農村裝配式裝修基礎部品碳排放核算研究

CARBON EMISSION MEASUREMENT STUDY OF BASIC COMPONENTS FOR RURAL PREFABRICATED DECORATION

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摘 要

建築行業在節能減排中發揮著重要的作用，而農村裝配式裝修基礎部品是其中的一個重要的組成部分，其優劣將直接影響裝配式建築的質量和性能。然而，裝配式建築碳排放評估的研究主要集中在裝配式建築的結構方面，很少有研究考慮農村裝配式裝修。因此，本研究首先以農村裝配式裝修基礎部品的碳排放核算爲重點，采用排放因子法建立碳排放核算體系；其次，引入案例并應用核算體系計算具體的農村裝配式裝修基礎部品的碳排放量。最後根據碳排放核算結果對農村裝配式裝修行業發展提出針對性的建議。研究結果表明，生產單位立方的預製外挂墻板所造成的碳排放量最多，預製樓梯的碳排放量次之，預製疊合樓板的碳排放量最少。通過本文的研究，為碳排放核算方法提供了一定的理論和實踐基礎，同時指明發展農村裝配式裝修基礎部品具有重大的意義。

關鍵詞：碳排放核算、農村裝配式裝修基礎部品、建築行業、排放因子法。

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ABSTRACT

The construction industry plays a pivotal role in energy conservation and emission reduction, with rural prefabricated decoration constituting a crucial aspect. The quality and performance of prefabricated buildings hinge directly upon the merit of these components. However, while studies have extensively examined the carbon emission assessment of structural aspects in prefabricated buildings, rural prefabricated decoration has received scant attention. Therefore, this study focuses on calculating the carbon emissions of rural prefabricated decoration. Firstly, it employs the emission factor method to establish a carbon emission accounting system. Subsequently, case studies are introduced to apply this accounting system for calculating the specific carbon emissions of rural prefabricated decoration. Finally, based on the results of the carbon emission calculations, targeted suggestions are made for the development of the rural prefabricated decoration industry. The findings reveal that the production of prefabricated exterior wall panels per cubic meter results in the highest carbon emissions, followed by prefabricated staircases, while prefabricated laminated floor panels exhibit the lowest carbon emissions. This research not only contributes to the refinement of carbon emission accounting methods but also underscores the significance of developing rural prefabricated decoration components. It provides both theoretical insights and practical implications for advancing sustainable practices in the construction industry.

Keywords: Carbon emission accounting, Rural prefabricated decoration, Prefabricated buildings, The emission factor method.

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1. Introduction

With the escalating urgency of global climate change, the imperative to mitigate carbon emissions has emerged as a shared global challenge [1]. China's construction sector, heralded as a cornerstone of the national economy, paradoxically stands as a significant emitter of carbon [2], responsible for approximately 46.5 % of total energy consumption and a third of the nation's emissions [3]. This surge in energy use and greenhouse gas emissions imperils the global ecosystem, amplifying the prominence of socio-environmental concerns [4]. According to the China Prospective Industry Research Institute, construction waste in China reached a staggering 2.379 billion tons in 2017, with construction and decoration waste comprising 6 % of this figure [5]. Recognizing the imperative to mitigate carbon emissions within the construction industry, concerted efforts must be directed towards carbon accounting and control.

Rural prefabricated decoration, a pivotal element within prefabricated building, holds considerable promise in advancing green, low-carbon development within the decoration industry. It facilitates enhanced construction efficiency, optimization of productivity structures, and directly impacts the quality and performance of prefabricated buildings. The integrated production of prefabricated rural decoration, coupled with dry operation methods, holds potential to curtail labor consumption, construction waste, dust pollution, and harmful gas emissions from paints. The advancement of rural prefabricated decoration stands as a linchpin in reducing energy consumption and pollution [6]. Moreover, it aligns with the principles of the "One Belt, One Road" initiative and fosters sustainable development within the construction industry [7]. Consequently, conducting a comprehensive study on carbon emissions accounting from rural prefabricated decoration holds both theoretical and practical significance.

Much of the current research is heavily focused on carbon emission assessment using life cycle assessment methods. Many scholars categorize carbon emission accounting methods into three main types: input-output life cycle assessment, process life cycle assessment, and hybrid life cycle assessment. Building upon these three methods, numerous scholars conduct studies on carbon emission assessment in the construction industry, taking into account the unique characteristics of their respective national building sectors. Nassen *et al.* [8] employed input-output assessment to evaluate the energy consumption and carbon dioxide emissions in the construction and manufacturing processes of the Swedish construction industry. This evaluation was then compared with the results of 18 bottom-up studies previously conducted using process life cycle assessment methods. Acquaye *et al.* [9] utilized input-output techniques to estimate the energy and greenhouse gas emission intensities of the Irish construction industry and its related sectors. They provided strategies for energy saving and emission reduction in the construction industry through both direct and indirect calculations. In contrast, input-output analysis methods calculate from a macro perspective using input-output tables, while process analysis methods focus on the processes throughout the life cycle of a building. For instance, Sandanayake *et al.* [10] estimated and compared the direct and indirect emissions and environmental impacts of buildings during the foundation and structural construction stages using a process-based approach. They also compared the environmental impacts of different construction stages from global, regional, and local perspectives. Hong *et al.* [11] divided the construction phase into three stages: material manufacturing, transportation, and on-site construction. They developed a model combining process-based life cycle assessment and input-output life cycle assessment to analyze that the energy consumption and greenhouse gas emissions were highest during the material manufacturing stage. Vasishta *et al.* [12] compared the environmental impacts and costs of prefabricated and cast-in-place construction using life cycle assessment and life cycle cost assessment. They concluded that prefabricated methods have less impact on the environment and economy compared to cast-in-place methods, making them a more effective and sustainable construction approach.

Some scholars have focused on research regarding rural prefabricated decoration. Rural prefabricated decoration simplifies the decoration process and reduces the time required at the construction site. This efficiency not only accelerates project completion but also saves a significant amount of labor costs [13]. By manufacturing decoration components in controlled factory environments and minimizing on-site work, prefabricated decoration evidently reduces the carbon footprint associated with construction projects. Rural prefabricated decoration represents a significant advancement in construction methods, aligning with contemporary environmental and economic needs, and providing an efficient, sustainable, and cost-effective solution [14]. Bian *et al*. [15] evaluated the carbon emissions of rural prefabricated decoration from the perspective of residential building life cycle and explored the potential of reducing carbon emissions by using prefabricated components to decorate buildings. Zhong *et al*. [16] utilized the Analytic Hierarchy Process (AHP) to construct a cost assessment system consisting of 5 primary indicators and 22 secondary indicators, conducting hierarchical analysis on it. From this point of view, previous studies have carried out full life cycle carbon emission accounting for assembled decoration, but few scholars have conducted in-depth and detailed research on assembled decoration from the component level, making it difficult to put forward targeted opinions on emission reduction. At the same time, the research results of domestic and foreign research in the field of construction using the theory of full life cycle evaluation cover a wide range, but the research on component-level components is not deep enough, and it mainly focuses on the macro level of carbon emission evaluation research on the building as a whole. Therefore, different from previous studies, this paper will conduct an in-depth study of carbon emission from the level of basic components of assembly decoration, and put forward targeted development suggestions by analyzing the differences in carbon emission of basic components of rural assembly decoration.

Overall, domestic and international scholars have made fruitful achievements in carbon emission accounting for prefabricated buildings. However, rural prefabricated decoration belongs to an emerging industry, and component development is still in its infancy. Therefore, carbon emission calculations for this field have not been thoroughly explored, leaving significant room for improvement in carbon emission accounting based on rural prefabricated decoration. Additionally, research on carbon accounting mainly focuses on life cycle assessment methods and largely remains theoretical, lacking exploration in practical implementation paths. Furthermore, China has actively encouraged the development of rural prefabricated decoration in recent years, but the market application and industrialization level of basic components for rural prefabricated decoration remain relatively low. Hence, this study aims to conduct carbon emission calculations for rural prefabricated decoration, analyze the differences in carbon emissions, and provide theoretical and practical foundations for achieving sustainable development of prefabricated buildings.

2. Methodology

Firstly, this paper establishes a basic overview of the carbon emissions of the rural prefabricated decoration on the premise of fully exploring the characteristics of carbon emission research. Then, the carbon emission accounting method was established, the emission coefficient of each part was established, and the carbon emission of the basic part of the rural prefabricated decoration was analyzed through regular analysis. Finally, the carbon emissions of each part are accounted for through a case example, and relevant recommendations are made based on the accounting results.

2.1 Overview of Rural Prefabricated Decoration

Rural prefabricated decoration refer to prefabricated, standardized components or materials used in building decoration, such as wall panels, floorings, and ceilings. Compared to traditional on-site construction, rural prefabricated decoration offer advantages like factory-based production, rapid installation, and resource conservation, making them widely applicable in various construction projects.

Throughout the life cycle of rural prefabricated decoration, including material production, manufacturing, transportation, installation, use, and disposal, carbon emissions are generated. Therefore, accurately calculating and assessing the carbon emissions of rural prefabricated decoration is of significant importance. By precisely calculating and assessing the carbon emissions of rural prefabricated decoration, scientific bases for carbon footprint assessment, carbon emission reduction strategy formulation, and sustainable design can be provided.

When conducting carbon emission calculations for rural prefabricated decoration, various factors need to be considered, including carbon content of materials, energy consumption and emissions during manufacturing, transportation distances, etc. Additionally, different types of rural prefabricated decoration may exhibit differences in carbon emissions, such as variations in materials and processes. Therefore, providing an overview and classification of rural prefabricated decoration to understand their characteristics and composition is essential for carbon emission accounting. This understanding not only facilitates the selection of carbon emission accounting methods but also provides necessary background information and foundational knowledge for subsequent method selection and case analysis. Furthermore, providing an overview of rural prefabricated decoration contributes to raising industry awareness and attention towards carbon emissions, promoting the sustainable development and carbon reduction of rural prefabricated decoration.

2.2 Accounting Methods

The mainstream methods for calculating carbon emissions in the academic field include Input-Output Analysis (I-O), the Emission Factor Method, Life Cycle Assessment (LCA), and Carbon Footprint Analysis. I-O calculates the carbon emissions of various industries based on the national economic input-output [17]. The emission factor method is a widely used method for monitoring and calculating greenhouse gas emissions [18]. LCA is employed to evaluate the environmental impacts of products or services throughout their life cycle [19-21]. Carbon footprint analysis is utilized to calculate the carbon emissions of individuals, organizations, or products [22-23].

Comparing the advantages and disadvantages of these four methods, it's evident that I-O has poor timeliness, while LCA yields precise results but is suitable for micro-level projects. Carbon footprint analysis is still in its developmental stage and is applicable to specific products. The emission factor method, on the other hand, is suitable for measuring carbon emissions at the macro-level for closed-system scenarios but cannot measure hidden carbon emissions. Given that this study focuses on the direct carbon emissions of rural prefabricated decoration, the emission factor method is chosen for carbon emission estimation.

The emission factor method, proposed by the Intergovernmental Panel on Climate Change (IPCC), is the first method for estimating carbon emissions. It's a factor-based and simulation-based carbon accounting method suitable for both macro and micro scenarios, widely applied at present. This approach establishes carbon emission factors for rural prefabricated decoration, considering factors such as material composition, production processes, and energy consumption, to calculate and predict carbon emissions. This method provides more detailed and comprehensive carbon emission estimation results, is easy to obtain data for, straightforward, covers a wide range, and has numerous reference examples. The basic principles of this method are as follows:

$$C = \mathrm{E}_i \times \xi_i \quad \text{...(1)}$$

Where, C represents the carbon emissions at each stage, E_i is the activity level leading to greenhouse gas emissions from production or consumption activities such as the consumption of each type of fossil fuel, consumption of limestone raw materials, net purchased electricity, net purchased steam, etc.; ξ_i is the emission factor, a coefficient corresponding to the activity level data, including carbon content per unit heat value or elemental carbon content, oxidation rate, etc., representing the greenhouse gas emission coefficient of per unit production or consumption activity. ξ_i can be directly adopted from known data provided by organizations such as the IPCC, the US Environmental

Protection Agency, the European Environment Agency, etc. (default values), or calculated based on representative measurement data.

The total carbon emissions of a building consist of the incremental carbon emissions of building components at each stage. The carbon emissions data for each stage of construction comprise three parts: "labor, materials, mechanical energy" carbon emissions, the equation is therefore as follows:

$$C = C_1 + C_2 + C_3 \quad \text{..(2)}$$

Where C refers to the total carbon emissions at the production stage of rural prefabricated decoration, C_1 represents the carbon emissions generated in the labor stage, C_2 represents the carbon emissions generated in the materials stage, and C_3 represents the carbon emissions generated in the mechanical energy stage.

2.3 Carbon Emission Factor

The carbon emission factor, also known as the carbon intensity factor, is a fundamental parameter utilized in calculating carbon emissions. It reflects the amount of carbon emitted per unit of product during production activities, thereby correlating energy and material consumption with carbon emissions and streamlining the calculation process. This study compiles pertinent domestic and international standards, regulations, literature, reports, and other relevant information to synthesize existing data on carbon emission factors. Through a meticulous screening process based on criteria such as authority, regional applicability, and timeliness, carbon emission factors for labor, materials, and mechanical energy are derived and finalized.

3. Case Study

3.1 Overview of the Case Study Project

The data collection project pertains to the pilot implementation of rural prefabricated concrete frame decoration parts. In this project, the prefabricated rate stands at 35 %, and the total floor area spans 2,577.32 m², segmented into 3 floors with a floor height of 3.2 m, resulting in a total building height of 10.6 m. The parts manufactured in the component factory for this pilot project encompass prefabricated stacked floor slabs, prefabricated exterior wall panels, and prefabricated stairs, with specific engineering quantities outlined in Tab. 1. By examining the entire building process and integrating the unique characteristics of rural prefabricated decoration, the carbon emissions of rural prefabricated decoration can be categorized into three components: labor carbon emissions, material carbon emissions, and mechanical energy carbon emissions.

Tab. 1. Quantity of project components

Component name	Unit	Wastage
Stacked floor slabs	m³	94.25
Exterior wall panels	m³	71.68
Stairs	m	6.40

3.2 Data Sources and Assumptions

The consumption of building materials for construction projects is usually determined based on the bill of quantities, while data on the transportation of building materials and prefabricated components are obtained through field research at factories and construction project sites. However, some of the data cannot be obtained through field research and need to be compiled by reviewing information. The use of different construction materials, transportation modes, system boundaries, emission factors and background data are all factors that can affect the accuracy and reliability of carbon accounting. Therefore, the effects of various factors need to be carefully considered to ensure the accuracy and comparability of results [24]. Differences in these basic factors can lead to obtaining different carbon emissions and thus different analytical results. Therefore the following assumptions are made in the calculation process:

(1) The building design and materials are based on the design drawings.
(2) The project is located in Wuhan province and most of the resources are located within a 100-kilometer radius of the city.

(3) The total weight of the selected main building materials should not be less than 95 % of the total amount of building materials consumed in the construction, and building materials with a weight ratio of less than 0.1 % may not be calculated.

(4) Most of the components involved in this project are presented in the form of main materials, so the carbon emission factor of building materials is used instead of the carbon emission factor of components.

3.3 Carbon Emissions Accounting

3.3.1 Labor Carbon Emissions

Based on the process layout of the component factory's production line, the relevant personnel allocation for each process on the automated assembly line, semi-automatic fixed mold production line and the consumption of the production stage of the project can be obtained. Specific data can be seen in Tab. 2 and Tab. 3.

Converting labor working hours into man-days and combining the project's engineering quantity of basic components with the personnel configuration of each process on each production line reveals the carbon emissions generated by labor consumption. Specific data can be seen in Tab. 4.

3.3.2 Material Carbon Emissions

According to the information provided by the project, and in accordance with the list of material consumption required for the production of one cubic meter of basic parts, the corresponding carbon emission factor of each material can be derived from the carbon emission of the production of one cubic meter of basic parts, and the carbon emission generated by the consumption of materials is shown in Tab. 5.

Tab. 2. Labor data table of automated flow production line

Component name	Unit	Wastage
Mold cleaning	1	5
Lineation	1	2
Ejective agent	1	2
A mold	2	26
Arrange steel cage	3	30
Installation of embedded parts	1	3
Concrete fabric	1	10
Vibrate	1	10
Floating	1	5
Form removable	2	20
Preparation of reinforcement	1	3
Amount	15	116

Tab. 3. Labor data table of semi-automatic fixed die line

Component name	Unit	Wastage
Mold cleaning	1	8
Ejective agent	1	15
A mold	3	45
Steel bar processing and binding	3	150
Installation of embedded parts	2	20
Pour concrete	3	90
Vibrate	2	40
Floating	1	20
Form removable	2	60
Concrete transportation	1	5
Amount	19	453

Tab. 4. Labor carbon emissions

Component name	Stacked floor slabs	Exterior wall panels	Stairs	Amount
Labor carbon emissions (kg CO_2)	235.625	50.750	143.450	429.825

Tab. 5. Carbon emissions of materials during unit production of cubic components

Material	Consumption of stacked floor slabs	Carbon emissions ($kgCO_2$)	Consumption of exterior wall panels	Carbon emissions ($kgCO_2$)	Consumption of stairs	Carbon emissions ($kgCO_2$)	Total carbon emissions
Concrete iron	158.519	370.934	136.563	319.557	147.042	344.078	1,034.569
C30 concrete Steel plate	1.029	303.555	1.029	303.555	1.029	303.555	910.665
PVC	5.754	13.810	31.836	76.407	48.510	116.424	206.641
Polystyrene	0.326	2.380	0.473	3.453	/	/	5.833
Carbon emission	/	/	1.449	6.694	/	/	6.694
		690.679		709.666		764.057	2,164.402

3.3.3 Mechanical Energy Carbon Emissions

Within the factory, the mechanical equipment energy used during the component production stage is electricity, with other major energy consumption being water.

Based on the energy consumption list required for the production of basic components per cubic unit and the corresponding energy carbon emission factors, mechanical energy carbon emissions can be seen in Tab. 6.

3.3.4 Total Carbon Emissions

The carbon emission accounting results will provide the overall carbon emissions of rural prefabricated decoration, usually expressed in terms of unit mass (*e.g.*, kilograms of CO_2 per square meter) or unit function (*e.g.*, kilograms of CO_2 per unit service life). This result reflects the carbon emission level throughout the entire product life cycle, including stages such as raw material acquisition, manufacturing, transportation, use, and disposal.

Summarizing the carbon emissions generated by labor consumption, material consumption, and mechanical energy consumption during the production process of basic components, the total carbon emissions generated by the project in the basic component production stage are calculated. Data can be seen in Tab. 7.

3.4 Data Analysis

Based on the above calculation data, the total carbon emissions of the prefabricated concrete component production stage of the project are determined to be 122,552.682 $kgCO_2$. Among these, the total carbon emissions of prefabricated stacked floor slabs, prefabricated exterior wall panels, and prefabricated stairs are 65,956.527 $kgCO_2$, 51,513.191 $kgCO_2$, and 5,082.964 $kgCO_2$ respectively.

By combining the project's prefabricated component engineering quantity, the carbon emissions produced per cubic component production are calculated, and they are aggregated with the carbon emissions caused by different carbon sources in the production stage of each prefabricated component. Due to significant differences in data, to clearly observe the relationship between carbon emissions from different carbon sources in the production stage, the carbon emissions corresponding to each component are converted into respective percentages based on the total carbon emissions of each carbon source. Specific details can be seen in Tab. 8 and in Fig. 1.

Tab. 6. Carbon emissions of mechanical energy

Component name	Stacked floor slabs	Exterior wall panels	Stairs	Amount
Mechanical energy carbon emissions ($kgCO_2$)	624.406	593.582	49.549	1,267.537

Tab. 7. Total carbon emissions

Component name	Stacked floor slabs	Exterior wall panels	Stairs	Amount
Total carbon emissions (kg CO_2)	65,956.527	51,513.191	5,082.964	122,552.682

Tab. 8. Summary of carbon emissions of each carbon source during the production stage

Unit: $kgCO_2$	Stacked floor slabs	Exterior wall panels	Stairs	Amount
Labor carbon emissions	235.625	50.750	143.450	429.825
	54.82%	11.81%	33.37%	
Material carbon emissions	65,096.496	50,868.859	4,889.965	120,855.319
	53.86%	42.10%	4.04%	
Mechanical energy carbon emissions	624.406	593.582	49.549	1,267.537
	49.26%	46.83%	3.91%	
Carbon emissions per unit of the cubic meter	699.804	718.655	794.213	2,260.148
	31.63%	32.48%	35.89%	
Total carbon emissions	65,956.527	51,513.191	5,082.964	122,552.682
	53.82%	42.03%	4.15%	

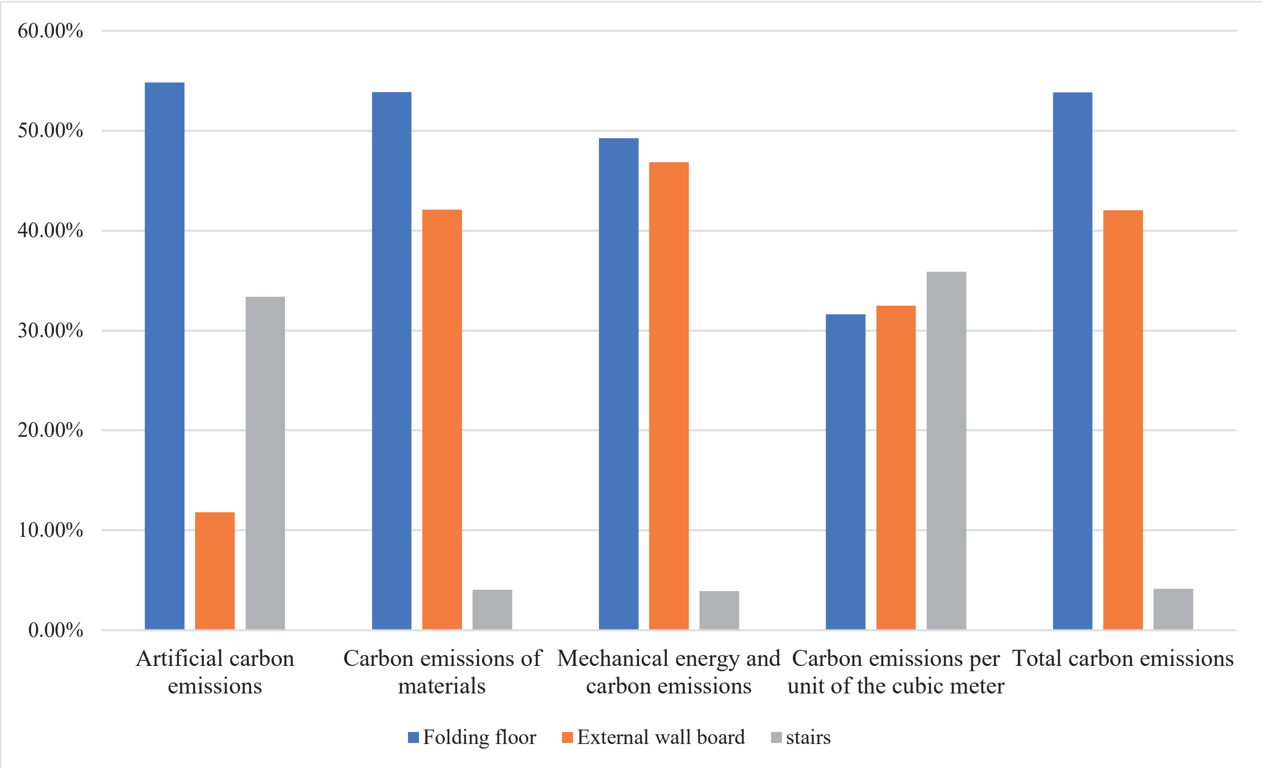

Fig. 1. Emission ratio of each basic part

3.5 Analysis of Carbon Emission Patterns

Regression analysis is a common statistical analysis method used to determine the quantitative relationship between two or more variables. It is mainly applied to determine the dependence relationship between variables containing independent variables. Based on the number of independent variables, it is mainly divided into regression analysis and multivariate regression analysis, and then classified into linear regression analysis and nonlinear regression analysis based on the relationship between independent variables and dependent variables. This paper uses SPSS software for regression analysis to measure the correlation and degree of correlation between the carbon emissions of stacked floor slabs, exterior wall panels, stairs and the total carbon emissions. This deeper analysis aims to study the regularity among the three relationships.

From the graphs, it can be observed that there is a highly significant positive linear relationship between the total carbon emissions and the carbon emissions of stacked floor slabs, with an equation of $y = 1.856x + 50.489$ and a determination coefficient R^2 of 0.999, as shown in Fig. 2.; a highly significant positive linear relationship exists between the total carbon emissions and the carbon emissions of exterior wall panels, with an equation of $y = 2.374x + 85.037$ and a determination coefficient R^2 of 1.000, as shown in Fig. 3.; a highly significant positive linear relationship is also observed between the total carbon emissions and the carbon emissions of stairs, with an equation of $y = 25.026x - 1{,}550.675$ and a determination coefficient R^2 of 0.999, as shown in Fig. 4.

Through SPSS analysis of the significance and correlation of the three variables' carbon emissions concerning total carbon emissions, it is evident that there is a strong linear relationship between the three independent variables and total carbon emissions. By conducting regression analysis, an estimation formula for the carbon emissions of prefabricated concrete component production stage, with material and mechanical energy carbon emissions as independent variables and total carbon emissions as the dependent variable, is obtained. This can provide a theoretical basis for quantifying the carbon emissions of prefabricated components for construction companies.

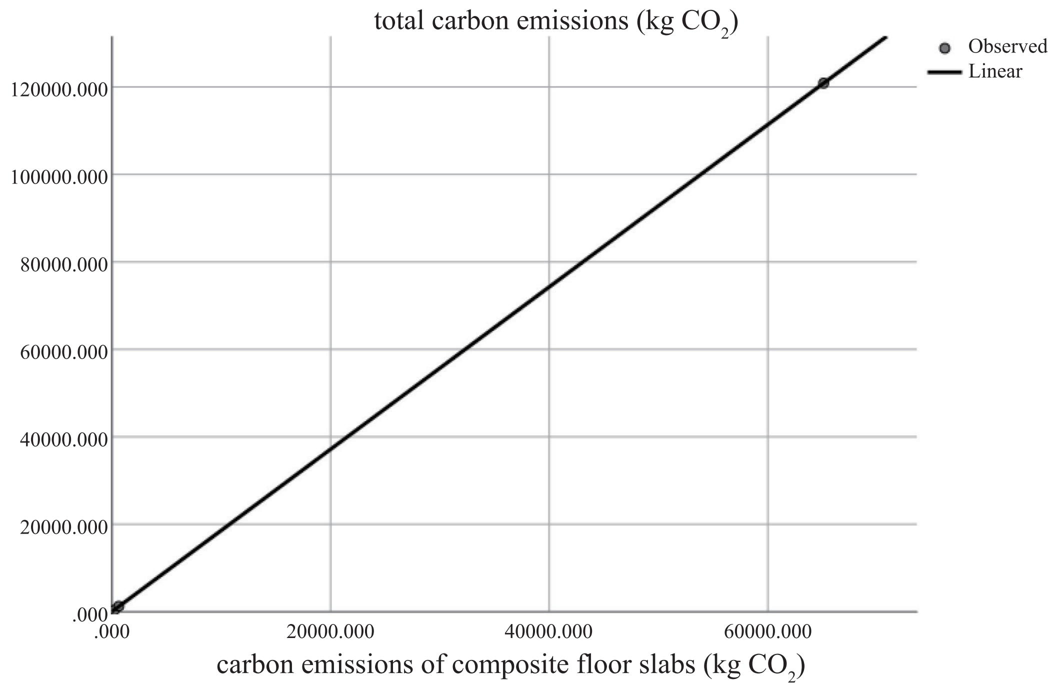

Fig. 2. Linear relationship between total carbon emissions of prefabricated concrete components at each stage and carbon emissions of composite floor slabs

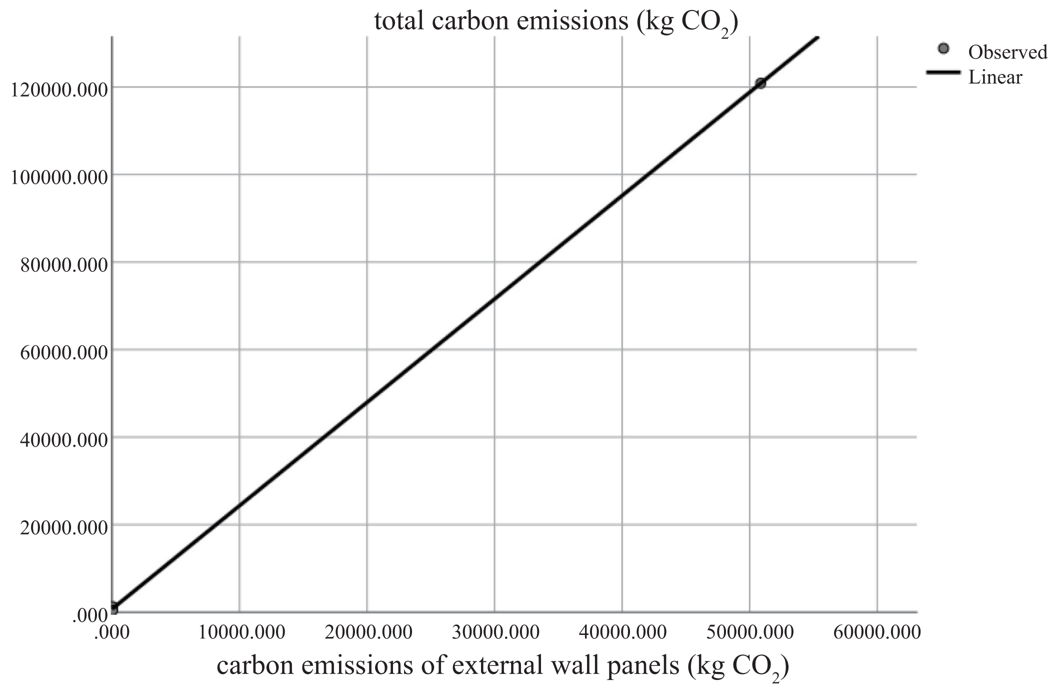

Fig. 3. Linear relationship between total carbon emissions of prefabricated concrete elements at each stage and carbon emissions of external walls panels.

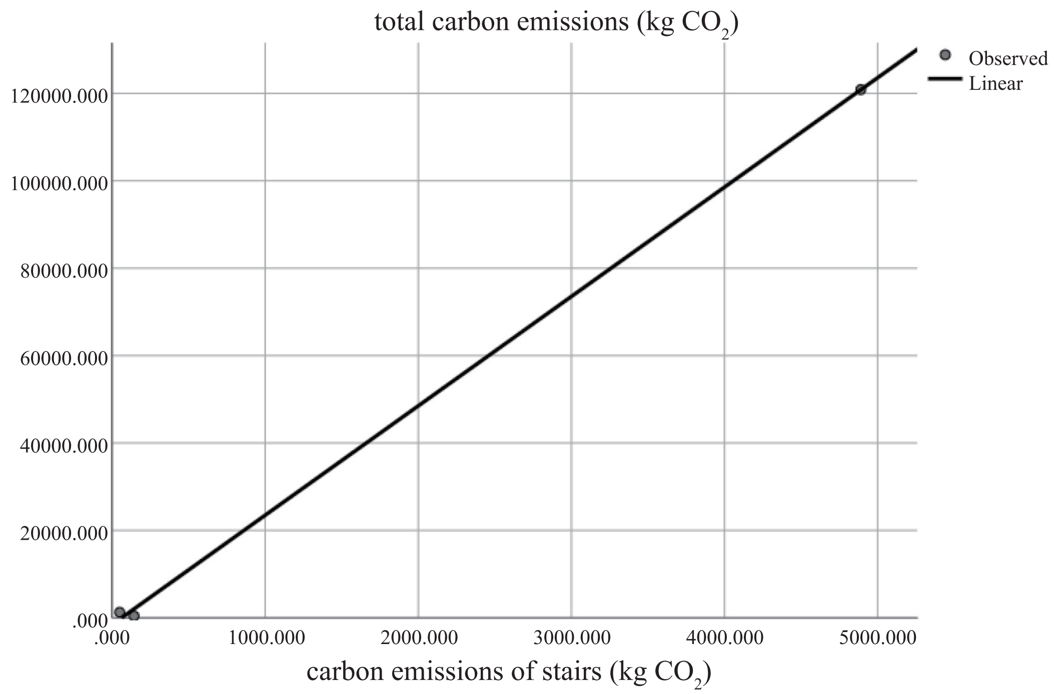

Fig. 4. Linear relationship between total carbon emissions of prefabricated concrete components at each stage and carbon emissions of stairs.

4. Suggestions for the Development of the Rural Prefabricated Decoration Industry Based on Carbon Accounting

4.1 Deepening the Understanding of Carbon Emissions in the Decoration Industry

The objective of advancing carbon emission accounting is to enhance environmental preservation and achieve sustainable development within the decoration industry, aligning with the requirements of the dual-carbon strategy. To this end, the development of the rural prefabricated decoration industry necessitates ensuring the standardization and scientific rigor of carbon accounting.

(1) Standardization of Methods and Indicators. To facilitate comparison and evaluation of carbon emission accounting outcomes, it is imperative to establish standardized methods and indicators. Metrics such as carbon emission intensity, carbon footprint, and carbon balance can gauge the carbon emission levels of fundamental components in rural prefabricated decoration. Furthermore, uniform units of measurement and data collection methods should be adopted to ensure comparability across various studies.

(2) Enhancing Data Reliability and Accuracy. The precision and credibility of carbon emission accounting are contingent upon the quality of data. Therefore, when undertaking carbon emission accounting for rural prefabricated decoration, reliance on dependable data sources and meticulous data collection and processing are essential. This entails securing accurate material life cycle data, energy consumption data, waste disposal data, to uphold the trustworthiness and precision of the findings.

(3) Utilization of Modeling and Software Tools. Employing models and software tools can streamline the calculation process and enhance efficiency when quantifying carbon emissions from rural prefabricated decoration. For instance, specialized

LCA software can simulate and analyze life cycle assessments, while material flow analysis models can facilitate process analysis. The judicious selection of suitable models and software tools can augment the efficiency and accuracy of the study.

By selecting appropriate carbon emission accounting methodologies, integrating standardized indicators and data sources, and ensuring data reliability and accuracy, the carbon emissions of rural prefabricated decoration can be effectively assessed. This, in turn, will contribute to formulating environmental protection policies and sustainable development strategies, furnishing a scientific underpinning for reducing carbon emissions and optimizing design and decision-making processes.

4.2 Utility of Monitoring Carbon Emission Indicators

In the design process of rural prefabricated decoration, carbon emission indicators can serve as crucial assessment metrics to guide and optimize product design and material selection. Here are several aspects of applying carbon emission indicators in the design of rural prefabricated decoration:

(1) Material Selection and Optimization. Carbon emission indicators can assess the carbon emission levels of different materials, aiding designers in selecting materials with lower carbon emissions. By comparing the carbon footprints of materials, environmentally friendly options can be prioritized, thus reducing overall carbon emissions.

(2) Product Optimization and Innovation. Carbon emission indicators can serve as a basis for product optimization and innovation. Analysis of carbon emissions can identify and improve carbon emission hotspots in rural prefabricated decoration, facilitating the implementation of relevant technological and design measures for improvement. This includes optimizing structural designs, refining manufacturing processes, promoting low-carbon materials, and energy innovation.

(3) Rational Selection of Construction Machinery and Techniques. While meeting construction requirements, opting for machinery with minimal power can further reduce carbon emissions generated during the construction process. Implementing optimal construction techniques allows for rational deployment of construction personnel, enhances the efficiency of construction equipment usage, and minimizes unnecessary waste.

(4) Environmental Certification and Compliance Standards: Carbon emission indicators can also be utilized for environmental certification and compliance assessment in the design of rural prefabricated decoration. Many countries and regions have established carbon emission certification and standard systems, requiring products to meet relevant carbon emission requirements for certification or standard compliance. Hence, carbon emission accounting is essential in the product design process to ensure compliance with certification and standard requirements.

By incorporating carbon emission indicators, the design of rural prefabricated decoration can prioritize environmental impact and sustainability, promoting low-carbon, green, and sustainable development. Additionally, through material selection optimization, process improvement, product innovation, and compliance with environmental standards, carbon emissions from rural prefabricated decoration can be reduced, achieving sustainable development goals.

4.3 Deepening Green Sustainability in Decoration through Multiple Factors

The State Council's “Action Plan for Peak Carbon Emissions by 2030” provides clear direction for achieving peak carbon emissions in various sectors including industry, transportation, and construction. In China, the traditional construction industry is categorized as a high-energy-consuming and high-polluting sector, thus forming a crucial part of subsequent energy conservation and emission reduction efforts. The State Council explicitly outlines the acceleration of new industrialization, the development of prefabricated construction, the promotion of building material recycling, and the enhancement of green development in design, construction, and management. Simultaneously, green sustainability assessment in construction is a critical aspect of the construction industry. By quantitatively calculating the total energy value and carbon emissions of typical buildings through methods such as energy value and carbon emission assessment, the green sustainability performance of buildings can be evaluated. The results of carbon emission accounting will contribute to assessing the sustainability of rural prefabricated decoration. In addition to carbon emissions, other environmental indicators such as energy consumption and resource utilization rates can be considered to comprehensively evaluate the environmental performance of products. This helps to develop sustainability strategies and goals for rural prefabricated decoration, providing guidance for product design, manufacturing, and usage stages.

5. Discussion

In order to realize the sustainable development of the construction industry, this study adopts the prefabricated workshop under the China Construction Wuhan Group as a case study, which has detailed data on the consumption of rural prefabricated decoration, and the production process is also divided into automated assembly line production and semi-automated fixed mold table production line, which is universally applicable. This study utilizes the emission factor method to establish a carbon emission accounting system for rural prefabricated decoration, analyzing their carbon emissions. It calculates and statistically analyzes the carbon emissions of labor, materials, and mechanical energy during the construction phase, as well as the impact of different rural prefabricated decoration on the total carbon emissions. Finally, recommendations are made to improve the carbon emission accounting for rural prefabricated decoration. The main conclusions of this study are as follows:

(1) Information on Carbon Emission Potential. The results of carbon emission accounting also provide information on the carbon emission reduction potential of rural prefabricated decoration. By analyzing the carbon emission results, it is possible to identify which processes or measures have a significant impact on carbon emission reduction, thereby guiding the formulation of strategies to reduce carbon emissions. This may involve measures such as material substitution, process improvement, and energy efficiency enhancement to reduce the environmental footprint of products. In addition to carbon emissions generated by material consumption during component production, a comparison of the data in Tab. 8. reveals that for components produced on automated assembly lines, the proportion of carbon emissions generated by mechanical energy consumption is higher than that generated by labor consumption, while for components produced on semi-automatic fixed mold platforms, the proportion of carbon emissions generated by labor consumption is higher than that generated by mechanical energy consumption.

(2) Production Characteristics. Rural prefabricated decoration produced on automated assembly lines are mostly relatively fixed in shape and have a high degree of standardization, with molds automatically moving to the next production process driven by relevant machinery after each step. Therefore, the frequency of machinery usage on this production line is high, while the frequency of manual operation is low. On the other hand, rural prefabricated decoration produced on semi-automatic fixed mold platforms are mostly irregular in shape and have a lower degree of standardization, requiring the mold to be fixed in the same position during production, with corresponding changes in machinery and manual operations to drive the relevant production processes. Therefore, the frequency of machinery usage on this production line is not high, and a larger number of workers are required.

(3) Carbon Emission Analysis by Component Type. Analysis of carbon emissions per cubic unit of rural prefabricated decoration reveals that among prefabricated stacked floor slabs , prefabricated exterior wall panels, and prefabricated stairs, prefabricated stairs contribute the most carbon emissions per cubic unit, followed by prefabricated exterior wall panels, with prefabricated stacked floor

slabs emitting the least carbon. Further research reveals that due to different manual configurations on factory production lines, the carbon emissions from labor for prefabricated stacked floor panels and prefabricated exterior wall panels produced on automated assembly lines are less than those for prefabricated stairs produced on semi-automatic fixed mold platforms.

(4) Carbon Emissions from Energy and Material Consumption. Although prefabricated exterior wall panels contribute the most carbon emissions per cubic unit in terms of energy consumption during production, followed by prefabricated stairs and prefabricated stacked floor slabs, prefabricated stairs contribute the most carbon emissions per cubic unit in terms of material consumption during production, followed by prefabricated exterior wall panels and prefabricated stacked floor slabs. The proportions of carbon emissions from various sources in the table indicate that carbon emissions during the production phase of rural prefabricated decoration mainly come from the carbon emissions generated by the consumption of relevant raw materials, accounting for over 95% in all cases.

In summary, within this factory, prefabricated exterior wall panels contribute the most carbon emissions per cubic unit, followed by prefabricated stairs, with prefabricated stacked floor slabs emitting the least carbon.

6. Conclusion

In order to realize sustainable development within the construction industry, this study adopts the emission factor method to investigate the carbon emission accounting of rural prefabricated decoration. It establishes a robust linear relationship between the total carbon emissions and those of stacked floor slabs, exterior wall panels, and stairs, enabling the estimation of carbon emissions for rural prefabricated decoration. Furthermore, the paper calculates and analyzes carbon emissions from labor, materials, and mechanical energy during the production phase of rural prefabricated buildings, while also statistically analyzing the impact of different assembly lines on carbon emissions. Finally, recommendations are provided for carbon emission accounting within the rural prefabricated decoration industry. The study's results offer crucial references and guidance for decision-makers and designers in related fields, promoting the sustainable design and application for rural prefabricated decoration.

Admittedly, this study has some limitations. It relies on only one case study for system validation, potentially limiting the generalizability of results due to its narrow regional scope. Additionally, the carbon reduction strategies discussed here do not account for associated costs, whereas stakeholders are primarily interested in making informed decisions that balance environmental concerns with costs and other objectives.

In summary, future research should aim to increase sample sizes and research depth, such as expanding studies to buildings of various structural types and climate zones, to supplement existing findings and enhance result generalizability. Secondly, establishing a standard system for carbon emission accounting from rural prefabricated decoration is crucial to unify accounting methods and data collection standards for enhanced comparability and data exchange among different products and enterprises. Moreover, future analyses of carbon emission reduction strategies should consider developing comprehensive evaluation indices that account for multiple objectives to align with real societal action. This will facilitate the widespread application of carbon emission accounting and foster the sustainable development of the industry.

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