and processing stage, the transportation stage of prefabricated components and building materials, and the on-site construction and assembly stage. According to the above calculation results, the unit area carbon emission intensity of the construction process is 5,398.31 $kgCO_2e/100\ m^2$. Among them, the highest carbon emission intensity is the prefabricated component production and processing stage, reaching 5,215.82 $kgCO_2e/100\ m^2$, accounting for 96.62%. This is followed by the transportation stage of prefabricated components and building materials, with a carbon emission intensity of 137.99 $kgCO_2e/100\ m^2$, accounting for 2.56%. The contribution ratio of carbon emission per unit area to site construction and assembly stage is small, about 0.82%. As shown in Fig. 8, the prefabricated component production and processing stage is the main source of carbon emissions, with great potential for emission reduction and space, but the environmental impact of the transportation stage of prefabricated components and building materials cannot be ignored. From the construction stage of PCS, the carbon emissions contribution from the prefabricated component processing and production stage is the largest, but the environmental impact of the prefabricated components and building materials transportation stage cannot be ignored. With the progress of technology and the development of the industry, the carbon emissions of PCS will gradually decrease in the long run, especially the research and application of new building materials will help reduce the carbon emissions in the material processing stage, and the widespread use of new energy vehicles and trucks can reduce the carbon emissions in

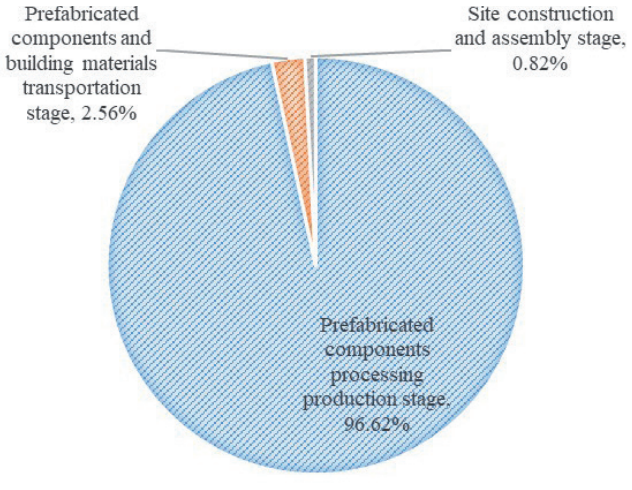

Fig. 8. Carbon emission intensity per unit area during PCS construction.

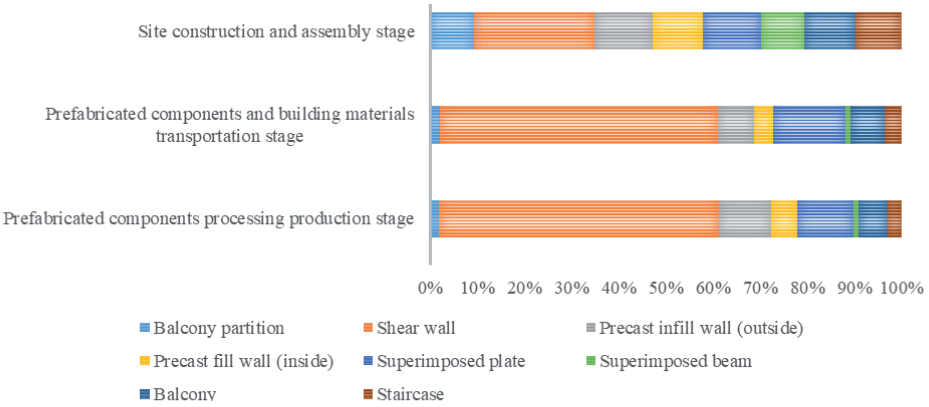

Fig. 9. Carbon emission intensity per unit area of various prefabricated components during the construction stage.

the transportation stage of prefabricated components and building materials.

From the perspective of component types, the unit area carbon emission intensity of various prefabricated components during the construction stage is shown in Fig. 9, assuming that the environmental impact of material transportation and alternating current welding is not taken into account. Through the above calculation results, the highest is prefabricated shear wall, with a carbon emission of 3,178.88 $kgCO_2e/100\ m^2$. The second is composite plate, with a carbon emission of 642.32 $kgCO_2e/100\ m^2$. The third is precast infill wall (outside), with a carbon emission of 587.05 $kgCO_2e/100\ m^2$. Prefabricated shear wall is the main source of carbon emissions, and its environmental impact should be closely monitored. The carbon emissions generated by composite plates and precast infill walls (outside) should not be ignored either. There are differences in carbon emissions of PCS in different regions. In economically developed areas, especially Shenzhen, where there is a large market demand for PCS, advanced technology, and complete industrial support, PCS components can be introduced with more advanced technology and equipment during production and on-site installation stages to reduce carbon emissions. Meanwhile, there are also differences in carbon emissions between different-sized construction projects. Large PCS projects usually have economies of scale, and prefabricated shear walls, stacked slabs, and balconies are already equipped with standardized molds. They can reduce carbon emissions levels through scale, standardization, and mass production.

From the perspective of building materials, since the prefabricated components during the on-site installation stage are raised to the designated position using crane equipment, no consideration has been given to the crane equipment from the perspective of building materials. As shown in Fig. 10, without considering the impact of lifting prefabricated components during the on-site installation stage, the unit area carbon emissions contribution of hot-rolled steel bars is the largest, reaching 2,609.33 $kgCO_2e/100\ m^2$. The unit area carbon emissions of C30 concrete are the second largest, reaching 1,800.48 $kgCO_2e/100\ m^2$, of which cement

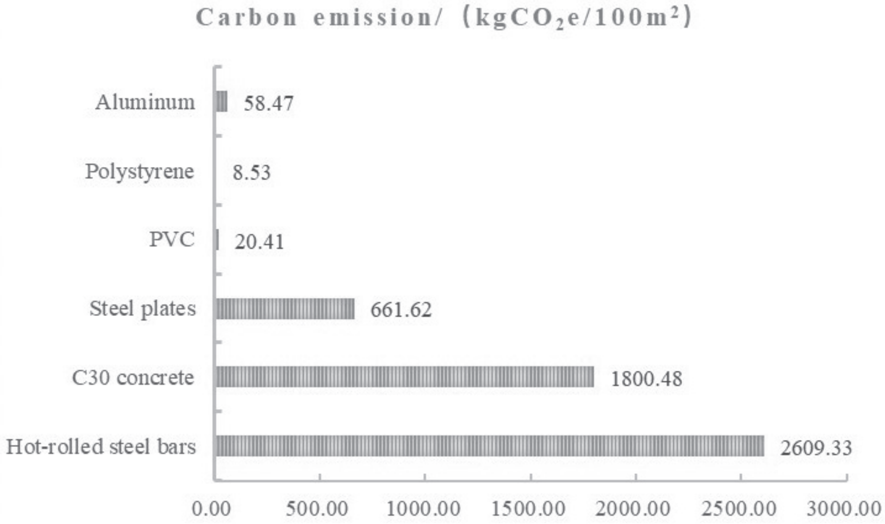

Fig. 10. Carbon emission intensity per unit area of various building materials during the construction stage.

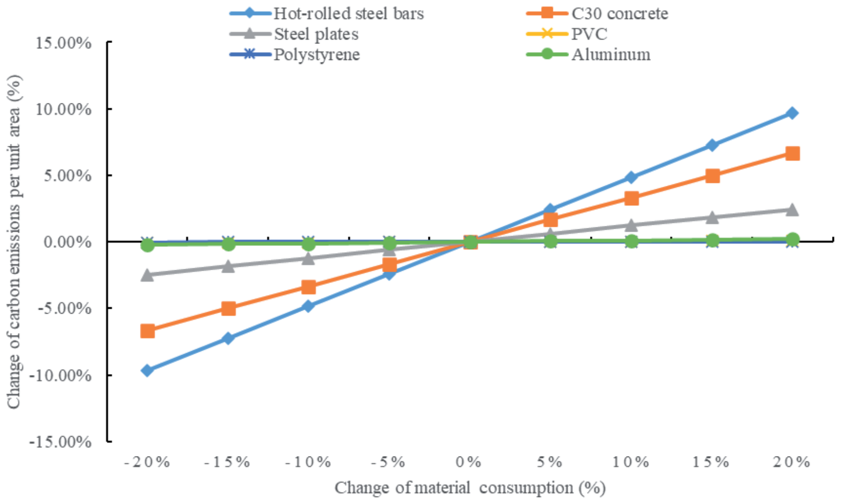

Fig. 11. Sensitivity analysis of material consumption.

contributes the most to the unit area carbon emissions, which is consistent with the conclusions of some experts and scholars. From the research results, it can be seen that hot-rolled steel bars and concrete contribute the most to carbon emissions, accounting for 85.48%, because the production of steel bars and concrete contains carbon-intensive cement, with high energy and resource consumption.

Carbon Emission Sensitivity Analysis of Building Materials

The results of the research in the previous section show that the carbon emission intensity of PCS is the largest during the prefabricated component processing and production stage. Therefore, it is necessary to analyze the carbon emission sensitivity of component production to better evaluate the stability and reliability of the model. Of course, if the sensitivity analysis of prefabricated components and building materials transportation stage and the on-site construction and assembly stage are also carried out according to this idea, it would be better. According to the Calculation Standard of Carbon Emission in Buildings (GB/T 51366-2019), the main factor affecting the carbon emissions of materials is their consumption and carbon emission factor, so this paper will conduct sensitivity analysis from the perspectives of consumption and carbon emission factor.

Table 5. Sensitivity analysis of material consumption.

Material	Change of material consumption (%)	Change of carbon emissions per unit area (%)
Hot-rolled steel bars	5	2.42
	10	4.83
	15	7.25
	20	9.67
C30 concrete	5	1.67
	10	3.34
	15	5.00
	20	6.67

(1) Sensitivity analysis of consumption. Assuming the carbon emission factor is a constant value, the impact of material consumption on the PCS carbon emissions per unit area was analyzed, as shown in Fig. 11 and Table 5. From the research results, it can be seen that material consumption is positively correlated with carbon emissions per unit area, with the ranking being hot-rolled steel bars > concrete.

(2) Sensitivity analysis of carbon emission factor. Assuming a constant material consumption, the study analyzed the impact of the carbon emission factor of materials on the carbon emissions per unit area of PCS, as shown in Fig. 12 and Table 6. From the research results, it can be seen that the carbon emission factor of materials is positively correlated with the carbon emissions per unit area, with the ranking being hot-rolled steel bars > concrete.

According to the sensitivity analysis, the hot-rolled steel bars and concrete have a significant impact on the total carbon emissions, which is consistent with the conclusion of Li et al. [9], indicating that the calculated model can ensure the reliability of PCS carbon emission intensity. In addition, attention should be paid to the actual consumption of hot-rolled steel bars and cement during the construction of PCS.

Study on the Emission Reduction Potential of PCS

PCS Emission Reduction Scenario Hypothesis

The Guiding Opinions of the General Office of the State Council on Vigorously Developing Prefabricated Buildings issued at the national level proposed that the

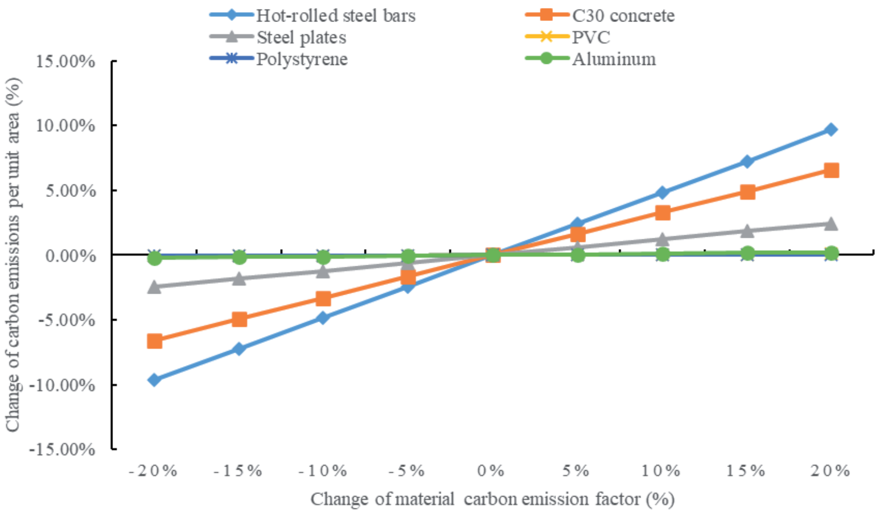

Fig. 12. Sensitivity analysis of material carbon emission factor.

area of prefabricated buildings accounts for 30% of the new building area. The Implementation Opinions of the General Office of the People's Government of Guangdong Province on Vigorously Developing Prefabricated Buildings issued at the provincial level proposed that by the end of 2025, the proportion of prefabricated buildings in the new building area should reach more than 35%. The 14th Five-Year Plan for the High-Quality Development of Shenzhen's Modern Construction Industry issued at the municipal level proposed that the newly added prefabricated building area should be no less than 50 million square meters, and the prefabricated building area should account for 60% of the new building area. According to the municipal-level plan, by the end of 2025, the prefabricated building area of the whole city will increase by at least 50 million square meters, and by the end of 2035, the prefabricated building area of the whole city will account for more than 70% of the new building area. The overall construction scale of prefabricated buildings in the future will face new "carbon reduction" challenges. From the market size of the PCS industry, its market is showing a growth trend. With the development of urbanization, it is expected that the PCS market will maintain stable growth in the coming years. According to data from the National Bureau of Statistics, the market size of prefabricated buildings in China is expected to reach 650 billion yuan in 2024, and the proportion of PCS in the new construction area of prefabricated buildings is 67.68%. Regarding industry trends, intelligent, digital, green, and low-carbon have become important directions of transformation in the construction industry. PCS has measures such as standardized design of prefabricated components, efficient production technology, lean construction, and intelligent construction to reduce emissions. From the perspective of efficient production technology, high-performance concrete and recycled materials can be used in the production of prefabricated components. High-performance concrete has higher strength and durability, which can reduce the amount of material used in components to reduce material waste and carbon emissions. Recycled materials, on the other hand, use waste materials processed after being discarded as raw materials for component production, thus reducing the extraction of natural raw materials to lower energy consumption and carbon emissions.

Table 6. Sensitivity analysis of material carbon emission factor.

Material	Change of material carbon emission factor (%)	Change of carbon emissions per unit area (%)
Hot-rolled steel bars	5	2.41
	10	4.83
	15	7.24
	20	9.66
C30 concrete	5	1.64
	10	3.29
	15	4.93
	20	6.58

According to the foregoing results, the prefabricated component processing and production stage has the largest carbon emissions during the construction process of PCS, with significant potential and space for carbon reduction. Moreover, hot-rolled rebar and concrete are the main sources of carbon emissions. The recycling of steel and concrete is regarded as one of the important measures for energy conservation and carbon reduction, which can reduce the environmental impact caused by the mining, transportation, and processing of raw materials. Therefore, this paper combines the scenario analysis method to predict the carbon reduction potential of recycled steel and recycled concrete of PCS in Shenzhen in the future and sets three scenarios, namely

Table 7. Scenario assumptions for scenario analysis during the construction stage.

Scenario name and indicator	Scenario 1 (Base type)		Scenario 2 (Middle)		Scenario 3 (Optimistic)	
	2025	2035	2025	2035	2025	2035
Recycled steel ratio (%)	0	0	10	20	20	30
Recycled concrete ratio (%)	0	0	15	25	30	50

Table 8. Carbon emission factors of recycled building materials.

Name of building materials	Carbon emission factor
Hot-rolled steel bars[20]	1.25 $kgCO_2e/kg$
Steel plates[20]	1.19 $kgCO_2e/kg$
C30 concrete[21]	254.26 $kgCO_2e/m^3$

the baseline type, the intermediate type, and the optimistic type, as shown in Table 7. The scenario settings refer to planning documents and schemes such as the 14th Five-Year Plan for Building Energy Conservation and Green Building Development in Guangdong Province, the 14th Five-Year Energy Conservation and Emission Reduction Implementation Plan of Guangdong Province, and the 14th Five-Year Plan for High-Quality Development of Modern Construction Industry in Shenzhen and so on. The research on recycled steel and recycled concrete is quite mature. The carbon emission factors of recycled building materials in this paper adopt the research results of Huang [20], Xiao [21], etc., as shown in Table 8.

Carbon Reduction Potential Analysis

Based on the above scenario assumption, the adoption of recycled steel and recycled concrete can reduce

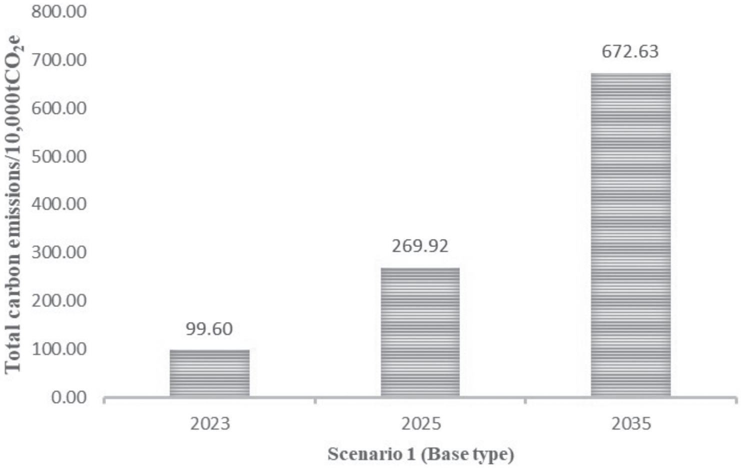

Fig. 13. Carbon emission and carbon reduction potential of PCS.

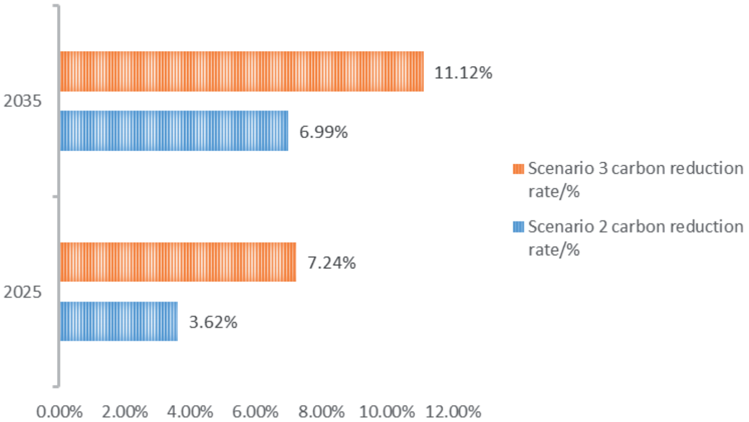

Fig. 14. Carbon reduction rates of PCS in 2025 and 2035.

the carbon emission intensity of PCS, thereby achieving the "carbon reduction" goal and green development of PCS. As shown in Fig. 13, in Scenario 1, without the use of any recycled steel and recycled concrete, by the end of 2023, the total carbon emissions of fabricated buildings already built in Shenzhen have reached 4.3652 million tCO_2e. The carbon emissions of PCS increased from 996,000 tCO_2e generated in 2023 to 2.6992 million tCO_2e in 2025 and then to 6.7263 million tCO_2e in 2035, with a growth multiple of 5.8 times that of 2023. Scenario 2 and Scenario 3 show the carbon emissions related to using recycled steel and concrete, respectively. In Scenario 2, the PCS carbon emissions increase to 2.60 million tCO_2e in 2025 and 6.25 million tCO_2e in 2035, with carbon reduction rates of approximately 3.62% and 6.99% compared to the baseline model. In Scenario 3, the PCS carbon emissions increase to 2.50 million tCO_2e in 2025 and 5.97 million tCO_2e in 2035, with carbon reduction rates of approximately 7.24% and 11.12%, as shown in Fig. 14.

Conclusions

Using the LCA theory, the carbon emission intensity of PCS was evaluated, and carbon emission calculation models were established for the stages of prefabricated component processing and production, transportation of prefabricated components and building materials, and on-site construction and assembly. The potential for carbon reduction and space for PCS in Shenzhen were predicted using the scenario analysis method. The main conclusions are as follows:

(a) The carbon emission intensity per unit area of the PCS construction process is 5,398.31 $kgCO_2e/100\ m^2$. Among them, the prefabricated component processing and production stage is the main source of carbon emissions, with a carbon emission volume of 5,215.82 $kgCO_2e/100\ m^2$. Among the building materials in this stage, the hot-rolled steel bars and C30 concrete have the largest carbon emissions, and there is a strong reduction space.

(b) From the perspective of component types, the carbon emission per unit area of prefabricated shear walls is the highest, reaching 3,178.88$kgCO_2e/100\ m^2$. The core reason lies in the complex production process of prefabricated shear walls and the large demand for building materials per unit area. Special attention should be paid to the environmental impact brought by the links, such as its production process, raw material mining, transportation, and processing. It is possible to reduce the waste of hot-rolled steel bars and concrete, improve the recycling rate of resources, and reduce the transportation distance of components, thereby achieving the goal of "carbon reduction".

(c) According to the sensitivity analysis results, the consumption of building materials, the carbon emission factor of materials, and the carbon emissions per unit area are positively correlated. The carbon emissions mainly come from hot-rolled steel bars and concrete, in the order of hot-rolled steel bars > concrete. In order to reduce carbon emissions in the prefabricated component production process, it is best to choose renewable steel bars and concrete from an environmental protection perspective.

(d) By the end of 2023, the carbon emission intensity of fabricated buildings that have been completed in Shenzhen was 4.3652 million tCO_2e. Without using any recycled steel and recycled concrete, the increment of carbon emissions will reach 2.6992 million tCO_2e by 2025 and 6.7263 million tCO_2e by 2035. However, if green construction technologies are promoted and recycled steel and recycled concrete are considered, according to the optimistic estimate, the carbon reduction rate in 2035 will be the highest, reaching 11.12%.

This study's developed carbon emission calculation model can provide reference advice for Shenzhen PCS construction projects, and also provide decision-making ideas for the government and industry to promote PCS green and low-carbon construction. In addition, the research results will provide a reference for scholars to compare the carbon emission intensity of PCS and cast-in-place structures. However, this study also has some research limitations, such as considering fewer indirect carbon emission factors when building the model, not getting more information on indirect carbon emission factors when collecting project data, the relationship between the life cycle carbon emissions of PCS in different regions, the relationship between prefabrication rate and carbon emissions per unit area, etc. Future research should pay more attention to: (1) building a more comprehensive carbon emission calculation model by considering more indirect carbon emission factors. (2) Studying the cost-effectiveness of different emission reduction measures. (3) Studying the carbon emissions and emission reduction potential of the entire life cycle of PCS. (4) The correlation between prefabrication rate and carbon emissions. Thus better promoting the green and low-carbon development of PCS.

Shenzhen, as a first-tier city in China, has a certain representativeness in terms of economic development level, urbanization process, and population density. Beijing, Shanghai, Guangzhou, and Chongqing, among other cities, are all facing limited land resources and high demand for housing. The initial development of PCS in these cities faced the difficulties of promoting new technologies and a lack of professional and technical personnel. The specific implementation details of PCS in various cities differ, but the trend of the construction industry is to promote industrialization and green development. In terms of similarities in city characteristics, common development trends in the industry, and policy orientation, the research findings of this paper have a certain universality and can provide exemplary cases for other cities. In the future, the author will actively explore in areas such as technology localization, talent cultivation mechanisms, market promotion, and innovation of cooperation models and will apply these research results to Beijing, Shanghai, Guangzhou, Chongqing, and other cities.

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Conflict of Interest

The authors declare no conflict of interest.

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