buildings

Article

Reducing Carbon Emissions from Prefabricated Decoration: A Case Study of Residential Buildings in China

Ji Bian [1,2], Changchun Liu [1,*], Chunyang Zuo [2], Jianli Hao [3], Wenting Ma [1], Baoyin Duan [3], Congda Chen [4] and Jixuan Liu [2]

[1] Jiangsu Province Engineering Research Center of Construction Carbon Neutral Technology, Suzhou University of Science and Technology, Suzhou 215011, China
[2] China Overseas Grand Oceans Lowcarbon Technology Co., Ltd., Shenzhen 518000, China
[3] Department of Civil Engineering, Xi'an Jiaotong-Liverpool University, Suzhou 215000, China
[4] Suzhou Kelida Co., Ltd., Suzhou 215011, China
* Correspondence: lcc@usts.edu.cn

Abstract: Since decoration is an essential part of buildings, the carbon emissions generated by decoration work should not be ignored. In recent years, prefabricated decoration has attracted much attention as efforts are made to pursue green, low-carbon, and waste-reducing buildings. However, research on carbon emissions assessment of prefabricated buildings has focused mainly on the structural aspect of prefabricated buildings, with few studies having considered prefabricated decoration. This study therefore focuses on assessing the carbon emissions of prefabricated decoration from the life cycle perspective of a case study residential building and explores the potential for reducing carbon emissions by decorating buildings with prefabricated components. The results show that using prefabricated decoration in the case study building reduced carbon emissions by 29.08% at the building material production stage compared to traditional decoration, and using an optimized design of prefabricated decoration, the building's energy consumption over its design life could reduce carbon emissions by 1046 $kgCO_2/m^2$. These findings demonstrate the benefits of prefabrication decoration for reducing carbon emissions. This study provides decoration companies with robust data and insights to guide future decisions and practices, helping to transform and achieve the carbon neutrality goal for the building decoration industry.

Keywords: prefabricated decoration; life cycle assessment; carbon emissions reduction; prefabricated buildings; building energy consumption

Citation: Bian, J.; Liu, C.; Zuo, C.; Hao, J.; Ma, W.; Duan, B.; Chen, C.; Liu, J. Reducing Carbon Emissions from Prefabricated Decoration: A Case Study of Residential Buildings in China. *Buildings* **2024**, *14*, 550. https://doi.org/10.3390/buildings14020550

Academic Editor: Constantinos A. Balaras

Received: 9 December 2023
Revised: 18 January 2024
Accepted: 29 January 2024
Published: 19 February 2024

1. Introduction

Against the backdrop of the country's rapid economic development, China's total carbon emissions and its share of the world's emissions are high and continually rising. As a major greenhouse gas, carbon dioxide not only leads to an increase in surface temperature but also causes degradation of the natural environment [1]. The Chinese government has established several low-carbon strategies to regulate and solve high carbon emissions by actively supporting the "energy saving and carbon reduction" program and encouraging the development of low-carbon cities and economies [2]. However, problems such as carbon inefficiency and high building energy consumption in construction remain a concern [3], and as China's urbanization progresses, its construction industry's share of energy consumption and carbon emissions will continue to increase [4]. The construction industry already represents one of the largest carbon emitters in China [5], is characterized by extensive resource consumption and long operation times, and has become a potential impediment to China achieving its dual-carbon goals [6]. It is therefore necessary to take effective measures to reduce carbon emissions from the construction industry, which can be achieved through technological innovation and low-carbon building development.

The rapid expansion of the real estate industry in China has boosted the construction industry, thus giving rise to many related decorating activities [7]. Building interior decoration as an essential part of buildings requires a large consumption of materials and resources for new building decoration and the refurbishment of existing buildings [8]. Traditional building decoration has concurrently highlighted the industry's detrimental environmental impacts [9]. Traditional decoration can lead to the generation of large quantities of waste and environmental issues due to the work that needs to be conducted on sites [10]. The current practices of traditional interior decoration, with their inadequate quality control, traditional techniques, safety risks, and resource wastage, necessitate a reevaluation and revolution [11]. In response to the shortcomings of traditional decoration, prefabricated decoration has gained popularity in recent years [12]. Prefabricated decoration exhibits four key features: standardized design, cohesive manufacturing, assembly-based construction, and collaborative information integration [13]. Prefabricated decoration offers similar advantages to prefabricated construction, including a cleaner and safer working environment for employees and a reduction in the amount of waste generated during construction [14]. In addition, prefabricated decoration has shown improvements in terms of reduced construction duration, labor savings, and increased material utilization [15]. Prefabricated decoration is a good alternative to traditional decoration in the pursuit of green and low-carbon goals [16]. Moreover, the current public and residential building sector is facing a plethora of existing building refurbishment projects that require the maintenance and upgrading of decoration products with minimal impact on operations [17]. The willingness of migrant workers in the current labor market to choose the construction industry is declining, and there is a gap in employment age, resulting in a continuous increase in labor costs [18]. Prefabricated decoration is helping to address these problems and, in doing so, presents new development opportunities.

With the advancement of prefabricated decoration, the construction industry has increased its attention to this decoration method [19]. However, the adoption of prefabricated decoration is low due to traditional decoration companies' unwillingness to change as well as the lack of identification of the environmental benefits of prefabricated decoration. Given the efforts to pursue low-carbon and green building practices, it is necessary to quantify the carbon emissions from prefabricated decoration. Therefore, the research questions (RQs) of this paper are provided as follows:

RQ_1: How to develop a model that can be used to quantify the carbon emissions of prefabricated decorations

RQ_2: What is the potential application of prefabricated decoration to reduce carbon emissions?

The novelty of this paper compared to the prior studies is that it focuses on the life cycle perspective of prefabricated decoration and develops a model to quantify carbon emissions. This research not only addresses the environmental impact of traditional interior decoration but also explores the potential of prefabricated decoration to contribute to carbon emission reduction goals, providing a pioneering study that integrates technological innovation, sustainable materials, and real-world application in the construction industry.

2. Literature Review

2.1. Carbon Emissions from the Construction Industry

As a major source of carbon emissions, the construction industry has received extensive research attention, and many different research directions have been generated for construction carbon emissions. Most of the literature analyzes the carbon emissions trend in the construction industry. The studies include global, national, and regional trends and emissions from various buildings [20,21], especially the projections of China's construction industry carbon emissions and reduction potential by 2060 [22–24]. This study's results can reveal whether carbon emissions are growing, stabilizing, or declining and the main factors contributing to such trends.

While gaining a deeper understanding of carbon emissions trends in the construction industry, focusing on how building design and technological innovations affect carbon emissions can help develop practical measures to reduce emissions. Yang et al. studied how digital technology affects construction carbon emissions, and the findings indicated that using digital technology and building a digital city can greatly decrease carbon emissions intensity [25]. In another study, digital infrastructure development was also shown to control carbon emissions effectively [26]. Karlsson et al. explored the potential of combining existing technologies and abatement measures in reducing carbon emissions by analyzing different building designs and the actual level of reduction of different abatement measures from a supply chain perspective and concluded that increasing the recycling rate of materials is the reduction measure that deserves the most attention in the short term [27]. Xu et al. demonstrated in a case study that sustainable material applications can effectively reduce carbon emissions [28]. Xu et al. also explored the use of bamboo as a building material, and the results have shown that bamboo buildings provide a valuable way to extend carbon storage and realize carbon emissions reductions [29]. In addition, the application of intelligent technologies can also greatly contribute to reducing carbon emissions, including artificial intelligence, robotics learning, artificial neural networks, and other technologies [30,31]. Fang et al. constructed a carbon emissions prediction model for the building construction stage based on the robot learning method, which provides great help for designers to clarify the relationship between carbon emissions and design parameters during the construction stage [32]. In summary, measures such as adopting efficient building design, improving building materials, and integrating intelligent technologies can be influential measures for controlling carbon emissions.

Quantifying carbon emissions from construction projects is necessary for more targeted development and implementation of emission reduction strategies and to clarify the effects of emission reduction. Also, in analyzing carbon emissions trends, accurate quantification of carbon emissions allows for a more precise identification of the influencing factors. Li and Chen measured the construction carbon emissions of a residential community project based on the Life Cycle Assessment (LCA) theory. Their results showed that among the different buildings in the project, tall buildings and villas produce the most carbon emissions per unit [33]. Zhang et al. specifically assessed the implied carbon emissions of tall residential buildings with a dataset of up to 403 buildings and explored cascading carbon reduction strategies according to the statistical data [34]. Yang et al. analyzed the carbon emissions and reduction potentials of thirty provinces in China from an urban construction land use perspective and discussed how energy structure, energy efficiency, and economic level affect carbon emissions [35]. Hung et al. quantified the carbon emissions from Hong Kong's construction industry and found that a significant amount of carbon emissions was generated by cross-boundary construction activities and proposed measures such as using low-carbon materials and fuels to minimize indirect construction carbon emissions [36]. Kang et al. illustrated the importance of embodied carbon assessment in the construction sector and developed a computational model based on probabilistic analysis for assessing embodied carbon emissions [37]. Typically, building-implied carbon assessments are based on the specific implementation of the particular project [38]. To assess the implied carbon emissions at the design stage, Cang et al. used Building Information Modeling (BIM) technology and the "building element" as the fundamental unit of measurement to provide a novel carbon emissions calculation method for the design optimization process [39]. In addition to BIM, the Internet of Things (IoT), blockchain, and other digital technologies can also improve carbon quantification [40]. Effective carbon emissions measurement can help the construction industry and stakeholders better understand the carbon emissions characteristics of construction activities and help construction projects set clear carbon reduction targets.

2.2. Prefabricated Construction Carbon Emissions

As an essential approach to the industrialization of construction, prefabricated buildings have seen an increasing level of application in recent years, bringing new directions for research on construction industry carbon monitoring and assessment. Regarding carbon emissions monitoring, prefabricated constructions offer opportunities for real-time monitoring and visualization of carbon emissions [41]. Tao et al. provided builders with a real-time system for monitoring building construction carbon emissions and enabled visualization and analysis of the monitoring results based on IoT technology [42]. Xu et al. also used IoT and integrated BIM technology to develop a prefabricated construction-embodied carbon detection system [43]. Yevu et al. presented a comprehensive view of digital twin technology in the prefabricated building's full supply chain, enabling carbon emissions monitoring through intelligent technology [44]. Integrating prefabrication technology and a new generation of digital technology can effectively realize the dynamic monitoring of prefabricated building carbon emissions, creating a novel paradigm for the construction industry to control carbon emissions.

Studies on the carbon emissions assessment of prefabricated buildings can be categorized into two main areas. The first topic of research is the carbon emissions generated by prefabricated buildings. Li et al. used BIM, LCA, and the Geographical Information System (GIS) to construct a carbon footprint accounting model for precast concrete composite panels in the materialization stage [45]. By integrating BIM and LCA, automated models can be developed for embodied carbon assessment of prefabricated constructions at various spatial scales [46]. It is also possible to assess the potential of prefabricated constructions to reduce carbon emissions throughout their life cycle without the need to construct physical facilities [47]. According to a study of previous research, BIM technology and LCA methodology are directly related to the assessment of prefabricated projects' carbon emissions. BIM technology can create detailed building models that provide material and quantity information, and these data can be used for LCA analysis, which can then be used to evaluate prefabricated buildings' carbon emissions [48]. BIM and LCA are the most popular and mature methods used in carbon assessment for prefabricated buildings.

The second area of research is comparative analyses of carbon emissions from prefabricated and traditional buildings. Luo et al. compared the carbon emissions of precast piles and cast-in-place piles based on a quantitative model of the process and two case studies and have explored the impact of transportation distance, sustainable materials, and equipment idle time on pile construction carbon emissions [49]. Zhao et al. included green materials in buildings based on comparing carbon emissions between prefabricated and traditional buildings. The results showed that prefabricated buildings are better at reducing environmental loads [50]. Research in both directions of carbon assessment provides important information for the construction industry's carbon management and sustainable development. Meanwhile, comparative analyses can help decision-makers and owners make more informed choices during the project selection and building design stages to reduce carbon emissions and support sustainable development goals.

2.3. Prefabricated Decoration

Prefabricated decoration is characterized by the pre-manufacturing of building decoration elements in the factory, which are later assembled on-site. One of the primary advantages of this method is the utilization of eco-friendly materials that substantially reduce the environmental footprint of construction projects. These materials are selected for their sustainability, durability, and lower carbon emissions, supporting the global shift towards environmentally responsible building practices [51]. Another significant benefit of prefabricated decoration is the reduction in construction time. By streamlining the decoration process through prefabrication, the time required for on-site work is considerably decreased. This efficiency not only expedites project completion but also results in notable savings in labor costs [52]. The construction industry, faced with challenges such as increasing labor costs and a shortage of skilled labor, finds a viable solution in prefabricated decoration. Furthermore, the method plays a crucial role in mitigating overall carbon emissions in the construction process [16]. By manufacturing decoration components in a controlled factory setting and minimizing on-site work, prefabricated decoration significantly reduces the carbon footprint associated with building projects [53]. Prefabricated decoration represents a significant advancement in construction methodologies. It aligns with contemporary environmental and economic demands, offering an efficient, sustainable, and cost-effective solution [54]. Embracing such innovative practices is indicative of the construction industry's commitment to environmental stewardship and operational efficiency, positioning prefabricated decoration as a key player in the future of sustainable building practices.

Through the comprehensive literature review, it is known that research on quantifying carbon emissions from prefabricated buildings has focused on the structural aspect of such buildings, with little attention paid to the specific field of prefabricated decoration. There is no unified and efficient carbon emission evaluation model applicable to prefabricated decoration, which affects the exploration of carbon emissions influencing factors and the quantitative expression of the carbon emissions change trend for prefabricated decoration. Therefore, the objective of this research is to develop a model to evaluate the carbon emissions of prefabricated decoration across its life cycle and to explore the application potential of prefabricated decoration to reduce carbon emissions.

3. Methodology

There are many ways to measure carbon emissions from buildings, with the most common being the carbon emissions factor (CEF) method. Many similar studies have applied the CEF method because of its clear measurement principles and simple data acquisition [55,56]. This method has been used for the study of carbon emissions from highway construction in Southwest China [57], the study of carbon emissions from high-rise residential buildings in Tehran during the construction stage [58], and the study of carbon emissions from precast concrete panels during the materialization stage [45]. Since prefabricated decoration has a high degree of standardization and accuracy, the CEF method can quickly estimate a project's carbon emissions. Moreover, many studies used this method to measure the material, prefabricated component, or building carbon emissions, which provided CEF data and research ideas for this study. Given the effectiveness of the methodology, this study adopted the CEF method for calculations and, based on that method, developed a framework for the carbon emissions measurement model for prefabricated decoration, as shown in Figure 1. The framework includes four steps that can realize the carbon emissions measurement of prefabricated decoration across its life cycle.

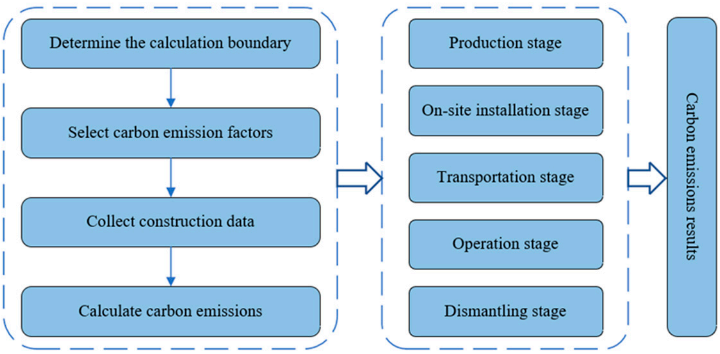

Figure 1. Carbon emissions measurement framework for prefabricated decoration.

The first step was to divide prefabricated decoration into five stages from a lifecycle perspective: production, transportation, on-site installation, operation, and dismantling. Then, based on field research, the process of prefabricated decoration was specifically analyzed, and the calculation boundaries of each stage were determined. The second step was to select the CEF applicable to this study by analyzing national norms, reports of professional research institutes, international carbon emissions databases, and scholars' research data, with timeliness, region, and applicability as evaluation criteria. The third step were to obtain consumption data on energy, labor, materials, and equipment in the relevant stages through research on prefabricated decoration construction sites, construction companies, and material suppliers. The fourth step was to calculate prefabricated decoration carbon emissions by substituting construction data and the corresponding CEF into the equations.

3.1. Carbon Emission Calculation Boundaries

Currently, most scholars apply LCA theory to analyze the sources of carbon emissions from buildings and assess the impact of buildings on the surrounding environment through calculations [59]. From a life cycle perspective, prefabricated constructions can be divided into six stages: building material production, component preparation, component transportation, on-site construction, operation and maintenance, and dismantling and recycling [60]. Zhang and Wang divided the life cycle of a building into three parts: the materialization stage, the operation stage, and the disposal stage, of which the materialization stage includes production, transportation, and on-site installation [61]. In this study, to account for the characteristics of prefabricated decoration, the life cycle of prefabricated decorations is divided into five stages: production, transportation, on-site installation, operation, and dismantling. Figure 2 shows the specific carbon emissions measurement boundaries.

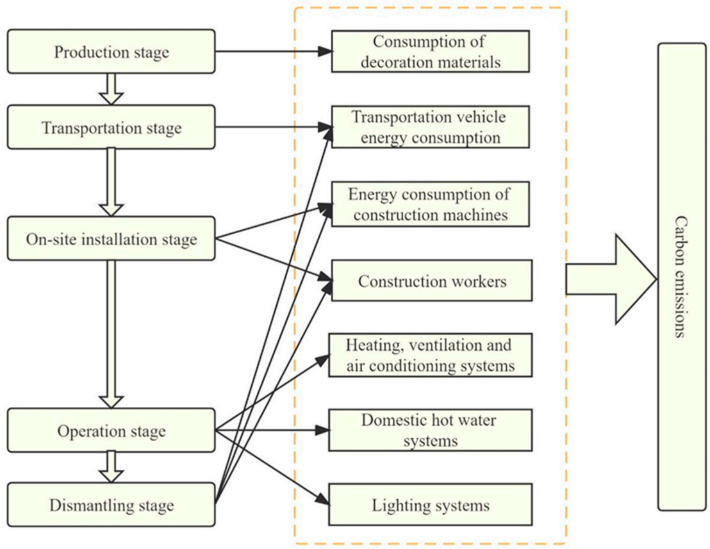

Figure 2. Measurement boundary for prefabricated decoration carbon emissions.

3.2. Carbon Emissions Factors

Many scholars, authoritative organizations, and institutions worldwide have compiled various databases on CEF after field research, which have specific reference values [62]. However, due to differences in experimental purposes, testing techniques, geographical areas, and measurement times, no standardized CEF database has been formed so far. Therefore, accounting accuracy, consistency of sources, and geographical affiliation should be followed to ensure the selection's validity. In this study, the CEF involved in calculating carbon emissions from prefabricated decoration includes four aspects: transportation, decoration materials, electricity, and labor.

The mode of transportation is selected based on the size, shape, quality, and delivery value of the goods being transported, and the specific means of transportation are also different. Table 1 shows the CEF for the transportation modes used in the case study project. For some decoration materials used in smaller quantities, the proportion of their carbon emissions is small, and the overall impact on the assessment results is negligible. Therefore, consideration can be given to selecting a few primary decoration materials used in larger quantities for accounting. Table 2 shows the CEF for the decoration materials of the case study project. The data are derived from the Standard for Calculating Carbon Emissions from Buildings (GB/T 51366-2019) [63] and the Standard for Calculating Carbon Emissions from Building Decoration (T/CBDA 69-2023) [64].

Table 1. CEF for different modes of transportation.

Mode of Transportation	Load Capacity	CEF ($kgCO_2e/(t{\cdot}km)$)
Medium gasoline truck	8 t	0.115
Heavy duty gasoline truck	10 t	0.104
Medium diesel truck	8 t	0.179
Heavy diesel truck	10 t	0.162

Table 2. Main materials required for prefabricated decoration and their carbon emissions.

Material	Consumption	CEF	Carbon Emissions ($kgCO_2e$)
Light steel keel	11.178 t	500 $kgCO_2e/t$	5589.00
Aluminum extrusions	3.381 t	2450 $kgCO_2e/t$	8283.45
Wooden floor	74.52 m^3	750.2 $kgCO_2e/m^3$	55,904.91
Bamboo and wood fiberboard	116.196 m^3	215.3 $kgCO_2e/m^3$	25,016.99
Galvanized steel	16.836 t	2760 $kgCO_2e/t$	46,467.36
Aluminum honeycomb composite panel	9.798 t	2450 $kgCO_2e/t$	24,005.10
Marble	15.663 m^3	307.5 $kgCO_2e/m^3$	4816.37
Aluminum composite panel	1.656 t	3327.76 $kgCO_2e/t$	5510.77
Polypropylene	0.414 t	3720 $kgCO_2e/t$	1540.08
Total			177,134.03

3.3. Carbon Emissions Equations

According to the boundary of carbon emissions calculation, prefabricated decoration can be divided into five stages: production, transportation, on-site installation, operation, and dismantling. Finally, the summary calculation is carried out to obtain the whole life cycle carbon emissions. The total carbon emissions of prefabricated decorations are calculated as follows:

$$W = W_1 + W_2 + W_3 + W_4 + W_5 \tag{1}$$

where W is the total carbon emissions of the prefabricated decoration, W_1 is the carbon emissions in the production stage, W_2 is the carbon emissions in the transportation stage, W_3 is the carbon emissions in the on-site installation stage, W_4 is the carbon emissions in the operation stage, and W_5 is the carbon emissions in the dismantling stage.

(1) Production stage

Carbon emissions at the production stage are only considered for producing raw materials, including those directly used in prefabricated decoration and those used in making component parts. The equation is as follows:

$$W_1 = \sum_{i=1}^{n} M_i F_i \tag{2}$$

where M_i is the consumption of the i-th building material (t), and F_i is the CEF corresponding to the i-th building material ($kgCO_2e$/unit quantity of material).

(2) Transportation stage

Carbon emissions in the transportation stage are directly proportional to material consumption, material capacity, and average transportation distance. It is closely related to the choice of transportation mode and the CEF per unit weight. The calculation formula is as follows:

$$W_2 = \sum_{i=1}^{n} M_i D_i T_i \quad (3)$$

where M_i is the consumption of the *i*-th primary building material, D_i is the average transportation distance of the *i*-th building material (km), and T_i is the CEF per unit weight of the *i*-th building material ($kgCO_2e/t \cdot km$) for the transportation mode of the *i*-th building material.

(3) On-site installation stage

The on-site installation stage needs to consider the carbon emissions generated during the construction of prefabricated decorations due to construction machinery and workers. The equations are as follows:

$$W_3 = \sum_{x=1}^{m} C_x \quad (4)$$

$$C_x = \sum_{y=1}^{n} C_{xy} \times Q_{xy} \quad (5)$$

where C_x is the carbon emissions generated by the *x*-th inventory in the prefabricated decoration construction stage (x = 1, 2, 3,. . ., m), C_{xy} is the volume of work for the *y*-th quantity within the *x*-th inventory in the prefabricated decoration construction stage, and Q_{xy} is the carbon emissions generated per unit for the y-th quantity within the *x*-th inventory in the prefabricated decoration construction stage (y = 1, 2, 3,. . ., n).

(4) Operation stage

The calculation of carbon emissions during the operation stage of prefabricated decoration refers to the building's operation in terms of the heating, ventilation, and air-conditioning (HVAC) system, the domestic hot water system, and the lighting system. This study does not consider the carbon emissions generated by the daily operation of other commonly used household appliances and equipment. The equation is as follows:

$$W_4 = W_{41} + W_{42} + W_{43} \quad (6)$$

where W_{41} is the carbon emissions from the operation of the HVAC system ($kgCO_2$), W_{42} is the carbon emissions from the operation of the domestic hot water system ($kgCO_2$), and W_{43} is the carbon emissions from the operation of the lighting system ($kgCO_2$). The equations are as follows:

$$W_{41} = E_{kt} \times EF \times N \quad (7)$$

$$W_{42} = E_{rs} \times EF \times N \quad (8)$$

$$W_{43} = E_{zm} \times EF \times N \quad (9)$$

where E_{kt} is the annual energy consumption of HVAC per unit area ($kWh/m^2 \cdot a$), E_{rs} is the annual energy consumption of domestic hot water per unit area ($kWh/m^2 \cdot a$), E_{zm} is the annual energy consumption of lighting per unit area ($kWh/m^2 \cdot a$), EF is the electricity CEF ($kgCO_2/kWh$), and N is the building design life (a).

(5) Dismantling stage

Data on the dismantling stage are not readily available. Carbon emissions during the dismantling stage include those generated during the dismantling of the building, the transportation of the demolition materials, and the recycling process. According to Li et al. (2022), carbon emissions from dismantling can be estimated at 90% of the construction stage, and the transportation of demolished items can be regarded as the inverse process of the material transportation stage, so that carbon emissions generated by the transportation of demolition items can be calculated at 90% of the material transportation stage [60]. Since carbon emissions from recycling are complex with very little data available, they are not considered in the dismantling stage of this study. The equation is therefore as follows:

$$W_5 = W_2 \times 90\% + W_3 \times 90\% \quad (10)$$

This is a life-cycle carbon accounting model for prefabricated decoration. When using this model, it is only necessary to record the actual data that occurred in the project and set it into the corresponding equation for calculation. In the following, the model is utilized with examples from the case study project.

4. Case Study

4.1. Overview of the Case Study Project

The Jinhua Haiyue Huafu project is in Jiangbei District, Jinhua City, Zhejiang Province. It is a large-scale residential project with a total construction area of about 213,700 m^2, consisting of 21 small and high-rise buildings of 15–26 floors. The project applies advanced prefabricated decoration technology, starting at the national strategic level. It adopts green and environmentally friendly decorative materials, forming an industrialized and standardized carbon-reducing pathway. To further study the carbon emissions pattern of prefabricated decoration, the 22# residential building of the Haiyue Huafu project was selected for empirical analysis. The surface area of the case study building is 8409.61 m^2, and the total building area for energy-saving calculation is 8260.18 m^2.

The selection of this case study building was based on its representativeness and typicality, while the size and characteristics of the project were considered necessary to draw stronger conclusions. The in-depth analysis of this case study project will help to understand prefabricated decoration's carbon emissions in actual projects more comprehensively and provide quantitative data on the patterns of carbon emissions from buildings adopting prefabricated decoration. Furthermore, findings from the case study are expected to provide the construction industry with information for managing carbon emissions, helping with environmental sustainability, and promoting the practice of green construction.

4.2. Prefabricated Decoration Techniques for the Case Study Building

The case study building was completed with prefabricated decoration for the floor and bathroom systems. In the floor system, prefabricated wood flooring is used in the bedrooms, from bottom to top: bottom adjustable bracket, oriented strand board base layer, underfloor heating module and underfloor heating coil, and solid wood composite flooring. In the dining room, prefabricated floor tiles are used, and the floor tiles can be used according to the design requirements to achieve the design effect. Prefabricated decoration flooring systems do not require wet concrete work and can therefore increase the speed of construction. The dry and wet areas of the case study building each use a separate aluminum honeycomb composite monolithic chassis, and the walls use aluminum honeycomb composite tile monolithic wall panels. The wall panels are connected to the monolithic chassis to form an overall waterproofing system. Compared with the traditional bathroom, aluminum honeycomb material has a better flame retardant and heat retardant effect, and its surface is treated with epoxy fluorocarbon, which has strong corrosion and aging resistance and can effectively avoid wall cracking.

In addition, the case study building adopts a prefabricated decoration integration design process at the design stage, synchronizing the interior design with the architectural design, thus avoiding the conflict between civil engineering structure and interior decoration and avoiding wall trenching for the construction of water and electricity pipelines at the decoration stage. The building can form a prefabricated decoration information platform at the design stage, including the code, model, material, manufacturer, and other information about the parts and components. Through this platform, transportation, on-site installation, and post-maintenance organization can be carried out efficiently. Prefabricated decoration breaks the traditional thinking of decoration and opens the assembly industry chain of integrated parts, unified design, lean manufacturing, assembly construction, and lightweight maintenance. The carbon emissions of the case study building using prefabricated decoration techniques can be quantified, and the carbon emissions characteristics and reduction potential of prefabricated decoration can be further analyzed based on the calculation results.

4.3. Case Study: Building Carbon Emission Results

4.3.1. Carbon Emissions from Decoration Materials Production

Based on Equation (2) and the construction data from the case study building, the total carbon emissions of the prefabricated decoration of the residential building at the production stage can be calculated. From the calculation process, the carbon emissions at the production stage are directly related to the consumption of materials and the corresponding CEF. Figure 3 illustrates the percentage of carbon emissions generated by different material consumption in the production stage of the case study residential building's prefabricated decoration.

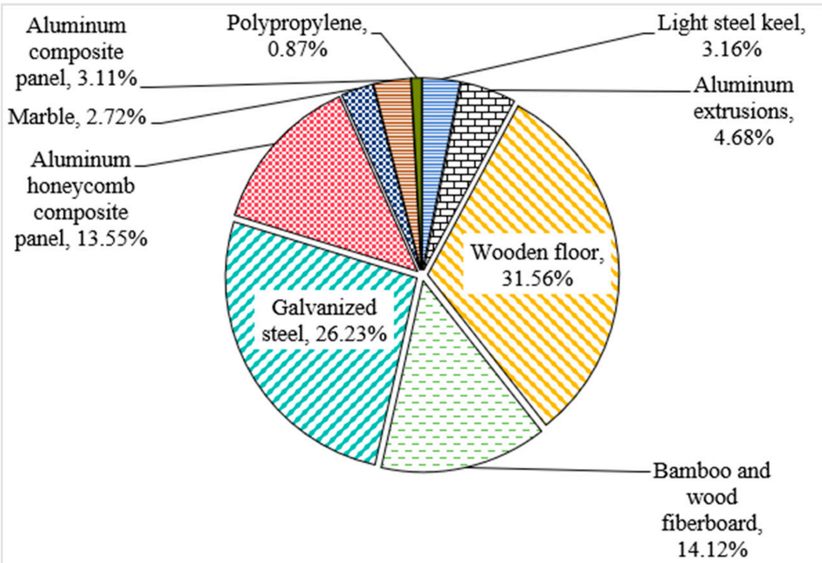

Figure 3. Material share of carbon emissions at the prefabricated decoration production stage.

To better compare the carbon emissions of prefabricated and traditional decoration, it is necessary to calculate the carbon emissions of adopting traditional decoration in the production stage. Using Equation (2) and the empirical data collected from the project, the estimated carbon emissions of the case study residential building using traditional decoration methods during the production stage can be calculated. The calculation results are shown in Table 3.

Table 3. Main materials required for traditional decoration and their carbon emissions.

Material	Consumption	CEF	Carbon Emissions ($kgCO_2e$)
Wooden floor	76.59 m^3	750.2 $kgCO_2e/m^3$	57,457.82
Cement mortar	28.152 t	735 $kgCO_2e/t$	20,691.72
Polyethylene film	20.079 t	2620.0 $kgCO_2e/t$	52,606.98
Putty	41.676 t	210 $kgCO_2e/t$	8751.96
Latex paint	10.074 t	4120 $kgCO_2e/t$	41,504.88
Light steel keel	11.799 t	5000.0 $kgCO_2e/t$	58,995
Aluminous gusset plate	1.449 t	2450.0 $kgCO_2e/t$	3550.05
Marble	16.491 m^3	307.5 $kgCO_2e/m^3$	5070.98
Galvanized steel suspension rod	0.414 t	2760 $kgCO_2e/t$	1142.64
Total			249,772.03

The main materials used in traditional decoration differ from the prefabricated decoration in terms of type and consumption, contributing to the different carbon emissions produced by the two types of decoration during the production stage. Figure 4 shows the percentage of carbon emissions generated by different material consumption during the production stage of the case study residential building using traditional decoration.

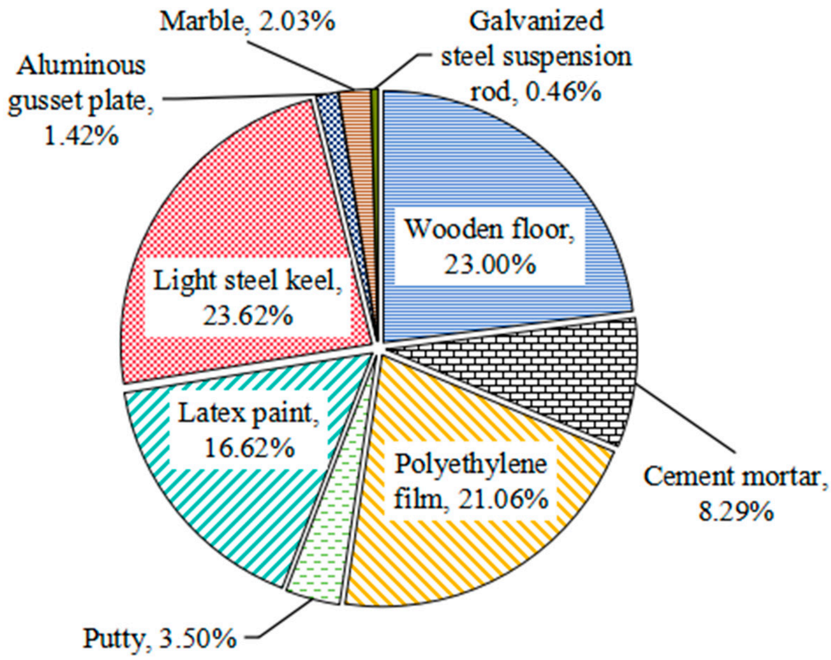

Figure 4. Material share of carbon emissions at the traditional decoration production stage.

4.3.2. Carbon Emissions from Transportation

This section calculates the carbon emissions generated by the energy consumed to transport traditional and prefabricated decoration materials between the plant and the worksite. In this project, the materials are transported by road, and the transportation distance is set to 500 km according to the source information. Based on Equation (3), the carbon emissions of traditional and prefabricated decoration at the transportation stage are as shown in Tables 4 and 5.

Table 4. Carbon emissions during the transportation stage of traditional decoration.

Material of Traditional Decoration	Weight (t)	Distance (km)	CEF ($kgCO_2e/(t \cdot km)$)	Carbon Emissions ($kgCO_2e$)
Wooden floor	70.838	500	0.162	5737.87
Cement mortar	28.152		0.162	2280.31
Polyethylene film	20.079		0.162	1626.39
Putty	41.676		0.162	3375.75
Latex paint	10.074		0.162	815.99
Light steel keel	11.799		0.162	955.71
Aluminous gusset plate	1.449		0.179	129.68
Marble	39.872		0.162	3229.63
Galvanized steel suspension rod	0.414		0.179	37.05
Total				18,188.38

Table 5. Carbon emissions during the transportation stage of prepabricated decoration.

Material of Prepabricated Decoration	Weight (t)	Distance (km)	CEF ($kgCO_2e/(t{\cdot}km)$)	Carbon Emissions ($kgCO_2e$)
Light steel keel	11.178	500	0.104	581.26
Aluminum extrusions	3.381		0.115	194.41
Wooden floor	68.93		0.104	3584.36
Bamboo-wood fiberboard	84.242		0.104	4380.58
Galvanized steel	16.836		0.104	875.47
Aluminum honeycomb composite panel	9.798		0.104	509.49
Marble	37.87		0.104	1969.24
Aluminum composite panel	1.656		0.115	95.22
Polypropylene	0.414		0.115	23.805
Total				12,213.84

4.3.3. Carbon Emissions from On-Site Installations

Carbon emissions sources during the on-site installation include labor and mechanical equipment. The prefabricated decoration on-site installation took a total of 56 days to complete, with a total of 25 professional workers on-site. Carbon emissions from labor activities are calculated using 1.11 $kgCO_2$/person-day as the CEF. Since the prefabricated decoration parts and components are pre-produced in the plant and transported directly for installation at the site, which reduces on-site cutting and other operations, the machinery used at the project's on-site installation stage mainly consists of electric drills, hoists, and temporary lighting equipment. The average daily power consumption during the on-site installation is 51.78 kWh. The carbon emissions from the on-site installation stage are shown in Table 6.

Table 6. Carbon emissions during the on-site installation stage of prefabricated decoration.

Carbon Source	Daily Electricity Consumption	Total Person-Day	CEF	Carbon Emissions ($kgCO_2e$)
Electric drills Hoists Temporary lighting equipment	51.78 (kWh)	-	0.8102 ($kgCO_2$/kWh)	2349.32
Labor	-	1400	1.11($kgCO_2e$/person-day)	1554
Total				3903.32

The carbon emissions distribution of the prefabricated decoration materialization stage can be derived from the carbon emissions calculation results of the production, transportation, and on-site installation stages, as shown in Figure 5.

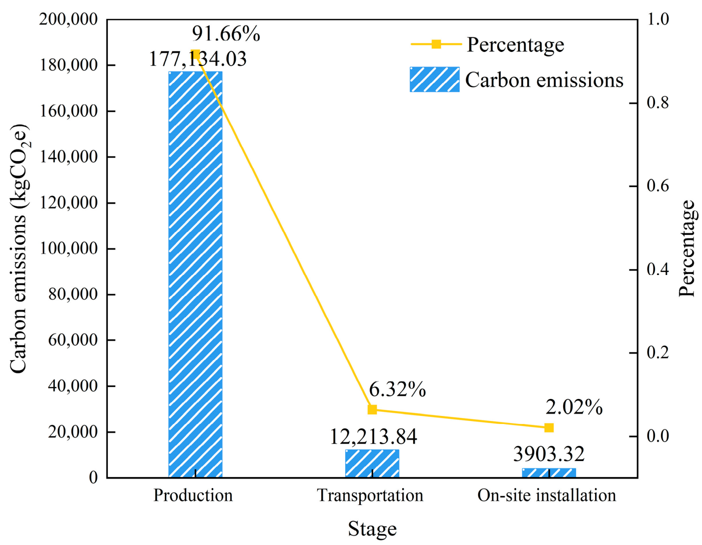

Figure 5. Carbon emissions distribution at the materialization stage.

4.3.4. Operational Carbon Emissions

The project adopts prefabricated decoration technology, and the operation stage is calculated according to the comprehensive index of building energy savings provided in the Energy Saving Design Standard for Residential Buildings in Zhejiang Province (DB33/1015-2021). The building calculation conditions are as follows: (i) The indoor temperature of the case study residential building is 16 °C in winter and 26 °C in summer; (ii) The heating calculation period is from December 15 to February 15 of the following year, and the air-conditioning calculation period is from June 15 to September 1 [65].

The split air conditioner of the case study building achieves level 1 energy efficiency, the Integrated Part Load Value (IPLV) value of the multi-connected system reaches more than 6.6, and the energy-saving standard requirement is 4.4. The energy-saving and emission-reduction analysis of the HVAC system is shown in Table 7.

Table 7. Calculation of emission reduction for HVAC systems.

	Case Study Building	**Traditional Building**
Annual HVAC energy consumption per unit area (kWh/m^2·a)	14.35	23.96
CEF (kgCO_2/kWh)	0.8102	0.8102
Annual carbon emissions per unit area of HVAC (kgCO_2/m^2·a)	11.63	19.41
Age of the building (a)	50	50
Carbon emissions per unit area of HVAC (kgCO_2/m^2)	581.5	970.5
Emission reduction (kgCO_2/m^2)	389	

Each household in the project uses an air-source heat pump to provide domestic hot water, with an energy efficiency of 4.4. Compared to a conventional electric water heater, the emission reduction analysis is shown in Table 8. The project's lighting system emissions reduction analysis is shown in Table 9.

Table 8. Calculation of domestic hot water system emissions reduction.

	Case Study Building	**Traditional Building**
Annual energy consumption per unit area for domestic hot water (kWh/m^2·a)	4.73	18.64
CEF (kgCO_2/kWh)	0.8102	0.8102
Annual carbon emissions per unit area of domestic hot water (kgCO_2/m^2·a)	3.83	15.10
Age of the building (a)	50	50
Carbon emissions per unit area of domestic hot water (kgCO_2/m^2)	191.5	755
Emission reduction (kgCO_2/m^2)	563.5	

Table 9. Calculation of emission reduction for lighting systems.

	Case Study Building	**Traditional Building**
Annual energy consumption per unit area of lighting (kWh/m^2·a)	11.00	13.31
CEF (kgCO_2/kWh)	0.8102	0.8102
Annual carbon emissions per unit area of lighting (kgCO_2/m^2·a)	8.91	10.78
Age of the building (a)	50	50
Carbon emissions per unit area of lighting system (kgCO_2/m^2)	445.5	539
Emission reduction (kgCO_2/m^2)	93.5	

Combining the results of the emission reduction analysis of the HVAC, lighting systems, and domestic hot water, the carbon emissions at the project's operation stage compared to a traditional building are shown in Figure 6.

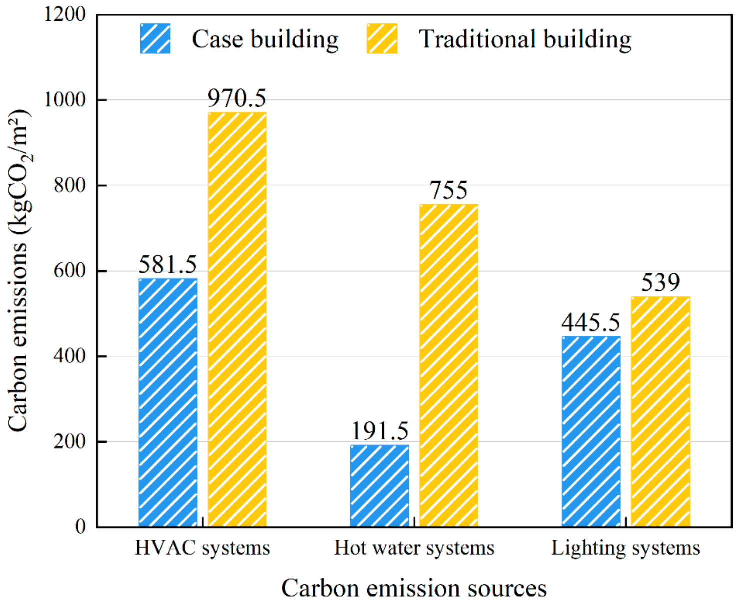

Figure 6. Comparison of carbon emissions at operation stage.

The reduction in carbon emissions during the operation phase in the case study of prefabricated decoration compared to traditional decoration can be attributed to the adoption of energy-efficient HVAC systems, the use of air-source heat pumps for domestic hot water, efficient lighting systems, and an integrated design approach that focuses on sustainability. The prefabricated decoration technology, along with the choice of materials and construction methods, contributes to overall energy savings and reduced carbon emissions during the building's operational life. These measures collectively result in a lower environmental impact during the operation stage compared to traditional decoration methods.

4.3.5. Dismantling Carbon Emissions

The demolition process typically requires workers to break down, dismantle, and clean up a building or component using hand tools and mechanical equipment, and both the worker activities and the operation of the mechanical equipment generate carbon emissions. Transportation of demolition items from the demolition site to a disposal or recycling site requires transportation, and the energy consumed during transportation results in carbon emissions. The waste disposal process may involve landfilling, incineration, recycling, or other methods, some of which may generate carbon emissions.

Since the project has not yet entered the dismantling stage, it is impractical to obtain the carbon emissions based on the actual situation, so the carbon emissions at this stage are measured by using the calculated results from the transportation and on-site installation stages along with Equation (10). Using this simplified method, the carbon emissions of the case study residential building at the dismantling stage are found to be 14,505.44 $kgCO_2e$.

5. Discussion

This study has developed a model that can calculate the carbon emissions of prefabricated decorations. The calculation results of the case study project are now discussed with reference to the carbon emissions of prefabricated decoration at various stages compared with the carbon emission levels of traditional decoration. This will provide a fuller understanding of the advantages of prefabricated decoration in terms of reducing carbon emissions.

5.1. Carbon Emissions from Different Materials

The calculation of carbon emissions at the production and transportation stages is directly related to the decoration materials used. Table 10 shows the carbon emissions of the different types of materials used in prefabricated decoration at the relevant stages.

Table 10. Carbon emissions from different decoration materials.

Material	Consumption	Production Stage Carbon Emissions ($kgCO_2e$)	Transportation Stage carbon Emissions ($kgCO_2e$)	Total ($kgCO_2e$)
Light steel keel	11.178 t	5589.00	581.26	6170.26
Aluminum extrusions	3.381 t	8283.45	194.41	8477.86
Wooden floor	74.52 m^3	55,904.91	3584.36	59,489.27
Bamboo-wood fiberboard	116.196 m^3	25,016.99	4380.58	29,397.57
Galvanized steel	16.836 t	46,467.36	875.47	47,342.83
Aluminum honeycomb composite panel	9.798 t	24,005.10	509.49	24,514.59
Marble	15.663 m^3	4816.37	1969.24	6785.61
Aluminum composite panel	1.656 t	5510.77	95.22	5605.99
Polypropylene	0.414 t	1540.08	23.805	1563.89

The table shows that the wooden floor generates the most carbon emissions at the production stage, while bamboo-wood fiberboard generates the most carbon emissions at the transportation stage. However, the wooden floor is still the one that produces the most overall carbon emissions in the production and transportation stages. This is mainly because most materials produce far more carbon emissions at the production stage than at the transportation stage, so the transportation stage has a lesser impact on the overall carbon emissions, which also reflects the importance of adopting emission reduction measures at the production stage. Carbon emissions at the production stage are strongly associated with the difficulty of obtaining raw materials, the technical level of the manufacturing plant, the type of materials used in construction, and the amount of construction materials consumed, which can be considered when analyzing measures for reducing emissions. In the case of marble, the carbon emissions at the production stage are not much, while the transportation stage generates more carbon emissions. This type of material should focus on the transportation stage when considering emissions reduction measures.

According to the results of this study, the reduction in carbon emissions during the production stage is primarily related to the consumption of materials and their corresponding carbon emission factors. Apart from the types of materials, there are also some other measures that can affect the quantity of carbon emissions generated during the production phase. At the production phase, the adoption of green materials, energy-efficient production processes, and improving the recycling rate of materials can reduce the carbon emissions from the production phase of prefabricated decorating components. Selecting materials with lower carbon footprints, such as recycled, renewable, or sustainably sourced materials. Applying lean manufacturing principles to minimize waste in the production process. In addition, implementing renewable energy sources, such as solar or wind power, in manufacturing facilities will decrease reliance on fossil fuels. All the measures mentioned above have the potential to reduce carbon emissions from the production phase.

5.2. Carbon Emissions at Different Stages

According to the prefabricated decoration carbon emissions calculations, the carbon emissions at each stage of the prefabricated decoration can be obtained, as shown in Table 11. The data show that the carbon emissions of the building present different focuses and characteristics throughout its life cycle. The share of carbon emissions at each stage is shown in Figure 7.

Table 11. Carbon emissions at different stages of prefabricated decoration.

Life Cycle Stage		Carbon Emissions
Materialization stage	Production stage	177,134.03 $kgCO_2e$
	Transportation stage	12,213.84 $kgCO_2e$
	On-site installation stage	3903.32 $kgCO_2e$
Operation stage		10,065,029.33 $kgCO_2e$ (1218.5 $kgCO_2/m^2$)
Dismantling stage		14,505.44 $kgCO_2e$

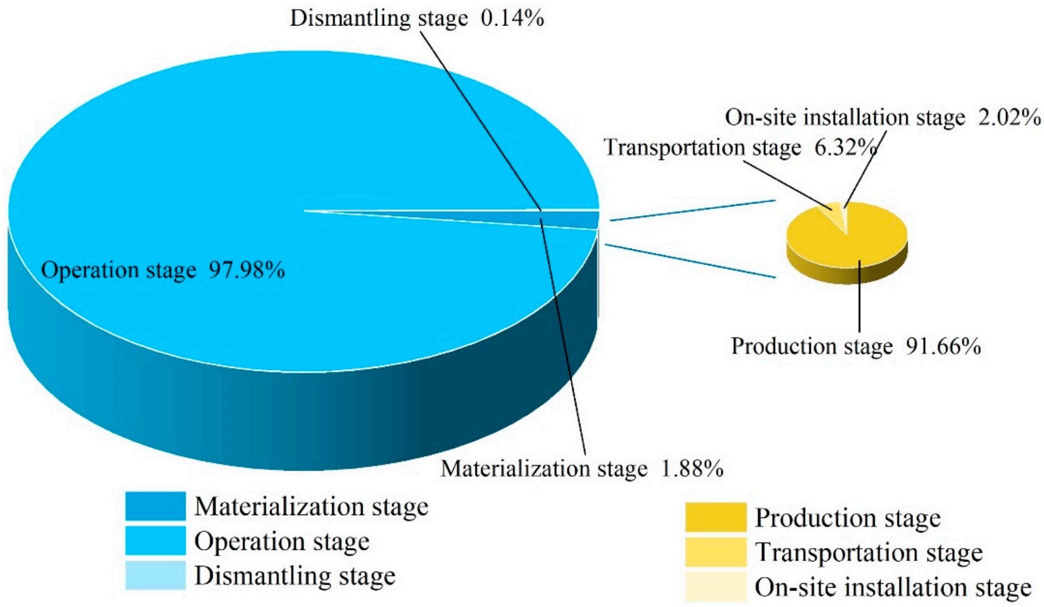

Figure 7. Carbon emissions percentage at each stage of the prefabricated decoration.

Paying attention to carbon emissions at the operation stage is the first step. The carbon emissions at the operation stage of the case study residential building are 10,065,029.33 $kgCO_2e$ (1218.5 $kgCO_2/m^2$), or 97.98% of the total. Although carbon emissions during the operation stage are produced over a longer timeframe, their impact cannot be ignored. Next are the materialization and dismantling stages, with 1.88% and 0.14% of the total, respectively. The data for the dismantling stage is an estimate based on a simplified model, which provides an approximate view of carbon emissions during the dismantling stage. Considering the relatively small share of the materialization stage and the fact that carbon emissions from the materialization stage are already actually occurring, this stage is discussed separately.

Carbon emissions from the production stage were 177,134.03 $kgCO_2e$, which accounted for 91.66% of the total amount of the materialization stage. Therefore, taking measures to reduce carbon emissions at this stage is crucial. The transportation stage comes next with 12,213.84 $kgCO_2e$, accounting for 6.32% of carbon emissions. Carbon emissions during the transportation stage are mainly influenced by material consumption, transportation distance, and transportation mode. The average transportation distance used in this research is a relatively simplified calculation, but the results still show that the transportation stage is essential to reducing carbon emissions from prefabricated decoration.

The on-site installation stage accounted for the least carbon emissions, with only 2.02%, or 3903.32 $kgCO_2e$. The carbon emissions during the on-site installation stage of the case study residential buildings are closely linked to the prefabricated decoration process, mainly regarding energy savings and reduced labor dependency. Through standardized design and industrialized production, prefabricated decoration components can be precisely manufactured in the factory, reducing the need for operations such as cutting on-site. Therefore, on-site installation avoids using high-energy-consuming mechanical equipment and can be completed with only simple electricity-using equipment. In addition, the classification of work involved in traditional decoration is more complicated, including plumbers, electricians, carpenters, painters, and more than ten types of work involved in the process. Moreover, the on-site installation of prefabricated decoration is highly organized, and only assembly workers are needed at the construction site to assemble the factory-produced parts according to the design requirements, which can achieve higher productivity with less labor.

5.3. Prefabricated Decoration Emission Reduction Potential Analysis

According to the calculation results, a comparison of the carbon emissions of the case study project using two different decoration methods at the production stage and operation stage can be obtained, as shown in Table 12.

Table 12. Comparison of carbon emissions from prefabricated versus traditional decoration.

Stage		Traditional Decoration ($kgCO_2e$)	Prefabricated Decoration ($kgCO_2e$)	Reduction Percentage
Production stage		249,772.03	177,134.03	29.08%
Transportation stage		18,188.38	12,213.84	32.85%
Operation stage	HVAC system	970.5	581.5	40.08%
	Hot water system	755	191.5	74.64%
	Lighting system	539	445.5	17.35%

At the decoration materials production stage, by using Equation (2) and the empirical data collected in the project, the estimated carbon emissions of the case study residential building using traditional decoration methods at the production stage can be calculated. The carbon emissions from applying prefabricated and traditional decoration at this project's production stage are 177,134.03 $kgCO_2e$ and 249,772.03 $kgCO_2e$ respectively, while the carbon emissions per unit of floor area are 21.44 $kgCO_2e/m^2$ and 30.23 $kgCO_2e/m^2$ respectively. The carbon emissions per unit floor area of prefabricated decoration are 8.79 $kgCO_2e/m^2$ less than those of traditional decoration, and the use of prefabricated decoration in this project reduces carbon emissions by 29.08% in the production stage of building materials compared to that of traditional decoration. This calculation clearly illustrates the significant carbon reduction benefits of prefabricated decoration at the material production stage.

The proportion of carbon emissions from different materials shown in Figures 3 and 4 reveals that carbon emissions from the traditional decoration production stage mainly come from light steel keel, wooden floor, and polyethylene film, while carbon emissions from the prefabricated decoration production stage mainly come from wooden floor, galvanized steel, and bamboo-wood fiberboard. The different types and amounts of materials used in the two types of decoration are directly responsible for the difference in carbon emissions during the production stage. While traditional decoration requires cement mortar, putty, and latex paint, prefabrication completely avoids using such wet-working materials, choosing the more environmentally friendly bamboo-wood fiberboard as the primary material. Therefore, the materials used in prefabrication have lower environmental impacts compared to traditional decoration.

At the operation stage, the data show that compared with the traditional residential building, the carbon reduction benefit of the HVAC system of the project building is 389 $kgCO_2/m^2$, which is a reduction of 40.08% of carbon emissions. The carbon reduction benefit of the domestic hot water system is 563.5 $kgCO_2/m^2$, reducing carbon emissions by 74.64%. The carbon reduction in the lighting system is 93.5 $kgCO_2/m^2$, a 17.35% reduction in carbon emissions. These significant emissions reduction benefits are mainly attributed to the use of prefabricated decoration and the fact that the overall energy efficiency of the building during the operation stage was considered in the design of the prefabricated decoration. The reduction in carbon emissions during the operation phase in the case study of prefabricated decoration compared to traditional decoration can be attributed to the adoption of energy-efficient HVAC systems, the use of air-source heat pumps for domestic hot water, efficient lighting systems, and an integrated design approach that focuses on sustainability. The prefabricated decoration technology, along with the choice of materials and construction methods, contributes to overall energy savings and reduced carbon emissions during the building's operational life. These measures collectively result in a lower environmental impact during the operation stage compared to traditional decoration methods.

The carbon emissions from transportation prefabricated decorating components are calculated at 12,213.84 kgCO_2e, 32.85% lower than traditional decoration transportation. The case study project uses industrialized means to solve complex decoration construction problems, including the use of prefabricated decoration parts manufactured and assembled in the factory to avoid the waste of materials brought by on-site construction. The material utilization rate of prefabricated decoration is improved, and the transportation turnover of the parts distribution process is reduced. Prefabricated floor systems can eliminate the need for wet-work materials, which saves transportation by reducing the number of vehicle trips without changing the type of vehicle or distance traveled, thus reusing transportation carbon emissions.

In addition, the project utilizes prefabricated bathroom systems manufactured in the factory and then assembled on-site. The composition of the prefabricated bathroom is shown in Figure 8. This method ensures that the flatness of the wall and the precision of the gaps between the tiles reach a high standard that is difficult to achieve with traditional methods while effectively eliminating leakage problems. The installation can be completed quickly with only two workers working for 4 h on-site, and the on-site environment is clean during the construction process, with almost no excess construction waste generated. In contrast, traditional bathroom decoration needs to rely on the skill level of the workers. Its waterproof treatment and tile laying are often prone to leakage, peeling, and other decoration quality problems. Traditional wet construction usually takes 15–20 days to complete and generates large amounts of construction waste and dust. Compared with prefabricated decoration, the construction speed is slower, and the construction quality problems and environmental impact are also more serious.

Considering the increasing maturity of prefabricated decoration, there is a challenge and an opportunity to achieve greater carbon reduction targets in future projects. One challenge is that the manufacture of prefabricated decorations is centralized in factories, generating significant front-end energy consumption, particularly when processes such as drying and curing are used. The other important challenge is that, as mentioned in the previous comment, certain materials, such as wooden floors and bamboo, can contribute significantly to carbon emissions. The industry needs to explore alternative materials and production methods that align with sustainability goals. Opportunities arise from advancements in technology, enabling more energy-efficient transportation strategies and refining production processes. Embracing innovative materials, optimizing transportation, and integrating sustainable practices throughout the life cycle can significantly reduce carbon emissions in future projects. Continuous research, development, and industry collaboration will play a crucial role in realizing these opportunities and addressing the challenges associated with the increasing maturity of prefabricated decoration.

In addition, incorporating circular economy principles into the production process and design of prefabricated decorations is challenging. Designing recyclable and reusable components and promoting zero-waste concepts requires more in-depth research and innovation. To address these specific material challenges, three strategies have been developed: (1) improve the production methods of the high-carbon emission materials; (2) replace the materials with more environmentally friendly materials; and (3) optimize the transportation strategies. Since the production phase of materials generates the largest proportion of carbon emissions, it could be effective to reduce carbon emissions by improving the production methods or replacing the high-carbon emission materials with lower ones. In addition, moving factories, such as wood floor production factories, closer to construction sites can reduce carbon emissions. In addition, as the global prefabricated decoration market grows, larger-scale production can lead to the development of a globalized supply chain, and more environmentally friendly and cost-effective production options are available to reduce carbon emissions.

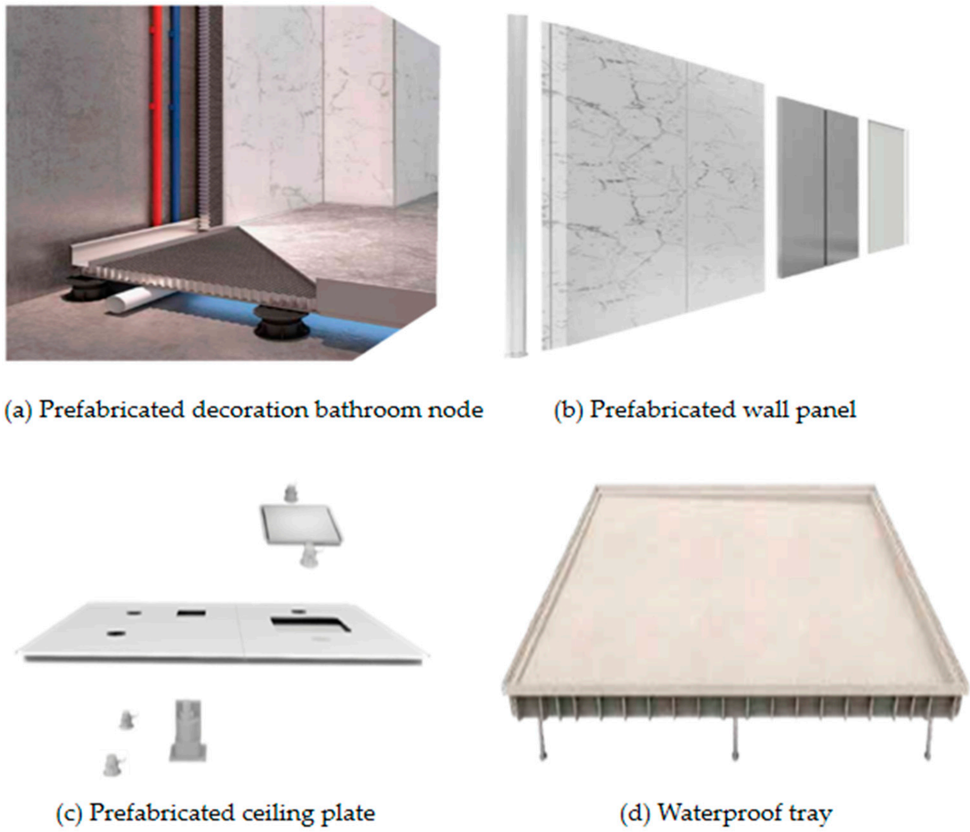

Figure 8. Prefabricated bathroom system.

5.4. Prefabricated Decoration Emission Reduction Strategies

Although prefabricated decoration effectively reduces carbon emissions in actual projects, there is still room for improvement. Achieving further reductions in carbon emissions requires clear and feasible strategies and measures.

The operation stage with the highest carbon emissions is inextricably linked to the energy-efficient design of the building and the users' awareness of energy efficiency. Raising users' awareness of energy conservation is crucial, as their behavior and habits directly affect the building's carbon emissions during operation. Providing easy-to-understand information about energy-efficient practices, such as proper usage of heating and cooling systems, can enhance user awareness. Additionally, workshops and training sessions can be organized to empower users with the knowledge and skills needed for regular maintenance. Creating user-friendly guides and manuals for maintaining prefabricated elements and promoting the use of eco-friendly products further encourages sustainable practices. Furthermore, carbon emissions reduction requires a regular maintenance program that includes inspection and maintenance of the prefabricated decoration, including the building's heating, ventilation, air conditioning, electrical, and water systems. This helps to ensure that these systems operate efficiently and reduces the risk of energy waste. In addition, regular energy efficiency assessments of the building need to be carried out, which in turn provide real-time information to managers about the energy use of the building. This helps to identify potential energy-saving opportunities and problems and to take steps to improve energy efficiency. Relevant policies and incentive programs can be implemented to encourage user awareness and regular maintenance practices for reducing carbon emissions in buildings with refabricated decoration.

In the production stage, strategies to further achieve carbon emission reduction by increasing the use of green materials, introducing energy-efficient production processes, and improving the recycling rate of materials Raising users' awareness of energy conservation is crucial, as their behavior and habits directly affect the building's carbon emissions during operation. Education and publicity campaigns are the first steps to convey to households the necessity of reducing carbon emissions and conserving energy. Wasteful use of energy in daytime lighting and turning on the air conditioner when no one is in the room will increase carbon emissions, so residents need to develop good habits to save energy and reduce emissions. Incentive programs can be established to encourage residents to adopt energy-saving measures. Rewards can be partial reductions in energy bills, the provision of energy-efficient equipment, or other incentives to motivate them to conserve energy.

At the transportation stage, carbon emissions can be further reduced by rationally planning transportation routes, choosing suppliers that are closer to the project site, and avoiding secondary transportation as much as possible. Advanced transportation management software can be used to plan the optimum routes, minimizing the distance traveled.

Although the on-site installation stage has a smaller carbon footprint, it cannot be ignored. The emission reduction potential of prefabricated decoration can be further realized through a highly organized installation process according to the design requirements, which can achieve higher productivity with less labor. It is necessary to formulate detailed process and task plans and harmonize construction regulations and operating procedures to ensure that each construction step is accurately planned and coordinated. The carbon reduction potential can be further enhanced by integrating prefabrication technology with digital technology; for example, BIM can provide details of the construction process, reducing errors and improving installation efficiency.

At the dismantling stage, carbon emissions can be further reduced by optimizing demolition methods, disposing of demolition materials close to the site, and enhancing the recycling and reuse of materials for prefabricated decoration. During the demolition process, different parts of the prefabricated decoration should be finely decomposed and categorized for subsequent recycling and reuse. For the transportation of demolition items, the principle of proximity is adopted, with preference given to treatment facilities closer to the demolition site, such as recycling stations, treatment centers, or recycling factories. During the decoration process, materials used are categorized and labeled to be more easily identified and recycled during the demolition stage.

6. Conclusions

By developing a measurement model for prefabricated decoration carbon emissions and applying it to a case project, this study offers a detailed evaluation of prefabricated decoration projects' carbon emissions, which will help to extend and deepen the theoretical basis of the carbon emissions assessment methodology for prefabricated decoration. The model analyzes the sources of carbon emissions at each stage and considers multiple variables and influencing factors to guarantee the evaluation's accuracy and comprehensiveness. The findings of this study have theoretical and practical contributions.

From a theoretical point of view, this study provides a more comprehensive and accurate methodology for prefabricated decoration carbon emissions assessment while injecting a new theoretical paradigm and methodological foundation into the field of carbon emissions assessment. Prefabricated decoration is gradually being used more and more in the construction industry, but the understanding and quantifying of its carbon emissions level is still insufficient. This paper not only demonstrates the environmental benefits of prefabricated decoration but also emphasizes the need for transitioning from traditional to prefabricated construction. The comparative analysis between prefabricated and traditional decoration methods contributes empirical evidence to the broader discourse on sustainable building practices.

From a practical point of view, the results of this research can accelerate the technological innovation of the decoration industry. The calculation results can be used as a reference for decoration enterprises to develop prefabricated decoration and help stakeholders understand the carbon emissions level and development potential of prefabricated decoration in depth. Decoration companies can use the results of this study to optimize the carbon emission reduction potential of prefabricated decoration projects, improve building sustainability, and reduce operating costs. It can also provide a basis for the government to develop relevant laws, policies, and standards to encourage the adoption of prefabricated decorations. This paper emphasizes the importance of collective action from the government, enterprises, designers, and industry associations, providing a framework for overcoming challenges and facilitating the broader adoption of prefabricated decoration in the construction industry.

In this study, a calculation model was developed to measure the carbon emissions of prefabricated decoration throughout its life cycle. The key findings of this study are summarized as follows: (1) The carbon emissions characteristics of each stage were derived by calculating and analyzing the carbon emissions of the residential building's prefabricated decoration. The operation stage of the residential building in the case study, with carbon emissions of 1218.5 $kgCO_2/m^2$, is the most significant stage in terms of carbon emissions. Next to the operation stage is the production stage with 177,134.03 $kgCO_2e$, followed by the demolition stage with 14,505.44 $kgCO_2e$, and the transportation stage with 12,213.84 $kgCO_2e$. The on-site installation stage has the smallest share of the prefabricated decoration's total lifecycle carbon emissions, with only 3903.32 $kgCO_2e$. Carbon emissions patterns from prefabricated decoration can be used to better formulate emission reduction strategies at each stage. (2) Through the calculation and comparative analysis of carbon emissions from using prefabricated decoration and traditional decoration in the case of residential buildings, it is possible to confirm the effectiveness of prefabricated decoration in reducing carbon emissions. Calculations show that using prefabricated decoration in this project reduces carbon emissions by about 29.08% compared to traditional decoration in the production stage. Optimized design through prefabricated decoration reduces carbon emissions by 1046 $kgCO_2/m^2$ for this building operation. Since increasingly mature prefabricated decoration offers lower cost, faster speed, and higher quality, it will eventually replace traditional decoration.

Although the advantages of prefabricated decoration are obvious, there are still barriers to its practical promotion and application. In China's current development of prefabricated decoration, the cost of materials and design has not been significantly reduced. Although prefabricated decoration may be more economical in the long run, the initial investment cost is higher. The lack of technical standards and regulations may also limit prefabricated decoration on the market. In addition, traditional decoration usually allows for greater flexibility and individualization, whereas prefabricated decoration can be limited by the design, making it difficult to adjust the initial design during construction. Promoting prefabricated decoration to replace traditional decoration requires concerted efforts from all parties, including the government, enterprises, designers, and relevant industry associations. Through technological innovation, policy support, the establishment of industry standards, and market promotion, these challenges can be gradually overcome to realize a wider application of prefabricated decoration in the construction industry.

Due to data collection limitations, the data were not sufficient to calculate all the carbon emissions values for certain stages and were not able to consider the effects of all possible factors; the carbon emissions of the moisture-proof and waterproof parts of the prefabricated decoration according to its special climate characteristics are not considered in this study; and carbon emissions from the recycling and reusing of the prefabricated decoration are not included in this research. The limitations are caused by the limited carbon emission factors database, which may lead to a deviation in the total carbon emissions calculated. Therefore, in future studies, it could be beneficial to expand the scope of data collection. For the data that cannot be directly collected, it could be estimated based on relevant data, models developed by previous studies, or expert interviews. Additionally, with the application of clean energy, process improvement, and the promotion of energy-saving technologies, carbon emissions factors could be updated. The carbon emissions of prefabricated decoration material recycling and reuse could be assessed to quantify the emission reduction benefits of recycling and reuse by examining the carbon emissions from the process, including the energy demand for reprocessing, repairing, or reinstalling.

Author Contributions: Conceptualization, J.B., C.L. and J.H.; methodology, C.L., C.Z. and W.M.; analysis, J.B. and C.L.; study design, J.B. and C.Z.; investigation, C.C.; data curation, C.L. and J.L.; writing—review and editing, J.B., C.L., J.H. and W.M.; writing—original draft preparation, visualization, B.D.; project administration, C.C. and J.L.; supervision, J.H. and W.M. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by National Natural Science Foundation of China, grant number 52078318.

Data Availability Statement: The data presented in this study are available on request from the corresponding author. The data are not publicly available due to privacy.

Conflicts of Interest: Authors Ji Bian, Chunyang Zuo and Jixuan Liu were employed by the company China Overseas Grand Oceans Lowcarbon Technology Co., Ltd. Author Congda Chen was employed by the company Suzhou Kelida Co., Ltd. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

References

1. Abbass, K.; Qasim, M.Z.; Song, H.; Murshed, M.; Mahmood, H.; Younis, I. A review of the global climate change impacts, adaptation, and sustainable mitigation measures. *Environ. Sci. Pollut. Res.* **2022**, *29*, 42539–42559. [CrossRef] [PubMed]
2. Yu, Y.; Zhang, N. Low-carbon city pilot and carbon emission efficiency: Quasi-experimental evidence from China. *Energy Econ.* **2021**, *96*, 105125. [CrossRef]
3. Li, R.; Liu, Q.; Cai, W.; Liu, Y.; Yu, Y.; Zhang, Y. Echelon peaking path of China's provincial building carbon emissions: Considering peak and time constraints. *Energy* **2023**, *271*, 127003. [CrossRef]
4. Ma, W.; Hao, J.L.; Zhang, C.; Di Sarno, L.; Mannis, A. Evaluating carbon emissions of China's waste management strategies for building refurbishment projects: Contributing to a circular economy. *Environ. Sci. Pollut. Res.* **2023**, *30*, 8657–8671. [CrossRef] [PubMed]
5. Wu, P.; Song, Y.; Zhu, J.; Chang, R. Analyzing the influence factors of the carbon emissions from China's building and construction industry from 2000 to 2015. *J. Clean. Prod.* **2019**, *221*, 552–566. [CrossRef]
6. Li, B.; Han, S.; Wang, Y.; Wang, Y.; Li, J.; Wang, Y. Feasibility assessment of the carbon emissions peak in China's construction industry: Factor decomposition and peak forecast. *Sci. Total Environ.* **2020**, *706*, 135716. [CrossRef] [PubMed]
7. Yu, S.; Hao, J.L.; Di Sarno, L.; Ma, W.; Guo, N.; Liu, Y. Enhancing pro-environmental behaviour of employees towards renovation waste for a circular economy: The role of external supervision and corporate environmental responsibility. *Sustain. Chem. Pharm.* **2023**, *33*, 101103. [CrossRef]
8. Fahlstedt, O.; Temeljotov-Salaj, A.; Lohne, J.; Bohne, R.A. Holistic assessment of carbon abatement strategies in building refurbishment literature—A scoping review. *Renew. Sustain. Energy Rev.* **2022**, *167*, 112636. [CrossRef]
9. Vasishta, T.; Hashem Mehany, M.; Killingsworth, J. Comparative life cycle assesment (LCA) and life cycle cost analysis (LCCA) of precast and cast–in–place buildings in United States. *J. Build. Eng.* **2023**, *67*, 105921. [CrossRef]
10. Wasim, M.; Vaz Serra, P.; Ngo, T.D. Design for manufacturing and assembly for sustainable, quick and cost-effective prefabricated construction—A review. *Int. J. Constr. Manag.* **2022**, *22*, 3014–3022. [CrossRef]
11. Wang, J.; Teng, Y.; Chen, Z.; Bai, J.; Niu, Y.; Duan, H. Assessment of carbon emissions of building interior decoration and renovation waste disposal in the fast-growing Greater Bay Area, China. *Sci. Total Environ.* **2021**, *798*, 149158. [CrossRef] [PubMed]
12. Xu, X.; Ding, X.; Wang, Q.; Chen, T.; Deng, R. Comparative Analysis and Empirical Study of Prefabrication Rate Calculation Methods for Prefabricated Buildings in Various Provinces and Cities in China. *Buildings* **2023**, *13*, 2042. [CrossRef]
13. Xia, H. Research on the Differences between Traditional Decoration and Pre-fabricated Building Decoration. In Proceedings of the 2018 International Conference on Culture, Literature, Arts & Humanities (ICCLAH 2018), Changchun, China, 5–7 November 2018.
14. Ma, W.; Hao, J.L.; Zhang, C.; Guo, F.; Di Sarno, L. System Dynamics-Life Cycle Assessment Causal Loop Model for Evaluating the Carbon Emissions of Building Refurbishment Construction and Demolition Waste. *Waste Biomass Valorization* **2022**, *13*, 4099–4113. [CrossRef]
15. Aghasizadeh, S.; Tabadkani, A.; Hajirasouli, A.; Banihashemi, S. Environmental and economic performance of prefabricated construction: A review. *Environ. Impact Assess. Rev.* **2022**, *97*, 106897. [CrossRef]

16. Zhong, C.; Zhang, M.; Cui, X.; Liu, Z. Comprehensive Evaluation of China's Prefabricated Decoration Cost Based on Analytic Hierarchy Process. *Adv. Civ. Eng.* **2020**, *2020*, 1583748. [CrossRef]
17. Sun, P.; Zhang, N.; Zuo, J.; Mao, R.; Gao, X.; Duan, H. Characterizing the generation and flows of building interior decoration and renovation waste: A case study in Shenzhen City. *J. Clean. Prod.* **2020**, *260*, 121077. [CrossRef]
18. Luo, T.; Xue, X.; Wang, Y.; Xue, W.; Tan, Y. A systematic overview of prefabricated construction policies in China. *J. Clean. Prod.* **2021**, *280*, 124371. [CrossRef]
19. Jiang, L.; Li, Z.; Li, L.; Gao, Y. Constraints on the Promotion of Prefabricated Construction in China. *Sustainability* **2018**, *10*, 2516. [CrossRef]
20. Li, G.H.; Chen, X.; You, X.Y. System dynamics prediction and development path optimization of regional carbon emissions: A case study of Tianjin. *Renew. Sustain. Energy Rev.* **2023**, *184*, 113579. [CrossRef]
21. Zhao, Q.; Gao, W.; Su, Y.; Wang, T. Carbon emissions trajectory and driving force from the construction industry with a city-scale: A case study of Hangzhou, China. *Sustain. Cities Soc.* **2023**, *88*, 104283. [CrossRef]
22. You, K.; Ren, H.; Cai, W.; Huang, R.; Li, Y. Modeling carbon emission trend in China's building sector to year 2060. *Resour. Conserv. Recycl.* **2023**, *188*, 106679. [CrossRef]
23. Zhu, C.; Li, X.; Zhu, W.; Gong, W. Embodied carbon emissions and mitigation potential in China's building sector: An outlook to 2060. *Energy Policy* **2022**, *170*, 113222. [CrossRef]
24. Huo, T.; Ma, Y.; Xu, L.; Feng, W.; Cai, W. Carbon emissions in China's urban residential building sector through 2060: A dynamic scenario simulation. *Energy* **2022**, *254*, 124395. [CrossRef]
25. Yang, Z.; Gao, W.; Han, Q.; Qi, L.; Cui, Y.; Chen, Y. Digitalization and carbon emissions: How does digital city construction affect china's carbon emission reduction? *Sustain. Cities Soc.* **2022**, *87*, 104201. [CrossRef]
26. Du, Y.; Zhou, J.; Bai, J.; Cao, Y. Breaking the resource curse: The perspective of improving carbon emission efficiency based on digital infrastructure construction. *Resour. Policy* **2023**, *85*, 103842. [CrossRef]
27. Karlsson, I.; Rootzén, J.; Johnsson, F.; Erlandsson, M. Achieving net-zero carbon emissions in construction supply chains—A multidimensional analysis of residential building systems. *Dev. Built Environ.* **2021**, *8*, 100059. [CrossRef]
28. Xu, J.; Deng, Y.; Shi, Y.; Huang, Y. A bi-level optimization approach for sustainable development and carbon emissions reduction towards construction materials industry: A case study from China. *Sustain. Cities Soc.* **2020**, *53*, 101828. [CrossRef]
29. Xu, X.; Xu, P.; Zhu, J.; Li, H.; Xiong, Z. Bamboo construction materials: Carbon storage and potential to reduce associated CO_2 emissions. *Sci. Total Environ.* **2022**, *814*, 152697. [CrossRef]
30. Farahzadi, L.; Kioumarsi, M. Application of machine learning initiatives and intelligent perspectives for CO_2 emissions reduction in construction. *J. Clean. Prod.* **2023**, *384*, 135504. [CrossRef]
31. Ye, H.; Ren, Q.; Hu, X.; Lin, T.; Shi, L.; Zhang, G.; Li, X. Modeling energy-related CO_2 emissions from office buildings using general regression neural network. *Resour. Conserv. Recycl.* **2018**, *129*, 168–174. [CrossRef]
32. Fang, Y.; Lu, X.; Li, H. A random forest-based model for the prediction of construction-stage carbon emissions at the early design stage. *J. Clean. Prod.* **2021**, *328*, 129657. [CrossRef]
33. Li, L.; Chen, K. Quantitative assessment of carbon dioxide emissions in construction projects: A case study in Shenzhen. *J. Clean. Prod.* **2017**, *141*, 394–408. [CrossRef]
34. Zhang, X.; Li, Y.; Chen, H.; Yan, X.; Liu, K. Characteristics of embodied carbon emissions for high-rise building construction: A statistical study on 403 residential buildings in China. *Resour. Conserv. Recycl.* **2023**, *198*, 107200. [CrossRef]
35. Yang, X.; Shang, G.; Deng, X. Estimation, decomposition and reduction potential calculation of carbon emissions from urban construction land: Evidence from 30 provinces in China during 2000–2018. *Environ. Dev. Sustain.* **2022**, *24*, 7958–7975. [CrossRef]
36. Hung, C.C.W.; Hsu, S.C.; Cheng, K.L. Quantifying city-scale carbon emissions of the construction sector based on multi-regional input-output analysis. *Resour. Conserv. Recycl.* **2019**, *149*, 75–85. [CrossRef]
37. Kang, G.; Kim, T.; Kim, Y.W.; Cho, H.; Kang, K.I. Statistical analysis of embodied carbon emission for building construction. *Energy Build.* **2015**, *105*, 326–333. [CrossRef]
38. Zhang, X.; Wang, F. Assessment of embodied carbon emissions for building construction in China: Comparative case studies using alternative methods. *Energy Build.* **2016**, *130*, 330–340. [CrossRef]
39. Cang, Y.; Luo, Z.; Yang, L.; Han, B. A new method for calculating the embodied carbon emissions from buildings in schematic design: Taking "building element" as basic unit. *Build. Environ.* **2020**, *185*, 107306. [CrossRef]
40. Lai, K.E.; Abdul Rahiman, N.; Othman, N.; Ali, K.N.; Lim, Y.W.; Moayedi, F.; Dzahir, M.A.M. Quantification process of carbon emissions in the construction industry. *Energy Build.* **2023**, *289*, 113025. [CrossRef]
41. Liu, G.; Yang, H.; Fu, Y.; Mao, C.; Xu, P.; Hong, J.; Li, R. Cyber-physical system-based real-time monitoring and visualization of greenhouse gas emissions of prefabricated construction. *J. Clean. Prod.* **2020**, *246*, 119059. [CrossRef]
42. Tao, X.; Mao, C.; Xie, F.; Liu, G.; Xu, P. Greenhouse gas emission monitoring system for manufacturing prefabricated components. *Autom. Constr.* **2018**, *93*, 361–374. [CrossRef]
43. Xu, J.; Zhang, Q.; Teng, Y.; Pan, W. Integrating IoT and BIM for tracking and visualising embodied carbon of prefabricated buildings. *Build. Environ.* **2023**, *242*, 110492. [CrossRef]
44. Yevu, S.K.; Owusu, E.K.; Chan, A.P.C.; Sepasgozar, S.M.E.; Kamat, V.R. Digital twin-enabled prefabrication supply chain for smart construction and carbon emissions evaluation in building projects. *J. Build. Eng.* **2023**, *78*, 107598. [CrossRef]

45. Li, X.; Xie, W.; Yang, T.; Lin, C.; Jim, C.Y. Carbon emission evaluation of prefabricated concrete composite plates during the building materialization stage. *Build. Environ.* **2023**, *232*, 110045. [CrossRef]
46. Xu, J.; Teng, Y.; Pan, W.; Zhang, Y. BIM-integrated LCA to automate embodied carbon assessment of prefabricated buildings. *J. Cleaner Prod.* **2022**, *374*, 133894. [CrossRef]
47. Hao, J.L.; Cheng, B.; Lu, W.; Xu, J.; Wang, J.; Bu, W.; Guo, Z. Carbon emission reduction in prefabrication construction during materialization stage: A BIM-based life-cycle assessment approach. *Sci. Total Environ.* **2020**, *723*, 137870. [CrossRef]
48. Ding, Z.; Liu, S.; Luo, L.; Liao, L. A building information modeling-based carbon emission measurement system for prefabricated residential buildings during the materialization phase. *J. Clean. Prod.* **2020**, *264*, 121728. [CrossRef]
49. Luo, W.; Sandanayake, M.; Zhang, G. Direct and indirect carbon emissions in foundation construction—Two case studies of driven precast and cast-in-situ piles. *J. Clean. Prod.* **2019**, *211*, 1517–1526. [CrossRef]
50. Zhao, Y.; Liu, L.; Yu, M. Comparison and analysis of carbon emissions of traditional, prefabricated, and green material buildings in materialization stage. *J. Clean. Prod.* **2023**, *406*, 137152. [CrossRef]
51. Liu, C.; Yang, Y.; Zhao, X.; Xu, X.; Hao, J.L.; Ma, W. Reducing carbon emissions by using prefabricated decoration floor systems. *J. Green Build.* **2023**, *18*, 119–145. [CrossRef]
52. Hong, J.; Shen, G.Q.; Li, Z.; Zhang, B.; Zhang, W. Barriers to promoting prefabricated construction in China: A cost–benefit analysis. *J. Clean. Prod.* **2018**, *172*, 649–660. [CrossRef]
53. Li, C.Z.; Xue, F.; Li, X.; Hong, J.; Shen, G.Q. An Internet of Things-enabled BIM platform for on-site assembly services in prefabricated construction. *Autom. Constr.* **2018**, *89*, 146–161. [CrossRef]
54. Rocha, P.F.; Ferreira, N.O.; Pimenta, F.; Pereira, N.B. Impacts of Prefabrication in the Building Construction Industry. *Encyclopedia* **2023**, *3*, 28–45. [CrossRef]
55. Teng, Y.; Pan, W. Systematic embodied carbon assessment and reduction of prefabricated high-rise public residential buildings in Hong Kong. *J. Clean. Prod.* **2019**, *238*, 117791. [CrossRef]
56. Guo, Y.; Shi, E.; Yan, R.; Wei, W. System based greenhouse emission analysis of off-site prefabrication: A comparative study of residential projects. *Sci. Rep.* **2023**, *13*, 10689. [CrossRef]
57. Wang, X.; Duan, Z.; Wu, L.; Yang, D. Estimation of carbon dioxide emission in highway construction: A case study in southwest region of China. *J. Clean. Prod.* **2015**, *103*, 705–714. [CrossRef]
58. Nasab, T.J.; Monavari, S.M.; Jozi, S.A.; Majedi, H. Assessment of carbon footprint in the construction phase of high-rise constructions in Tehran. *Int. J. Environ. Sci. Technol.* **2020**, *17*, 3153–3164. [CrossRef]
59. Xu, X.; You, J.; Wang, Y.; Luo, Y. Analysis and assessment of life-cycle carbon emissions of space frame structures. *J. Clean. Prod.* **2023**, *385*, 135521. [CrossRef]
60. Li, X.; Xie, W.; Xu, L.; Li, L.; Jim, C.Y.; Wei, T. Holistic life-cycle accounting of carbon emissions of prefabricated buildings using LCA and BIM. *Energy Build.* **2022**, *266*, 112136. [CrossRef]
61. Zhang, X.; Wang, F. Life-cycle carbon emission assessment and permit allocation methods: A multi-region case study of China's construction sector. *Ecol. Indic.* **2017**, *72*, 910–920. [CrossRef]
62. Lu, K.; Deng, X.; Zhang, Y.; Jiang, X.; Cheng, B.; Tam, V.W.Y. Extensible carbon emission factor database: Empirical study for the Chinese construction industry. *Environ. Sci. Pollut. Res.* **2023**, *in press*. [CrossRef] [PubMed]
63. *GB/T 51366-2019[S]*; Ministry of Housing and Urban-Rural Development of China. Standard for Calculating Carbon Emissions from Buildings. China Building Industry Press: Beijing, China, 2019.
64. *T/CBDA 69-2023[S]*; China Building Decoration Association. Standard for Calculating Carbon Emissions from Building Decoration. China Building Industry Press: Beijing, China, 2023.
65. *DB33/1015-2021[S]*; Zhejiang Provincial Department of Housing and Urban-Rural Development. Energy Efficiency Design Standards for Residential Buildings. China Building Industry Press: Beijing, China, 2021.