Research on Carbon Footprint Calculation and Evaluation in Assembled Building Phase

Miaomiao Zhao, Jiwei Zhu, Pengwei Han, and Chengling Liu

Abstract This study takes the carbon footprint of prefabricated buildings as the research object, and divides its physical and chemical process into four stages: building materials mining (production), prefabricated component production, material transportation and on-site construction. According to the carbon footprint sources of each stage, a carbon footprint model is established, and the carbon footprint factors and consumption factors required in the model are analyzed. Build a three-dimensional model based on BIM technology, and convert the consumption in combination with the project consumption quota to provide a data basis for calculation. The carbon footprint concentration produced in each stage of prefabricated buildings and cast-in-place buildings is analyzed by cases, and corresponding countermeasures and suggestions are put forward.

Keywords Fabricated Buildings · BIM · Materialization Stage · Carbon Footprint

1 Introduction

After China announced the goal of "carbon peaking and carbon neutralization" in September 2020, it rekindled the global attitude towards climate change. Now, China has become an innovator, practitioner and leader of global green, low-carbon and environmental protection. The carbon emission of China's construction industry increased from 1.354 billion tec in 2009 to 2.126 billion tec in 2018, with a growth rate of 57.02%. The energy consumption situation of the construction industry is still severe [1]. Assembled buildings characterized by energy conservation and emission reduction, low carbon environmental protection and high efficiency have become

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the focus of the world today, playing a pivotal role in the green development of the construction industry.

The prefabricated building is a green building with sustainable development. Its main characteristics are standardized design, factory production, prefabricated construction, information management and intelligent application. Quantitative analysis on energy conservation and emission reduction of prefabricated buildings is of great scientific significance [2]. Wang Guangming et al. [3] conducted a comparative study on the data of energy consumption, noise emissions and carbon emissions of traditional cast-in-place buildings and prefabricated buildings, and analyzed the social and economic benefits. Liu Meixia et al. [4] discussed and studied the energy-saving benefits and carbon emissions of prefabricated residential buildings, taking Building 5, the demonstration base of Zhengfangli Civilian Industrialized Construction Group, as an example.

It can be seen that at present, the domestic research on energy conservation and emission reduction of prefabricated buildings mainly focuses on the establishment of their carbon emission models, while the comparative analysis between them and traditional cast-in-place buildings is rare. This study is aimed at a specific prefabricated residential project, studying the building stage, through the carbon emission factor method to quantify the carbon footprint evaluation model, comparative analysis of the main differences of different structural construction of the same building. The BIM model is used to derive the project quantity, and the carbon footprint of the two building structures is calculated and analyzed based on the consumption quota and carbon footprint factor combined with the actual case, so as to provide a practical basis for energy conservation and emission reduction of prefabricated buildings.

2 Construction of Carbon Footprint Model for Assembled Building Process

2.1 System Boundary

Carbon Footprint was originally proposed by British experts, but it evolved from the "ecological footprint" proposed by scholars from Columbia University and is a quantitative description of carbon emissions in the whole life cycle of buildings [5]. According to the whole life cycle process, the project is mainly divided into three stages: materialization, use and demolition. In this study, the materialization stage is subdivided into building material mining (production) stage, prefabricated component production stage, material transportation stage and on-site construction stage, as shown in Fig. 1.

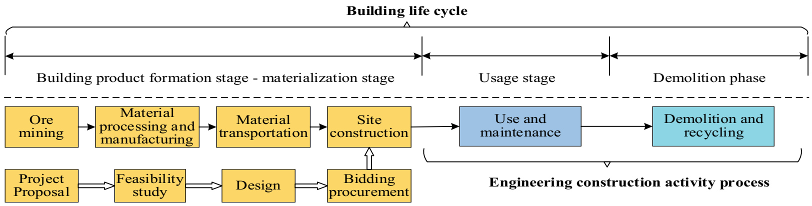

Fig. 1 Phase division of the whole life cycle of the building

2.2 *Analysis on Consumption of Prefabricated Buildings*

In this study, the combination of quota and work quantity has realized the conversion of material consumption and machine shift consumption. The specific statistical framework of project consumption is shown in Fig. 2.

According to the quantities of subdivisional works, the appropriate consumption quota is selected for resource consumption statistics. In this study, the straight stairs of cast-in-place projects are taken as an example for material consumption statistics. The BIM export volume is 43.5484 m^2. Since the project is located in Shaanxi, the 2019 Consumption Quota of Housing Construction and Decoration Works is selected as the quota standard for quantity conversion. Quota 5–56 is selected. See Table 1 for material consumption statistics.

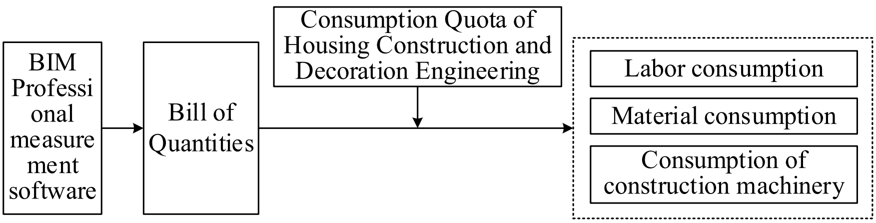

Fig. 2 Statistical Framework of Engineering Consumption

Table 1 Calculation Process of Construction Quantities of Straight Stairs

Quota No	Export Quantities	Company	Quota Details	Name	Quota consumption	Company	Actual consumption
5–56	43.5484	10m^2 horizontal projected area	Man-day	man-day	2.138	Man days	9.311
			Material	Concrete C35	2.586	m^3	11.262
				Plastic film	11.529	m^2	50.207
				Water	0.722	m^3	3.144
				Power	1.560	kWh	6.794

2.3 Carbon Footprint Calculation Model for Prefabricated Buildings

According to the divided system boundary, the construction process of prefabricated buildings is divided into four stages to calculate their physical and chemical carbon footprint, respectively: building materials mining (production), prefabricated component production, materials (building materials and prefabricated components) transportation and on-site construction [6]. The calculation formula is expressed as:

$$E = E_r + E_p + E_t + E_s \tag{1}$$

$$UCE = {}^{E}/_{A} \tag{2}$$

where: E—total carbon footprint concentration in the prefabricated building stage; E_r—carbon footprint in the exploitation (production) stage of building materials; E_p—carbon footprint in the production stage of prefabricated components; E_{tp}—carbon footprint in component transportation stage; E_{tu}—carbon footprint in the transportation stage of building materials; E_s—carbon footprint of building construction; UCE—carbon footprint in the materialization stage of unit building area; A—Building area.

(1) Mining (production) stage of building materials

$$E_r = \sum\nolimits_{j=1}^{j} M_j \times f_j \times \left(1 + \theta_j\right) \tag{3}$$

where: M_j—consumption of the jth building material; f_j—The jth carbon footprint factor of building materials considering recovery coefficient; θ_j—The loss rate of mining production of the jth material.

(2) Prefabricated component production stage

$$E_p = \sum C_p \times AU_i \times f_{ni}(i = 1, 2) \tag{4}$$

where: C_p—volume of prefabricated components; AU_1—Power consumption of prefabricated components per unit volume; AU_2—Fuel consumption of prefabricated components per unit volume; f_{n1}—electric power carbon footprint factor; f_{n2}—diesel carbon footprint factor.

(3) Material transportation stage

$$E_t = Q_p \times D_l \times H_p \times f_{n2} \tag{5}$$

where: Q_p—the number of means of transport; D_l—The distance from the material factory to the construction site; H_p—Fuel consumption per kilometer of material transport vehicles.

Table 2 Energy carbon footprint fact

Name	Carbon footprint factor	Company
Gasoline	3.5	$kgCO_2/kg$
Diesel oil	3.67	$kgCO_2/kg$
Natural gas	1.56	$kgCO_2/kg$
Power (Northwest)	0.94	$kgCO_2/kWh$

(4) Site construction stage

$$E_s = \sum\nolimits_{v=1}^{n} MU_i \times M_i \times f_{ni}(i = 1, 2) \quad (6)$$

where: MU_i—consumption of machinery required in the construction process of item i; M_i—Energy consumption per unit shift of machinery used in the construction process of item i.

3 Carbon Footprint Factor Analysis

3.1 Energy Carbon Footprint Factor

As the basis of all research data, the accuracy of energy carbon footprint factor selection is crucial. In the selection, some selected the relevant data provided by IPCC and other institutions, and the other part was calculated by referring to the domestic energy calorific value and energy default emission factor. The obtained energy carbon footprint factor is shown in Table 2.

3.2 Material Carbon Footprint Factor

The carbon footprint factors of finished or semi-finished materials are calculated in combination with the carbon emission data of some raw materials in IPCC. The summary of calculated building carbon footprint factors is shown in Table 3. This study mainly analyzes six different carbon footprints of concrete, cement mortar, steel, water, welding rod and block. The use of other materials is small, which has little impact on the carbon footprint calculation results, so they are not included in the calculation.

Table 3 Summary of Carbon Footprint Factors of Common Materials

Material name		Carbon footprint factor
Concrete	Concrete C25	262.50kgCO_2/m^3
	Concrete C30	278.80kgCO_2/m^3
	Concrete C35	290.50kgCO_2/m^3
	Concrete C40	301.40kgCO_2/m^3
	Concrete C45	315.40kgCO_2/m^3
Steel products	Medium and small section steel	1420kgCO_2/t
	Hot rolled ribbed bar	1777kgCO_2/t
	Cold rolled ribbed bar	2133kgCO_2/t
Welding rod		20.5kgCO_2/kg
Autoclaved aerated concrete blocks		365.05kgCO_2/m^3
Cement mortar		393.65kgCO_2/m^3
Water		0.26kgCO_2/m^3

3.3 Carbon Footprint Factor of Transport Machinery

The carbon footprint of the material transportation phase in this study refers to the carbon footprint generated during the transportation of building materials, including prefabricated components, from the production plant to the construction site. The carbon footprint factor of transport means the fuel consumption standard per kilometer of the transport means under the rated load, which is determined in combination with the energy carbon footprint factor.

3.4 Carbon Footprint Factor of Construction Machinery

The carbon footprint of mechanical equipment is generated by energy consumption in the construction process, rather than energy consumption due to the operation of machinery itself [7]. In this study, the carbon footprint factor of mechanical equipment is determined by the shift energy consumption and energy carbon footprint factor in the construction process of mechanical equipment. Since there are too many types of machinery, they will not be listed here one by one.

4 Case Analysis

4.1 Project Overview

This study takes a residential project in Xixian New Area of Xi'an as a case, and selects a single project. The building has 25 floors above the ground (3.15 m high) and 2 floors underground, with a building height of 79.15 m. The foundation structure is raft foundation, the pile foundation is CFG composite pile, and the building area is about 14,237.3 m^2. SPCS fabricated system technology is adopted for construction, and the main types of prefabricated components include prefabricated walls, composite slabs and prefabricated stairs. The overall assembly rate reaches 50%.

4.2 Carbon Footprint Calculation

In order to analyze and compare the carbon footprint difference between the prefabricated construction and the traditional cast-in-place construction in the physical and chemical stage, this study designs two different structures for the same building. The first scheme is the traditional cast-in-place structure; The second scheme is prefabricated structure.

According to the carbon footprint model of each phase of the building, the carbon footprint of the exploitation (production) phase of building materials in Scheme I is calculated as shown in Table 4.

It should be noted that in the material transportation stage, the transportation machinery and transportation distance of the same material in the two schemes are the same, while prefabricated buildings need to be transported. The carbon footprint calculation in other stages is the same, and the carbon footprint concentrations in each stage of the two schemes are shown in Table 5.

4.3 Comparative Analysis of Carbon Footprint Concentration

The carbon footprint concentrations generated by two different structures of the same building are different. Compared with previous studies, the carbon concentrations of the two cases in this study are at a moderate level. The carbon footprint concentrations per unit area in the materialization stage of the two building structures are respectively: traditional cast-in-place building structures: 352.33kgCO_2/m^2, and prefabricated building structures: 321.81kgCO_2/m^2. The carbon footprint per unit area of prefabricated structures is 30.52kgCO_2/m^2 less than that of traditional cast-in-place structures.

Table 4 Calculation of carbon footprint in the exploitation stage of building materials in scheme I

Building material	Company	Actual consumption	Carbon footprint(kgCO_2)
Autoclaved concrete block	m^3	1291.27	471,378.11
Concrete C20	m^3	165.77	43,514.23
Concrete C30	m^3	3355.60	935,541.75
Concrete C35	m^3	899.87	261,413.22
Concrete C40	m^3	116.63	35,151.11
Concrete C45	m^3	966.27	304,762.69
Deformed bar	t	796.10	1,414,669.70
Medium and small section steel	t	25.67	36,451.40
Cement mortar	m^3	1507.58	593,460.44
Dinas	m^3	3708.85	20,732.45
Gravel	m^3	931.60	2906.61
Welding rod	kg	5575.93	114,306.53
Iron piece	t	29.08	66,874.06
Coating	t	3.69	13,284.00
Waterproof roll	m^2	2842.11	36,805.32
Water	m^3	10,491.26	2727.73
Gasoline	kg	2660.56	9311.95
Diesel oil	kg	40.33	148.01
Quick lime	t	216.94	438.85
Aluminum alloy square tube	m	4054.36	14,352.41379
Summary			4,378,230.60

Table 5 Carbon Footprint Summary of Two Schemes kgCO_2

Stage	Carbon footprint of traditional cast-in-place buildings	Carbon footprint of prefabricated buildings
Mining (production) of building materials	4,378,230.60	4,015,708.00
Prefabricated component production	—	5507.83
Material transportation	55,634.01	45,805.38
Site construction	582,304.24	514,701.62

By comparing the total carbon footprint of different building structures in different stages of the same building, it is found that the largest contribution to the carbon footprint is in the building materials mining (production) stage, and the carbon footprint concentration in each stage is as shown in Fig. 3.

When analyzing the carbon footprint in the production stage of building materials, the main materials are classified into six categories: masonry, concrete, steel,

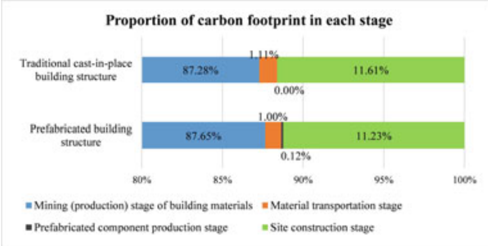

Fig. 3 Proportion of carbon footprint in each stage

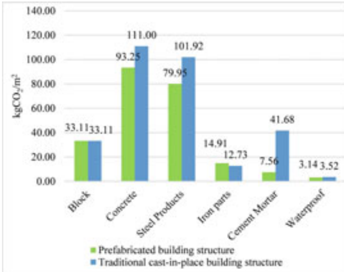

Fig. 4 Carbon footprint concentration of six main materials

cement mortar, iron parts and waterproof materials. The carbon footprint of some materials accounts for a small proportion of the total carbon footprint. This study will not conduct a detailed analysis temporarily. The carbon footprints of six types of materials are calculated respectively, as shown in Fig. 4. Through analysis, it can be concluded that:

(1) From the analysis of the figure and the material consumption table, it can be seen that the amount of steel is not the largest, but its carbon footprint concentration is at a higher level. Therefore, the carbon footprint concentration of materials with large amount of steel is not necessarily high. On the contrary, the carbon footprint concentration of materials with small amount of steel is not necessarily low. Therefore, the carbon footprint of buildings cannot be reduced by reducing the amount of steel.

(2) As a building material with a large carbon footprint, reducing the carbon footprint of steel can effectively control the carbon footprint of the project. According to the recyclability of steel, improve its production process and recovery rate, reduce its carbon footprint, and achieve emission reduction.

In the material transportation stage, due to prefabricated components in the prefabricated building structure, the amount of steel bars, concrete and other materials that need to be transported to the site is greatly reduced. In this case, the prefabricated component factory is closer to the construction site, so the carbon footprint concentration generated during the transportation process is reduced.

At the site construction stage, the total carbon footprint of prefabricated building structure is 514701.62kgCO_2, and that of traditional cast-in-place building structure is 582304.24kgCO_2. The total carbon footprint of prefabricated building structure is reduced by 104,803.85kgCO_2, because the prefabricated building adopts the construction methods of factory production and on-site assembly, which reduces the consumption of materials and energy. The concrete pumping, vibrating, rebar binding, welding and other operations are significantly reduced compared with the traditional cast-in-place structure, thus effectively reducing the carbon footprint concentration in the on-site construction stage.

5 Conclusion

In this study, a quantitative model of carbon footprint in the building stage was established. A single building of a prefabricated residential project was selected as a case, and a comparative analysis of carbon footprint of different structures was conducted based on the same building, namely prefabricated building structure and traditional cast-in-place building structure. The main differences between the two and some influencing factors were analyzed, and the following conclusions were obtained:

(1) Through case analysis, it is found that the carbon footprint is the highest in the building materials mining (production) stage, followed by the on-site construction stage, and the proportion of prefabricated components in the production stage is the lowest, which can be ignored compared with the first three items. Therefore, there is a great potential for carbon emission reduction during the production and on-site construction of building materials. Through carbon footprint calculation, the carbon footprint of prefabricated buildings is calculated in advance, the design scheme is deepened, the materials are selected reasonably, and the carbon footprint of prefabricated buildings is reduced.

(2) In this case, the three building materials with the largest carbon footprint in the building materials mining (production) stage are concrete, steel and block. For materials, the carbon footprint concentration cannot be reduced by reducing the consumption. Therefore, improving the recycling rate of building materials is an effective way to reduce carbon emissions in the stage of prefabricated buildings.

(3) Compared with the carbon footprint of two different structures in the same building, the carbon footprint per unit building area of prefabricated structure is reduced by 30.52kgCO_2/m^2 compared with that of traditional cast-in-place structure. It shows that prefabricated buildings have obvious carbon emission reduction advantages.

In conclusion, empirical research has proved that the application of prefabricated construction technology can reduce building carbon emissions to a certain extent. Therefore, in order to further reduce emissions, it is very important to expand the scale of prefabricated buildings. In addition, since the largest source of carbon footprint is the construction mining (production) stage, further promoting low-carbon materials and improving the recovery rate of building materials in the process of building industrialization is also an effective way to reduce carbon emissions.

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