

Article

An Empirical Study of Carbon Emission Calculation in the Production and Construction Phase of A Prefabricated Office Building from Zhejiang, China

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Abstract: This study analyzes an office building located in Hangzhou, Zhejiang region, with a high assembly rate of 96.8%. Based on whole-process records and first-hand factory data, using an original method, we empirically investigate the carbon emissions associated to the assembly production and construction phase by comparing the results collected in the field with the calculation results for the simulated non-prefabricated building. The calculation results show that the production and construction stage of the prefabricated office building is characterized by a large reduction in carbon emissions, where the total measured carbon emissions of the subject building were 2265.73 tCO₂e, which is 22 kgCO₂e/m² less than that under the non-prefabricated method. In the future development of China's construction industry, taking Zhejiang Province as an example, the implementation of prefabricated office buildings with a PEC structure system can effectively reduce carbon emissions, which can help China to achieve the carbon peak as soon as possible.

Keywords: prefabricated building; materialization stage; carbon emissions

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1. Introduction

The impacts of human construction activities on the environment [1,2] are rapidly leading the international community to find effective strategies to combat global warming and to develop strategies to mitigate climate change [3]. In the face of climate problems, the Intergovernmental Panel on Climate Change (IPCC) has proposed a goal of limiting global warming to 1.5 °C. This goal requires deep reductions in energy, land, urban and infrastructure, and industrial systems, in order to achieve carbon neutrality by 2050. In response, China pledged, at the 75th session of the United Nations General Assembly in September 2020, to peak by 2030 and work toward carbon neutrality by 2060.

At present, China's construction sector accounts for 51.3% of its national carbon emissions, and is the highest-emitting sector. According to the data of the Energy Consumption Statistics Committee of China Construction Energy Conservation Association, the total carbon emissions of China's buildings have presented a continuous growth trend, reaching about 2.1 billion tons in 2019, an increase of about 3.14 times compared with 668 million tons in 2000, with an average annual growth of 6.96%. If this is taken as the benchmark, the time for China's construction industry to reach its peak is expected to be around 2039, which is 9 years later than the time when the country as a whole is expected to achieve its carbon peak, and there will still be 1.5 billion tCO₂ by 2060, which will seriously restrict the

achievement of China's carbon neutrality target [4]. Therefore, how to effectively reduce carbon emissions in the building sector and achieve the carbon peak as early as possible is a key challenge for the building sector.

1.1. Carbon Reduction Path in the Building Sector

The reduction in carbon emissions in the building sector can be realized in two ways: reducing emissions in the operational phase of existing buildings, or reducing emissions in the production and construction phase of new buildings. From previous studies, building emissions reduction is mainly focused on the operational phase; as about 80% of carbon emissions during the whole life-cycle of a building is generated during the operational phase of the building [5], many studies have focused on developing advanced technologies, policies, and measures to control and reduce carbon emissions during the operational phase.

While there is historical evidence that most building emissions are related to operations, recent studies have suggested that implied emissions may account for more than half of total building life-cycle emissions [6,7]. In terms of the carbon peak, carbon emissions per unit time of buildings have been emphasized, and the concentration of carbon emissions and the absolute amount of emissions in the building phase, compared to the operational phase, of a building are key to the early achievement of carbon peak in the building sector. In 2018, for example, the carbon emissions in the production and construction stages of the construction industry were found to be 7.4% higher than those in the construction and operational stages [4]. According to one study, the carbon emissions in the building phase for one year are equivalent to those of the operation phase over eight years [8]. Recent findings have suggested that housing-related GHG emissions are under-estimated by 60%, as GHG emissions are not included in emissions projections [9]. In the upcoming decade, there will be a large number of new buildings in China, with an expected 14.947 billion m² of housing construction, for an annual increase of 3.68% [10], and this large base of building construction activities will lead to a large amount of carbon emissions. Therefore, how to ensure carbon emissions reduction in the building construction phase must urgently be studied.

Among the existing building construction methods, prefabricated buildings are considered to be an effective approach for carbon emissions reduction [11]. Prefabrication, modularization, and information technology can significantly reduce water and wastewater discharge during the construction process, and can reduce noise, wastewater discharge, and dust pollution at the construction site [12,13]. Some studies have shown that prefabricated buildings can provide significant carbon emissions savings, compared to non-prefabricated buildings, especially in the residential sector. For example, Quale et al. compared the construction process of prefabricated buildings with that of traditional residential non-prefabricated buildings, and found that the carbon emissions of non-prefabricated buildings were 40% higher than those of prefabricated buildings. [14]. Aye et al. calculated and analyzed the specific energy savings of modular prefabricated steel and wood-frame residential buildings, and demonstrated that prefabricated means can achieve energy savings of up to 81% and material mass savings of 51% [15].

Dong et al. compared the carbon emissions of prefabricated and non-prefabricated materialization stages considering a private residential building in Hong Kong as an example, further demonstrating that the prefabricated approach can reduce carbon emissions by 10% per one cubic meter of concrete [16]. Teng et al. provided a more systematic understanding of the cradle-to-end of construction, where the embodied carbon generated from typical high-rise public residential buildings in Hong Kong was 561 kgCO₂/m², mainly generated from the consumption of materials [17]. In contrast, relatively few scholars have studied prefabricated office buildings. Kumanayake et al. assessed the embedded carbon in commercial office buildings in Sri Lanka, focusing on the material production phase of the building life-cycle, and found that the embedded carbon in the material production phase was 629.6 kgCO₂/m² of the total floor area. Reinforced concrete and clay bricks were the main carbon-emitting materials, accounting for over 70% [18].

Over the whole life-cycle of a prefabricated building, there are many complex processes involved, and it is almost impossible to calculate the carbon emissions of the whole process completely and accurately; thus, some scholars have targeted the carbon emissions measurement research of certain processes. In the construction phase, Li et al. studied precast concrete pile products and their carbon footprints during the construction phase, based on the life-cycle assessment (LCA) method, and compiled a database of carbon emission factors for mechanical equipment [19]. Xu et al. investigated a life-cycle carbon emission calculation model for the three stages of component production, logistics and transportation, and on-site installation during the whole construction process of composite beams in prefabricated buildings [20]. Fang et al. assisted construction managers in identifying carbon emissions, in order to optimize them through better construction scheduling. They first defined the system boundary of the construction phase and identified relevant activities in the construction process. A method to identify carbon emissions sources in the construction process based on the Chinese quota method was also proposed [21]. In the phase of building materialization, Li et al. aimed to study precast concrete (PC) buildings and their carbon footprint in the production and construction phase. The development of PC buildings can potentially reduce resource and energy consumption, thus meeting the low carbon and environmental requirements of the construction industry. They also compiled a database of carbon emission factors based on the databases of the Intergovernmental Panel on Climate Change (IPCC) and the China Life Cycle Database (CLCD) [22]. Emanuele Bonamente et al. conducted a systematic analysis of greenhouse gas emissions (carbon footprint) and primary energy consumption (energy footprint) throughout the life-cycle of prefabricated industrial buildings [23].

Partial carbon reduction studies have also been carried out on building materials. A comparison of life-cycle carbon emissions (LCCO₂) and embodied energy calculations between two types of bricks—sun-dried and fired clay bricks—was presented by Dabaieh et al. as a way to assess the energy and climate impacts and production economics of each type of brick [24]. Saad et al. developed a conceptual stage-specific carbon measurement tool that can be used in the design phase of building projects to calculate the carbon content [25]. Ding et al. developed a carbon measurement system for prefabricated residential buildings (PRBs) during the production and construction phase, based on building information modeling (BIM) and carbon emissions measurement models [26]. Meneghelli et al. described how data collected during LEED certification can serve as a viable and representative description of an entire project at a LEED-certified public library in Chicago, IL, USA, examining regional differences in recycled steel and aluminum content, product loss, transportation of materials to the site, and anticipated repairs and replacements [27].

However, few studies have taken into account the uncertainty caused by errors in input parameters, scenario assumptions, and analytical uncertainty in model selection in the study of carbon emissions from prefabricated buildings, which may lead to the misinterpretation of the results. Teng et al. developed a five-level framework for assessing deterministic embedded carbon in prefabricated buildings using a process-based approach. Using the SimaPro 9.0 software, a Monte Carlo simulation approach based on data quality indices was used for uncertainty analysis [28]. Mastrucci et al. proposed a spatio-temporal LCA framework to evaluate retrofit options for urban housing, including: (1) A geospatial building model, (2) an energy demand model, (3) product-based LCA, and (4) a scenario generator. Both the LCA and the LCA phases consider the temporal factor, take into account the evolution of existing housing, and apply a time-adjusted carbon footprint calculation [29].

Through the above literature analysis, the following three shortcomings of existing studies can be summarized: (1) the carbon emissions are mostly calculated through software simulations and compared with similar types of buildings, but the comparison results may not be accurate, due to the many differences in areas, floor areas, and construction processes [30]; (2) the prefabrication rate of prefabricated buildings is usually low, generally below 50% (Wang et al. 2020), which cannot fully allow for the carbon reduction advantages

of prefabricated construction. Thus, the carbon reduction advantages of prefabricated construction methods have not been fully demonstrated; and (3) existing studies on carbon emissions of prefabricated buildings have focused on the residential scope, while few have analyzed prefabricated office buildings. However, there are still a large number of new prefabricated office buildings every year, and different functions will lead to different research scopes.

1.2. Research Purpose and Advantages

The collection of carbon emissions during the production and construction of assembled buildings requires a large amount of data support and calculation, and in most of these projects either open data is used but at a low level of detail (city/region/country), or a high level of detail (below city level) is used but the user needs to enter a large amount of private data to get to the planning stage [31]. Much of these data, as a process, are private and not easily available to the public. Energy engineers and planners must provide the simplest and most powerful tools to collect, process, and analyze data to provide reliable data-based evidence for building, district, and regional-scale future projections for effective system planning [32]. Therefore, this collection, processing, and analysis of data is ultimately presented in terms of total carbon emissions (kgCO₂e) and carbon emissions per unit area (kgCO₂e/m²), and these data can be used as open data to contribute to the political, social and economic development of a country [33]. With reliable data, citizen participation can be stimulated, and sustainable behavior and CO₂ reduction can be encouraged.

Considering the above, in this paper, a 96.8% prefabricated—where the concept of assembly rate generally refers to the ratio of the number (or area) of prefabricated components and building components in a building to the total number (or area) of similar components—office building in Hangzhou, Zhejiang Province, designed and built by the author's team, is used to study the carbon emissions of prefabricated buildings at the construction stage, based on whole-process records and first-hand factory data, as well as the empirical calculations of existing buildings with reference to the non-prefabricated equivalent of this building. The purpose of this study is to demonstrate the accuracy of the empirical data collected and to fill the data gaps in the field through the use of accurate primary data compared to traditional simulation methods, to demonstrate the carbon reduction efficiency of prefabricated public buildings through calculations and references, and to provide calculated data to assist in the design decision-making process regarding the development of low carbon buildings optimized for environmental performance, in order to contribute toward carbon neutrality.

2. Materials and Methods

From previous studies, three main approaches have been used to assess the carbon impact of buildings: process-based analysis, input–output analysis, and hybrid analysis [34]. However, the first two methods have their limitations, and the use of such methods can lead to incomplete system boundaries [35–37]. The implied carbon emissions can be reduced by 31.6% by analyzing the uncertainty of the model itself [28]. To further explore the completeness of the LCA model, Manfred Lenzen et al. demonstrated that the boundaries of the hybrid assessment analysis method can be well-confirmed to accommodate specificity, accuracy, cost, labor, and time requirements [35]. Robert H. et al. further showed that the hybrid life-cycle inventory method is sufficiently accurate, as long as the data quality and availability are guaranteed [38]. The author, as the designer and participant of the case study in this paper, has a large amount of first-hand project data—including detailed design process and cost control information—and, after a comprehensive comparison, we chose the hybrid life-cycle inventory approach as the method for study and evaluation. However, it should be emphasized here that the process-based LCA used in the research process is dominant.

2.1. Comparison Path

The differences between prefabricated construction and traditional non-prefabricated construction are mainly reflected in the three stages of production, transportation, and construction. Compared with the traditional construction method of on-site operation, the prefabricated construction method reduces the impact of seasonal and manual operation on construction. In the transportation stage, the prefabricated construction method involves transporting the finished components to the site, according to the construction schedule, while, in the traditional non-prefabricated method, the materials are transported to the construction site according to the design instructions. In the construction stage, the prefabricated construction method lifts and installs the finished components directly at the site. In the construction stage, the finished components transported to the site are directly lifted and installed, and can be quickly positioned and accurately installed through the mortise and tenon combination method, which greatly reduces the amount of open-air work on site, as in traditional non-prefabricated buildings, and reduces the mechanical construction steps, such as concrete pumping, pounding, and the tying and welding of the rebar [39,40]. In order to compare the exact difference in carbon emissions between the physical phase of the prefabricated office building and conventional non-prefabricated practice, we re-designed the B1 building with the same functional plan using the non-prefabricated method as the reference building. The reference building was re-designed as a frame shear wall structure and re-calculated according to the non-prefabricated method, without changing its floor area, function, or form, but only changing its structure and internal wall practices. The differences between the specific methods are detailed in Table 1.

Table 1. Comparison of carbon emissions between prefabricated empirical and non-prefabricated simulation.

Project Description	B1 Building Prefabricated Demonstration	B1 Building Non-Prefabricated Simulation
Type	Office building	Office building
Location	Hangzhou, Zhejiang Province	Hangzhou, Zhejiang Province
Area	8888 m ²	8888 m ²
Building height	16.3 m	16.3 m
Structure system	PEC structure system	Frame shear wall structure
Floor height	4.78 m	4.78 m
Seismic Intensity	7.0	7.0
Construction Method	Prefabricated construction	Non-prefabricated construction
Prefabricated level	86.5%	0
Structural frame: column, beam, slab, structural wall, slab	Steel structure, prefabricated	Reinforced concrete, non-prefabricated
Structural frame: staircase, floor slab	Steel structure, assembly	Reinforced concrete, non-prefabricated
External works: Exterior walls	UHPC + LOW-E glass + perforated aluminum panels, prefabricated	Reinforced concrete + perforated aluminum panels, non-prefabricated
External works: Roof	Steel structure, prefabricated	Reinforced concrete, non-prefabricated
Internal works: Partition wall	ALC slat wall, prefabricated	Shale bricks, masonry

2.2. Scope of the Study

The production and construction phase of a building usually includes the production, transportation, and construction stages. However, the prefabricated building construction method is different from the traditional non-prefabricated building, as shown in Figure 1. The prefabricated building is constructed by processing the prefabricated components in a factory and assembling them on site. In the study of carbon emissions, the carbon emissions in traditional building construction come from the material factory, transportation, and construction site, while most of the components of a prefabricated building are prefabricated and produced in factories, and the carbon emissions are calculated according to the material factory, material transportation, component factory, component transportation, and assembly site [41]. In this paper, the emissions boundary for the production and construction phase of the prefabricated building is calculated from the cradle to the end of completion. Specifically, it includes the implicit carbon emissions of materials, the carbon emissions

of the material transportation stage, the carbon emissions of the factory processing stage, and the carbon emissions associated with the on-site construction and assembly stage.

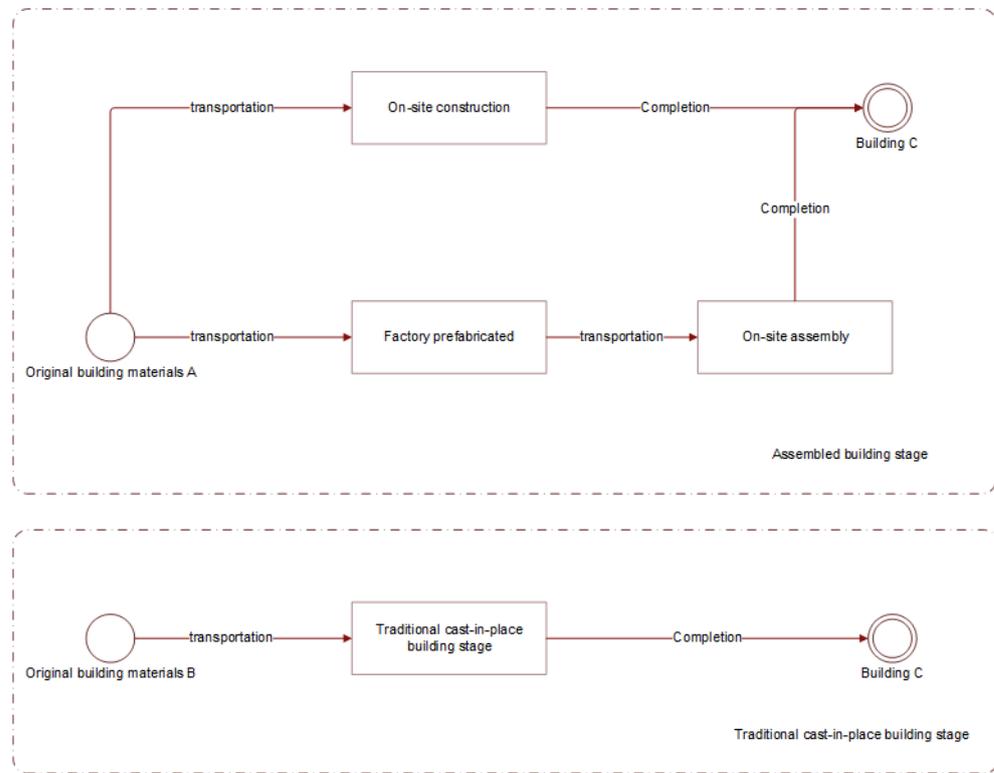


Figure 1. Comparison of assembled and cast-in-place construction processes.

According to the above calculation boundary, the carbon emissions of prefabricated buildings can be mainly separated into two parts, prefabrication factories and construction sites, while non-prefabricated buildings have no prefabrication factory part. Through specific refinement, we can divide the carbon emissions in the materialization stage into three parts, which can be specifically divided into E1–E7, as shown in Figure 2.

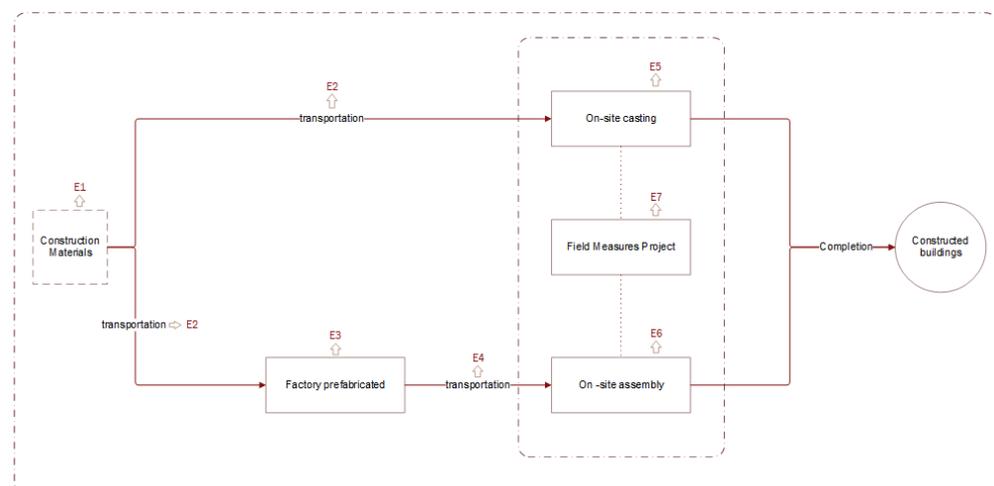


Figure 2. Carbon emission sources for assembled buildings.

Off-site carbon emissions:

E1: Specific carbon emissions of major permanent construction materials;

E3: Carbon resource and energy consumption emissions from the operation of equipment and construction techniques for building components—in this case, resources and energy including labor, natural gas, electricity, water, and auxiliary materials.

Transportation carbon emissions:

E2: Carbon emissions from fuel combustion during the transportation of construction materials, either from the distribution center to the off-site prefabrication plant or from the distribution center to the project site;

E4: Carbon emissions from fuel combustion during the transportation of prefabricated components from the off-site prefabrication plant to the project.

On-site carbon emissions:

E5: Carbon emissions from energy use in on-site construction subcomponent projects;

E6: Carbon emissions from energy use in on-site assembly sub-projects;

E7: Carbon emissions from scaffolding, formwork and bracing, vertical transportation, building super-elevation, and other measure items that can be counted as work volume.

2.3. Calculation Model

For activities occurring during the assembly and building-up, quantification can follow the guidance of ISO 14064-1:2006 [42] for direct and indirect emissions. Therefore, the first step in this section is to establish a calculation method for all emission sources during a given period, where the emission factors for direct fuel combustion and energy use are adjusted according to the recommendations of the IPCC guidelines [43]:

$$C_z = \sum_{i=1}^7 E_i, \quad (1)$$

where C_z is the total carbon emissions for the whole construction phase, and E_i is the carbon emission source in the construction process.

2.3.1. Construction Materials

Equation

$$E_1 = \sum_{j=1}^j M_j * f_j^b * (1 + \epsilon_j), \quad (2)$$

where E_1 denotes the specific carbon emissions of all construction materials (in tCO₂e), M_j is the quantity of construction material j (in tons), f_j^b is the carbon emissions factor of construction material j (in kgCO₂e/kg), and ϵ_j is the waste factor of construction material j during material transportation or building installation. The value of the waste factor depends on the type of construction material and, given the limited data on carbon emissions factors of construction materials in China, the values used in this study are based on highly cited scholarly articles [5,44,45]. Table 2 collates the relevant waste factors and emission factors used in this study.

Table 2. Construction material waste factors and carbon emissions factors.

Material Name	Waste Factor	CO ₂ Emissions Factor (kgCO ₂ e/kg)
Steel components	5%	0.352
Precast concrete	0%	0.113
Non-prefabricated concrete	2.5%	1.021
Gypsum board	2.5%	0.218
Cement	2.5%	0.653
Aerated concrete block	5%	0.106
Architectural glass	5%	1.735
Cement fiberboard	2.5%	0.629
Wood	5%	−1.655
Aluminum	5%	0.622

Waste factor from Tingyao Chen et al. [28,46,47]; carbon emission factor from [48–50].

2.3.2. Prefabrication Stage

The CO₂ emissions from the production process of prefabricated components originate from three components: CO₂ from the combustion of minerals or fuels, CO₂ converted from electricity consumption, and CO₂ that may be generated from chemical reactions. Therefore, the carbon emissions of prefabricated components can be calculated from the total carbon emissions associated with the raw materials, fossil fuels, people, water, and electricity [51]. The calculation is expressed as follows:

$$E_2 = \left(\sum_{j=1}^j M_a * f_a^t \right) + M_{bi} * f_{bi} + M_c * f_c + M_d * f_d + M_e * f_e \quad (3)$$

where E_2 is the specific carbon emissions (in tons) of all precast plant processes, M_a is the amount of precast auxiliary material a (in tons), f_a^t is the general carbon emissions factor of auxiliary material a in the production phase, M_{bi} is the energy consumption in the production process, f_{bi} is the carbon emission factor of the i source of energy, M_c is the total number of labor days in the manufacturing process, f_c is the human carbon emissions factor, M_d is the water consumption in the production process, f_d is the water carbon emissions factor, M_e is the electricity consumption in the production process, and f_e is the electricity carbon emissions factor.

The data of potential emissions factors and carbon oxidation rates by fuel species in the 2006 IPCC Guidelines for National Greenhouse Gas Inventories were used to derive the CO₂ emissions factors per kWh of coal power in the East China Power Grid, in terms of the average over the period 2015–2017 [45] in Table 3.

Table 3. Summary of calculation results of OM emissions factors for six regional grids in China in 2019.

Region/Time (Year)	2015	2016	2017	Three-Year Weighted Average
	tCO ₂ e/MWh	tCO ₂ e/MWh	tCO ₂ e/MWh	tCO ₂ e/MWh
North China Regional Grid	0.9590	0.9242	0.9437	0.9419
Northeast regional grid	1.0959	1.0634	1.0886	1.0826
East China Regional Grid	0.7987	0.7894	0.7888	0.7921
Central China Regional Grid	0.8767	0.8564	0.8444	0.8587
Northwest regional grid	0.9178	0.8614	0.8990	0.8922
Southern regional grid	0.8080	0.7900	0.8139	0.8042

Baseline Emissions Factors for China Regional Grid for the 2019 Emission Reduction Project.

2.3.3. Transportation Phase

Equation

$$E_3 = \sum_{k=1}^k \sum_{j=1}^j \frac{M_j * L_j^m * f_k^t}{1000}, \quad (4)$$

where E_3 is the total carbon emissions from fuel combustion for the transportation of construction materials (in tons), L_j^m is the distance (in km) from the distribution center to the off-site prefabrication plant or from the distribution center to the project site, and f_k^t is the carbon emissions factor for fuel combustion for transportation method k (in kgCO₂/tkm), such as vehicle, train, or ship. Table 4 lists the carbon emissions factors for different modes of transportation.

Table 4. Construction material waste factors and carbon emissions factors.

Energy Type	Carbon Emissions Factor (gCO ₂ e/MJ)	Source	Carbon Emissions Factor (gCO ₂ e/MJ)	Source
Coal	90.4	Baines, 1993 [45,52]	89	Carbon emissions calculation standard for buildings
Oil	68	Baines, 1993	72.23	Carbon emissions calculation standard for buildings
Gasoline	66.6	Baines, 1993	67.91	Carbon emissions calculation standard for buildings
Diesel	68.7	Baines, 1993	72.59	Carbon emissions calculation standard for buildings

Source: China's Standard for Calculating Carbon Emissions from Buildings (GB/T51366-2019)(GB/T51366-2019).

2.3.4. Construction Site

Equation

$$E_x = E_5 + E_6 + E_7, \quad (5)$$

where E_x denotes the total energy use in the building construction phase (kwh or kg), E_5 denotes the carbon emissions from the energy use of non-prefabricated sub-projects (kwh or kg), E_6 denotes the carbon emissions from the energy use of on-site assembly sub-projects (kwh or kg), and E_7 denotes the carbon emissions from the energy use of scaffolding, formwork and bracing, vertical transportation, building superstructure, and so on.

The energy usage of sub-projects is calculated according to the following formula:

$$E_5 + E_6 = \sum_{i=1}^n Q_f * f_f, \quad (6)$$

$$f_f = \sum_{i=1}^n T_{ij} * R_{ij} + E_k, \quad (7)$$

where Q_f is the volume of the i^{th} project in the sub-project, f_f is the energy consumption coefficient of the i^{th} project in the sub-project (kwh/volume measurement unit), T_{ij} is the j^{th} type of construction machinery shift consumption in the i^{th} project (shift), R_{ij} is the energy consumption of the j^{th} construction machinery unit shift (kwh/shift) in the i^{th} project (determined in accordance with Appendix C of this standard or according to

empirical data, when it is available), and E_k is the consumption of energy included in the material part of the energy consumption (kwh); note that small construction machinery is not included in the mechanical shift consumption. The energy consumption associated to scaffolding, formwork and brackets, vertical transportation, building super-elevation, and other measure items that can be calculated for the volume of work should be calculated according to the following formula:

$$E_7 = \sum_{i=1}^n Q_c * f_c, \quad (8)$$

$$f_c = \sum_{i=1}^n T_{Aj} * R_{ij}, \quad (9)$$

where Q_c is the quantity of work of the i^{th} item in the measure project, f_c is the energy consumption coefficient (kwh/volume unit of measure) of the i^{th} project in the measure project, T_{Aj} is the consumption of the j^{th} construction machinery shift (shift) for the i^{th} measure project unit quantity, and R_{ij} is the energy consumption of the j^{th} construction machinery unit shift for the i^{th} project (kwh/shift).

3. Embodied Carbon Calculations

Building B1 of Zijin Campus of Zhejiang University Architectural Design and Research Institute (hereinafter referred to as Building B1) is a sub-project of Zijin Crowd Town, with two underground floors connected to other single units and 3 above-ground floors with a construction area of 8888 square meters. In the project, professional BIM technology was adopted throughout the whole process, from design to construction. Its assembly rate is 96.8%, which is a leading position in China. It is a national AAA-grade assembly building and three-star green building, and is also a 2019 Ministry of Housing and Construction assembly building technology demonstration project. It is depicted in Figure 3.



Figure 3. Real-life photograph of building B1.

The building information model (BIM) method can help to make environmentally sustainable decisions, in order to reduce the energy waste in projects [53]. China has demonstrated a good practice of using BIM to reduce carbon emissions [22,54]. Combined with the BIMLCA method, the error in statistical process can be reduced [55]. Some scholars have developed a new tool, pycab, based on BIM, which can directly calculate the implied carbon of buildings in the design stage [56]. In this study, the BIM inventory tool is used to obtain statistics and conduct proof-reading of case materials, including concrete and reinforced concrete works, metal structure works, roofing and waterproofing works, heat insulation and anti-corrosion works, painting and fuel framing works, and some supplementary list works, as detailed in Table 5.

In order to collect accurate process data on and off the B1 building site, the author solicited the help and cooperation of the EPC, designers, suppliers, and other stakeholders, aided by a breakdown of the BIM model. Process data were collected from multiple sources, after interviews and field surveys with the aforementioned individuals. The concrete and reinforced concrete works in this project were non-prefabricated works, while the rest of the works were prefabricated. The main aspects of the building are summarized according to the list of the specific parts used in the project

The amount of materials used in the main part of the building are summarized, according to the specific parts in the project, and on-site energy consumption data were compiled through on-site construction energy consumption records. The data for the construction phase were mainly obtained from the design plans and test data provided by the design institute, and the data and materials were provided by the prefabricated project. The main purpose of this study is to compare the carbon emissions of prefabricated and non-prefabricated building projects. The prefabricated components of the factory mainly comprise structural and envelope components, while other practices, such as electromechanical, finishes, and decoration, are basically the same as those of non-prefabricated buildings; therefore, we excluded these parts to facilitate the calculation and reduce the workload.

Table 5. Summary of calculation results of OM emission factors for six regional grids in China in 2019.

Work Method Classification	Project Part	Component Type
Non-prefabricated part	Envelope walls and internal partition walls	Prefabricated partially laminated floor slab
		Precast laminated floor slab
		Prefabricated steel stairs
		Prefabricated honeycomb beams
		Prefabricated partially filled steel-concrete composite beams
		Unit curtain wall for non-load-bearing exterior parapet walls
Concrete works	Reinforced concrete works	PC integrated external wall panels
		Perforated aluminum panels
		Decoration integrated ALC slats
		PC laminated beam
		Non-prefabricated component reinforcement

3.1. Calculation of Carbon Emissions during the Production and Construction Phase of the B1 Building

The carbon emission calculation for the production building phase of the B1 building consists of four components: off-site carbon emissions (E1) calculation, off-site carbon emissions (E2) calculation, transportation carbon emissions (E3 and E4) and on-site carbon emissions calculation (E5, E6, E7).

3.1.1. Off-Site Carbon Emissions (E1) Calculation

The B1 building consumed a wide range of building materials, and the calculations in this study focus on 17 major building materials. The total amount of all construction materials was summarized from the project list, and the total carbon emissions of the construction materials were calculated by matching the carbon emissions factors of corresponding materials (Table 6).

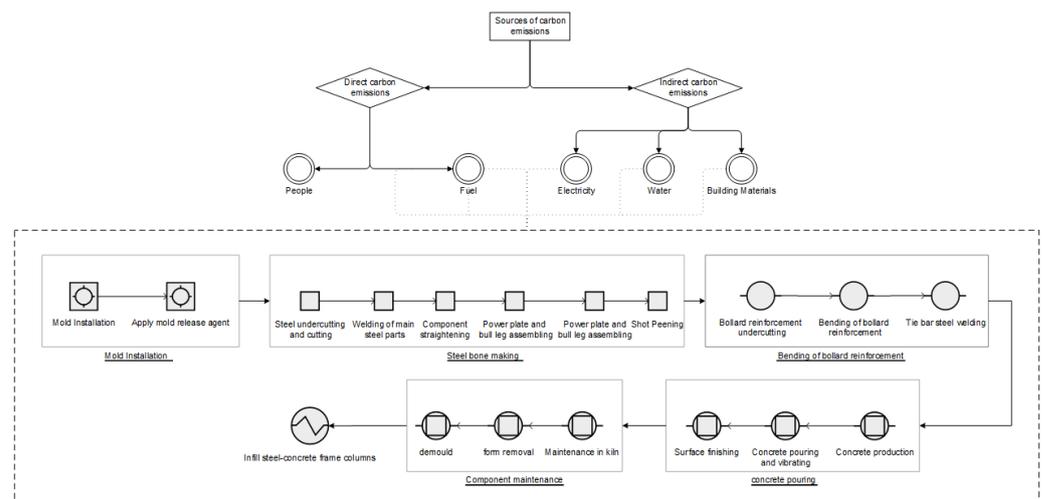
Table 6. E1 calculation table.

Building Materials	Mass/Volume	Waste Factor	Carbon Emissions Factor	Total Carbon Emissions (kgCO ₂ e)
ALC slatwall	769.76 m ³	2.50%	336 kgCO ₂ e/m ³	265,105.34
C35 Concrete	267.71 m ³	2.50%	295 kgCO ₂ e/m ³	80,948.81
C30 Concrete	932.35 m ³	2.50%	295 kgCO ₂ e/m ³	281,919.33
H section steel	1512.69 t	5%	352 kgCO ₂ e/t	559,090.22
SBS modified asphalt waterproofing membrane	16.45 t	2.50%	4620 kgCO ₂ e/t	77,898.98
C25 fine stone concrete precast block	2493.83 m ²	5%	295 kgCO ₂ e/m ³	77,245.46
Metal drainage ditch	44.760 t	5.00% [28]	112 kgCO ₂ e/t	5263.776
	588.2 m ²	5%	254 kgCO ₂ e/m ²	156,872.94
112.5 thick XPS extruded plastic benzene board	6.2 t	2.50%	5020 kgCO ₂ e/t	31,902.1
C15 fine stone concrete bedding layer	248.76 m ³	2.50%	295 kgCO ₂ e/m ³	75,218.81
25mm UHPC Ultra High Performance Concrete Slab	72.27 m ³	0%	295 kgCO ₂ e/m ³	21,320.39
Steel keel	161.45 t	5%	352 kgCO ₂ e/t	59,671.92
Insulation rock wool board	12.92 t	2.50%	1980 kgCO ₂ e/t	26,221.14
Curtain wall liner (aluminum veneer)	884.11 m ²	5%	8.06 kgCO ₂ e/m ²	7482.22
Curtain wall glass	135.32 t	5%	1130 kgCO ₂ e/t	160,557.18
Perforated aluminum panel	3282 m ²	5%	8.06 kgCO ₂ e/m ²	27,775.57
Aluminum keel	36.403 t	5%	622 kgCO ₂ e/t [45]	23,774.8
Insulation liner (galvanized thin steel)	14.16 t	5%	2050 kgCO ₂ e/t	30,479.4
E1				1968.75 tCO ₂ e

The carbon emissions factors are derived from the Chinese national standard “Carbon Emission Calculation Standard for Buildings” (GB/T51366-2019).

3.1.2. Off-Site Carbon Emissions (E2) Calculation

According to the above calculation model, the carbon emissions in the prefabrication stage of the plant are mainly generated through the consumption of labor, fuel, electricity, water, and building materials, and each part of the plant processing line generates different carbon emissions; take the production line of PEC columns as an example, as shown in Figure 4. We conducted a carbon emissions calculation regarding the prefabrication stage of this study, based on plant survey visits and reliable data obtained from the plant.

**Figure 4.** Sources of carbon emissions from concrete frame columns.

(1) Calculation of electricity consumption of prefabricated components

Based on the factory survey, the factory production line was calculated based on a one-shift system with 8 h per shift and 250 working days, and the corresponding electricity, water, and natural gas consumption data were collected, as detailed in Table 7.

Table 7. Factory survey data sheet.

Plant Survey Data	Electricity Consumption (Million kWh)	Water Consumption (Million Tons)		Natural Gas (Million Cubic Meters)	
	Domestic and production	Domestic	Production	Domestic	Production
Area Consumption	1013	0.5	2.5	1	20

At present, there are several production lines in the Green Building Group factory, and the annual output and price of each production line were provided by the factory, together with the total installed power of each production line. The total installed power can be divided by the total power of the factory to obtain a production line power consumption ratio H_j . It is difficult to record the electricity consumption of a single component in the production process, as the factory only records annual statistics of electricity consumption, which includes both production and domestic electricity. Therefore, we assumed that the consumption of water, electricity, labor, and auxiliary materials for the precast component production line was positively correlated with the production line output; for example, prefabricated cellular beams corresponding to the factory steel component production line. Under this assumption, we calculated the ratio Q_i of prefabricated components in Building B1 to the annual output value of the corresponding factory production line, and used this value to indicate the share of prefabricated components in the total production line. In this way, the power, labor, and water consumption of the prefabricated components could be derived from the total power, total labor, and total water consumption, along with the share of prefabricated components in the production line. The total power consumption of prefabricated components in the factory process is detailed in Tables 8 and 9. It should be noted that the prefabricated components were not produced by one manufacturer, and the decorative integrated ALC panels were purchased from Green Building Group; as the data of the purchasing company were not convenient to obtain, we adopted the existing research results instead. The carbon emissions factor of the prefabrication process of interior wall panels was taken as $637.0028 \text{ kgCO}_2\text{e}/\text{m}^3$ [57].

(2) Water consumption and labor calculation for prefabricated components

There was no process wastewater generated during the production process in the project, and the wastewater mainly comes from the domestic sewage of workers. According to the survey, there are 700 people working in the Green Building Group factory, including 440 people in the steel structure production line, 120 people in the PC production line, 70 people in the door and window assembly line, and the remaining 70 people are management personnel. The living water consumption of the residential staff was taken as 175 L per person. The total water consumption of the project was 160 t/d, assuming a one-shift system with 8 h per shift and 360 working days. The calculation is shown in the following Table 10 and 11.

Table 8. Annual power consumption of plant lines.

Factory Production Line	Quantity	Installed Power (kW)	Total Installed Power (kW)	Share Based on Total Power	Electricity (Million kWh)
Steel joist floor joist Production line	2	260	520	7.40%	75
PC secondary processing line	1	200	200	2.90%	29.38
Door and window processing line	2	120	240	3.40%	34.44
Concrete mixing plant	1	75	75	1.00%	10.13
PC component production line	2	1300	2600	37.20%	376.84
Steel structure parts components	Multiple	Multiple	3350	47.90%	485.23

Table 9. Carbon emissions of W_{pi} .

Main Part Amount (t)	Name of Components (Total)	Total Factory Consumption of Electricity (Million kWh)	Percentage of Q_i	Electricity Consumed by Prefabricated Components (Million kWh)	Carbon Emissions (tCO ₂ e)	
Main structure	Prefabricated partially filled steel-concrete frame columns	514.61	0.54%	2.778894	22.01	
	Prefabricated partially laminated floor slabs	376.84	0.47%	1.771148	14.03	
	Prefabricated laminated floor slabs	376.84	0.16%	0.602944	4.78	
	Prefabricated steel stairs	485.23	0.07%	0.3542179	2.81	
	Prefabricated honeycomb beams	485.23	0.93%	4.512639	35.74	
	Prefabricated partially filled steel-concrete composite beams	514.61	0.15%	0.771915	6.11	
	pc exterior wall panel	376.84	0.04%	0.1431992	1.13	
	Prefabricated pc board	376.84	0.14%	0.527576	4.18	
	Enclosing walls and internal partitions	Non-load-bearing perimeter parapet wall using unit curtain wall	34.44	0.94%	2.383248	2.56
		PC integrated external wall panels, perforated aluminum panels	376.84	1.63%	3.01472	48.65
Decoration integrated ALC slats		769.76 m ³ * 637.0028 kgCO ₂ /m ³ [45]			0.49	
Total Carbon Emissions					142.49 tCO ₂ e	

Table 10. Carbon emissions of W_{pi} .

Main Part	Component Name	Percentage of Q_i	Production Line Labor	Prefabricated Components Labor	Personnel Domestic Water Consumption	Water Carbon Emissions Factor	Total Carbon Emissions Amount (kgCO ₂ e)
Main structure	Steel-filled concrete frame column	0.54%	560	94.5	175 L/person.d	0.4137	886.6667
	Prefabricated partially laminated floor slabs	0.47%	120	17.625	175 L/person.d	0.4137	143.9335
	Prefabricated laminated floor slabs	0.16%	120	6	175 L/person.d	0.4137	16.68038
	Prefabricated steel stairs	0.07%	440	10.0375	175 L/person.d	0.4137	12.73161
	Prefabricated honeycomb beams	0.93%	440	127.875	175 L/person.d	0.4137	2066.348
	Prefabricated partially filled steel-concrete composite beams	0.15%	560	26.25	175 L/person.d	0.4137	68.41564
	PC exterior wall panel	0.04%	120	1.425	175 L/person.d	0.4137	0.940878
	Prefabricated PC board	0.14%	120	5.25	175 L/person.d	0.4137	12.77092
Enclosing walls and internal partitions	Non-load-bearing perimeter parapet wall using unit curtain wall	0.94%	70	20.5625	175 L/person.d	0.4137	335.8448
	PC integrated external wall panels, perforated aluminum panels	1.63%	70	35.65625	175 L/person.d	0.4137	1009.853
							4.55 tCO ₂ e

Data from prefabricators.

Table 11. Carbon emissions of T_{pi} .

Main Part	Component Name	Percentage of Q_i	Production Line Labor	Labor Hours (Unit)	Human Carbon Emission Factor (kg/unit)	Carbon Dioxide Emissions (kgCO ₂ e)
Main structure	Steel-filled concrete frame column	0.54%	560	750	0.73	1655.64
	Prefabricated partially laminated floor slabs	0.47%	120	750	0.73	308.79
Floor slabs	Prefabricated laminated	0.16%	120	750	0.73	105.12
	Prefabricated steel stairs	0.07%	440	750	0.73	175.857
	Prefabricated honeycomb beams	0.93%	440	750	0.73	2240.37
	Prefabricated partially filled steel-concrete composite beams	0.15%	560	750	0.73	459.9
	PC exterior wall panel	0.04%	120	750	0.73	24.966
	Prefabricated PC board	0.14%	120	750	0.73	91.98
Enclosing walls and internal partitions	Non-load-bearing perimeter parapet wall using curtain wall	0.94%	70	750	0.73	360.255
	PC integrated external wall panels perforated aluminum panels	1.63%	70	750	0.73	624.6975
						6.05 tCO ₂ e

(3) Calculation of natural gas use for prefabricated components

According to the factory investigation, the hot water from the gas boilers set up in the Green Building Group factory campus enters the radiators of each workshop and the attached rooms for heating through a pipe network. The heating pipes for each workshop and attached rooms are buried underground. The heating temperature of workshops and auxiliary rooms is controlled at 14–18 °C. Assuming that the temperature is uniformly distributed inside each space and that each production line workshop is relatively independent, the annual gas consumption of each production line can be derived from the ratio of workshop area to total factory area S_i . The calculation is detailed in the following Table 12.

Table 12. Carbon emission of N_{pi} .

Factory Production Line	Area (m ²)	Total Factory Floor Area (m ²)	Percentage of Production Line Workshop Area	Total Annual Natural Gas Consumption of the Plant (Million m ³)	Natural Gas Carbon Emissions Factors	Carbon Emissions (tCO ₂ e)
Steel truss floor joist production line	6300	103,000	6.10	20	55.54 tCO ₂ e/TJ	0.71
PC secondary processing line	7236		7.00%			0.82
Door and window processing line	12,492		12.10%			1.41
Concrete mixing plant	4000		3.90%			0.45
PC component production line	17,708		17.00%			1.99
Steel structure parts	33,216		32.20%			3.77
						9.18 tCO ₂ e

(4) Calculation of auxiliary materials for prefabricated components

The raw and auxiliary materials in the prefabrication process mainly include welding materials, polyurethane glass sealant, butyl rubber for insulating glass, neutral silicone glass glue, and so on. According to the factory survey, the annual consumption of raw and auxiliary materials in each production line of the factory is known, and the total

consumption of raw and auxiliary materials of prefabricated components in Building B1 can be obtained through the correspondence between prefabricated components in Building B1 and factory processing; see Table 13 for the specific calculation. In this study, the raw and auxiliary materials mainly consider the recycling of shaped steel, steel bars, and glass, while other materials are not included in the calculation due to their small dosage range.

Table 13. Calculation of carbon emissions of main auxiliary materials.

Name of Auxiliary Material	Total	Carbon Emissions Factor	Carbon Emissions (t)
Knot 422 welding material	59.01 t	2350 kgCO ₂ /t	7.06
Polyurethane glass sealant	94 kg	5.22 kgCO ₂ eq/kg	0.49
Mold release agent	24.08	3.6 kgCO ₂ eq/kg	0.08
			7.63

The amount of auxiliary materials was obtained from the statistics of the prefabrication plants.

In summary, E3 could be calculated as

$$E3 = E_{pi} + T_{pi} + W_{pi} + N_{pi} + F_{pi} = 169.90 \text{ tCO}_2\text{e}$$

3.1.3. Calculation of Transportation Carbon Emissions (E3 and E4)

According to the analysis of the above calculation model, the carbon emissions for the transportation stage were mainly divided into non-prefabricated materials and prefabricated components transported to and from the factory, where the transportation method uses heavy-duty gasoline trucks for transport (10–18 t). The distance of Building B1 from the Green Building Group was taken as 63 km, according to Google Maps, and the carbon emissions of the transportation process E2 and E4 were calculated as shown in Tables 14 and 15. Overall, the total carbon emissions associated to transportation were 94.67 tCO₂e

Table 14. E2 calculation table.

Transport Material	Mass	Carbon Emissions Factor	Transportation Distance	Total Carbon Emissions (kgCO ₂ e)
Concrete	1200.06 t	0.104 kgCO ₂ e/(t·km)	20 km	24,960.1248
Steel	3608.98 t	0.104 kgCO ₂ e/(t·km)	65 km	24,396.7048
Aluminum (Al)	4705.6 kg	0.104 kgCO ₂ e/(t·km)	85 km	41.597504
Rock wool board	12.92 t	0.104 kgCO ₂ e/(t·km)	75 km	100.776
E2				49.50 tCO ₂ e

Shaoxing Lvzhu Building Materials Co., Ltd. 65 km; rock wool, Shaoxing Shengzhou Ding's Rock Wool Insulation Material Co., Ltd., 75 km; aluminum, Ningbo Fubang Jingye Aluminum, 85 km; concrete, green building plant self-produced, 0 km; concrete sand and stone raw material, Shaoxing Qianqing Shaoxing Pier (original source not determined), 20 km.

Table 15. E4 calculation table.

Transport Material	Mass	Carbon Emissions Factor	Transportation Distance	Total Carbon Emissions (kgCO ₂ e)
Unit type curtain wall	291.29 t	0.104 kgCO ₂ e/(t·km)	63 km	1908.532
Prefabricated steel components	1197.41 t	0.104 kgCO ₂ e/(t·km)	63 km	7845.43
Prefabricated concrete components	2411.57 t	0.104 kgCO ₂ e/(t·km)	63 km	15,800.61
Concrete	2880.14 t	0.104 kgCO ₂ e/(t·km)	63 km	18,870.68
Metal	44.760 t	0.104 kgCO ₂ e/(t·km)	65 km	302.5776
Insulation liner (steel plate)	14.16 t	0.104 kgCO ₂ e/(t·km)	65 km	95.7216
25mm UHPC plate	169.54 t	0.104 kgCO ₂ e/(t·km)	20 km	352.6432
E4				45.17 tCO ₂ e

Building B1 is 63 km from Shaoxing Green Building Group Co.

3.1.4. On-Site Carbon Emissions Calculation

The time period for carbon emissions calculation at the site phase was from the start of the project to the completion and acceptance of the project. The site construction profile was known, according to the investigation of the component works list; for example, the ALC strip panel wall was a 220 thick prefabricated lightweight strip internal wall panel, the wall masonry mortar was pre-mixed mortar with capacity weight $\leq 8.0 \text{ kN/m}^3$, the solid web steel column was prefabricated semi-parcel welded H-beam-concrete frame column, and the concrete strength grade was C30. The calculation process is detailed in the table below. The sum of the total carbon emissions of all activities in the site construction phase was 32.41 t, and the planar carbon emissions per unit was 4.05 kg/m^2 , accounting for 1.3% of the carbon emissions of the whole production and construction phase. Among the values, E5 was $0.07 \text{ tkgCO}_2\text{e}$, accounting for 0.2% of the total carbon emissions of the construction site; E6 was 20.92 t, accounting for 65.4%; and E7 was $11.42 \text{ tkgCO}_2\text{e}$, accounting for 34.4%. The specific calculation is detailed in Table 16.

After the above analysis and calculation, the total carbon emissions in the production and construction phase of Building B1 were obtained, as follows:

$$C_z = E1 + E2 + E3 + E4 + E5 + E6 + E7 = 2265.73 \text{ tCO}_2\text{e}$$

$$V_{C_z} = 2265.73/8888 = 0.283 \text{ tCO}_2/\text{m}^2 = 255 \text{ kgCO}_2\text{e}/\text{m}^2$$

where C_z is the total carbon emissions for the materialization stage of B1, and V_{C_z} is the carbon emissions per unit area for the materialization stage of B1. A total of 86.9% of the carbon emissions were for building materials, thus accounting for most of the carbon emission; 4.2% of the carbon emissions were for the transportation stage; 7.5% of the carbon emissions were for factory prefabrication and processing; and 1.4% of the carbon emissions were for the construction site.

Table 16. Calculation of carbon emissions by site phase.

Construction Activities	Project	Quality	Energy Type	Natural Gas Carbon Emissions Factors	Total Carbon Emissions (kgCO ₂ e)
On-site transportation	Steam crane	2639 kg	Diesel fuel	2298 gCO ₂ /L	6064.422
	Lifting arm truck	2343.2 kg	Diesel fuel	2618 gCO ₂ /L	6134.498
	Forklift	131.25 kg	Diesel fuel	2618 gCO ₂ /L	343.6125
Welding process	Lorry	81.25 kg	Gasoline	2298 gCO ₂ /L	186.7125
	Handlebar welding	463.89 kW/h	Power	0.7898 kgCO ₂ e/kWh	366.3803
	Carbon dioxide gas shielded welding	49 kW/h	Power	0.7898 kgCO ₂ e/kWh	38.7002
Purchased electricity for construction	On-site electricity	23,980 kW/h	Power	0.7898 kgCO ₂ e/kWh	18,939.4
On-site worker activities kgCO ₂ e/kg	Resident Activities	No solid waste	-	3.17	
	Water Production	250 m ³	Water	0.42 kgCO ₂ e/m ³	105
	Unorganized emissions	None	-		
	Unorganized emissions	311.77 /Workday		0.73 kgCO ₂ /Workday	227.5921
E5 + E6 + E7					32.41 tCO ₂ e

The above data were collected from the site and recorded data.

3.2. Calculation of Carbon Emissions in the Production and Construction Phase of the Non-Prefabricated Simulation of Building B1

Compared with prefabricated buildings, the main difference of non-prefabricated buildings is reflected in the main structure and internal wall parts, where the specific materials include steel reinforcement, concrete (including sand, stone, and cement), masonry materials, mortar (including cement and sand), and some admixtures (e.g., admixtures in concrete and mortar). Therefore, in this simulation, we kept the building area, function, and form of the B1 building unchanged. Under these conditions, the main structure and internal wall parts were re-designed by the structural designer as a reference simulated

building using the non-prefabricated method of construction; part of the structural design drawings are shown in Figure 5.

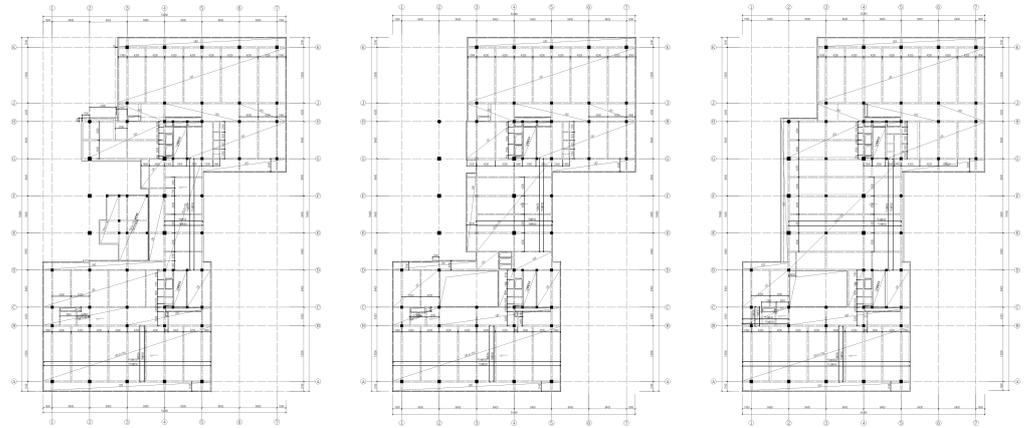


Figure 5. Structural plan layout of reference building.

3.2.1. Calculation of Carbon Emissions for Materials of B1 Building in the Non-Prefabricated Simulation

Considering the waste of materials such as rework on site, the amount of material work for the building structure was multiplied by a factor of 1.1, according to the experience of structural engineers, and the amount of work was calculated as shown in Table 17, where the total carbon emissions associated to building materials was 2242.50 tCO₂e.

Table 17. Calculation of carbon emissions in site phase.

	Material	Total Amount	Carbon Emissions Factor	Carbon Emissions (kgCO ₂ e)
Structural component	Concrete	3588 m ³	295 kgCO ₂ e/m ³	1085.22
	Steel	65.12 t	352 kgCO ₂ e/t	24.07
	Steel reinforcement	676.03 t	352 kgCO ₂ e/t	249.86
	SBS modified asphalt	16.45 t	4620 kgCO ₂ /t	77,898.98
	C25 fine stone concrete	2493.83 m ²	295 kgCO ₂ /m ³	77,245.46
Internal wall part	Shale bricks	382.06	292 kgCO ₂ /m ³	111.56
		350.8		102.43
		386.18		112.76
	Cement mortar	67.14 m ³	496 kgCO ₂ /m ³	33,301.44
	Putty powder	11.19 m ³	501 kgCO ₂ /m ³	5606.19
External envelope part	25 mm UHPC ultra high performance concrete slab	72.27 m ³	295 kgCO ₂ e/m ³	21,320.39
	Steel keel	161.45 t	352 kgCO ₂ e/t	59,671.92
	Insulation rock wool board	12.92 t	1980 kgCO ₂ e/t	26,221.14
	Curtain wall liner (aluminum veneer)	884.11 m ²	8.06 kgCO ₂ e/m ²	7482.22
	Curtain wall glass	135.32 t	1130 kgCO ₂ e/t	160,557.18
	Perforated aluminum panel	3282 m ²	8.06 kgCO ₂ e/m ²	27,775.57
	Aluminum alloy keel	36.403 t	622 kgCO ₂ /t	23,774.8
	Insulation liner (galvanized thin steel plate)	14.16 t	2050 kgCO ₂ e/t	30,479.4
	Metal Drains	44.760 t	112 kgCO ₂ e/t	5263.776
				2242.50 tCO ₂ e

The above data are from structural calculations and building plan statistics. ² The carbon emission factors derived from the Chinese national standard “Carbon Emission Calculation Standard for Buildings” (GB/T51366-2019).

3.2.2. Carbon Emissions Calculation for the Transport Phase of Building B1 in the Non-Prefabricated Simulation

The carbon emissions in the transportation phase of the reference building were 136.59 tCO₂e, as calculated in the following Table 18:

Table 18. Calculation of carbon emissions of transportation of Building B1 in non-prefabricated simulation.

Material Transported	Mass	Vehicle Emissions Factor (kgCO ₂ e/(t·km))	Transportation Distance	Total Carbon Emission (kgCO ₂ e)
Concrete	8417.45 t	0.104 kgCO ₂ e/(t·km)	20 km	24,960.1248
Steel	714.15 t	0.104 kgCO ₂ e/(t·km)	65 km	24,396.7048
Aluminum	4705.6 kg	0.104 kgCO ₂ e/(t·km)	85 km	41.597504
Rock wool board	12.92 t	0.104 kgCO ₂ e/(t·km)	75 km	100.776
Metal	44.760 t	0.104 kgCO ₂ e/(t·km)	65 km	302.5776
Insulation liner (galvanized thin steel)	14.16 t	0.104 kgCO ₂ e/(t·km)	65 km	95.7216
Concrete slab	169.54 t	0.104 kgCO ₂ e/(t·km)	20 km	352.6432
Steel keel	161.45 t	0.104 kgCO ₂ e/(t·km)	65 km	1091.402
				136.59 tCO ₂ e

Shaoxing Lvzhu Building Materials Co., Ltd. 65 km; rock wool, Shaoxing Shengzhou Ding's Rock Wool Insulation Material Co., Ltd., 75 km; aluminum, Ningbo Fubang Jingye Aluminum, 85 km; concrete, green building plant self-produced, 0 km; concrete sand and stone raw material, Shaoxing Qianqing Shaoxing Pier (original source not determined), 20 km.

3.2.3. Carbon Emissions Calculation for the Construction Stage of the B1 Building in the Non-Prefabricated Simulation

The construction phase of the B1 building reference building included steel works, commercial concrete works, formwork works, transportation works, and scaffolding works, among others, which involve specific energy consumption and material usage that is difficult to estimate. Therefore, the method for converting the carbon emissions ratio in the non-prefabricated building construction stage was adopted from previous studies. According to analysis of China's building energy consumption research report, the carbon emissions in the building material stage and building construction stage account for 55.17% and 2.02% of the carbon emissions of the whole building process, respectively; if this is taken as a basis, the carbon emissions of the B1 building, with reference to the building construction stage, would be 82.11 t. However, the data of China's building energy consumption research report include both non-prefabricated buildings and prefabricated buildings, as well as regional differences. If we take the same regional buildings as reference, for example, the results of carbon emissions analysis for Qianjiang Century City of Zhejiang University College of Construction and Engineering were 91.53%, 5.08%, and 3.39% for construction materials, transportation, and construction stages, respectively. Keeping the simulated estimated total carbon emissions of construction materials unchanged, a difference of 12.13 t between the standard transportation stage of ZJU Construction (with an error value of −8.8%) was calculated, as detailed in the following Table 19. The difference between the two was not large and, so, we took the calculation result in China's building energy consumption research standard, and the carbon emissions for the B1 building in the non-prefabricated construction stage were 82.11 t.

Table 19. Calculation of carbon emissions of B1 building construction by casting-in-place simulation.

Accounting Standards	Construction Materials	Transportation Phase	Construction Phase Carbon Emissions (tCO ₂ e)
B1 building reference building accounting	2242.50	136.59	-
Chinese building energy consumption research standard	2242.50	136.59	82.11
ZJU Construction Statistics Standard	2242.50	124.46	83.06
			136.59 tCO ₂ e

4. Results And Discussion

In summary, the total carbon emissions of the non-prefabricated simulated Building B1 were 2462.15 tCO₂e, with average carbon emissions of 277 kgCO₂/m², as shown in Figures 6 and 7. Compared with the actual calculation result for Building B1, the total

carbon emissions increased by 197.15 tCO₂e, while the average carbon emission increased by 22 kgCO₂e/m².

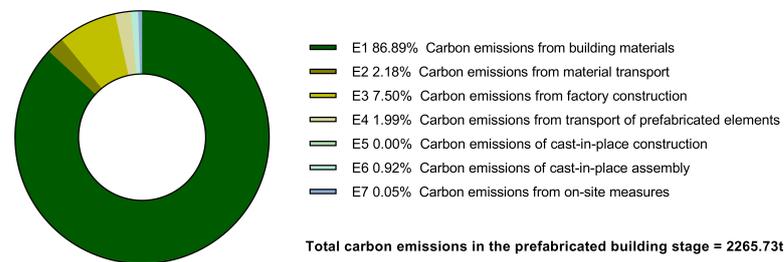


Figure 6. B1 building prefabrication method materialization stage carbon emissions.

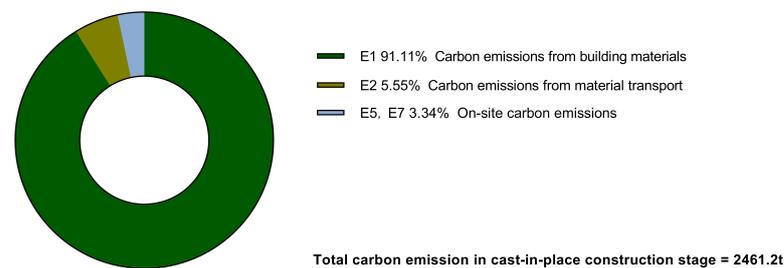


Figure 7. B1 building non-prefabricated simulation method transportation and construction phase carbon emissions.

4.1. Comparison of Off-Site Carbon Emissions for B1 Building

The off-site carbon emissions under the precast method for B1 building of were 103.85 t less than those under the non-prefabricated method. First, at the material level, the E1 under the precast method in B1 building were 273.75 t less than those under the non-prefabricated method, as shown in Figure 8. Second, at the design level, B1 building assembly design was conducted using BIM forward design technology, architecture, structure, equipment, interior, lighting, landscape, curtain wall, and other disciplines, based on the BIM model, as well as decorative structural integration of design, indoor, and ceilings, in order to optimize the overall material consumption. Third, at the technical level, we developed a B1 building structural system using UAD and construction units jointly developed by the “partially filled-concrete frame structure” (PEC) system, through a reasonable combination between concrete and steel members, in order to reduce the cross-sectional area of members. Fourth, the non-prefabricated method utilized a larger amount of materials, such as in the building of a concrete floor structural layer, which requires cement mortar leveling and fine stone concrete smoothing, while shale brick walls require cement–lime plaster priming, leveling, and a paint finish, and so on.



Figure 8. Comparison of material carbon emissions.

Notably, the carbon emissions (E2) relating to the prefabrication stage exist only in terms of the prefabrication method. The total carbon emissions of all prefabricated components in factory processing were calculated to be 142.49 t for electricity consumption, 4.55 t for total water consumption, 6.05 t for project labor, 9.18 t for natural gas in prefabrication processes, and 7.63 t for auxiliary materials (total, 169.90 t). Among the above, the largest carbon emissions were associated to electricity consumption (84%), followed by natural gas (5%), while the least relative carbon emissions came from water consumption, auxiliary material and labor (4%, 4%, and 3%, respectively), as shown in the Figure 9 below.

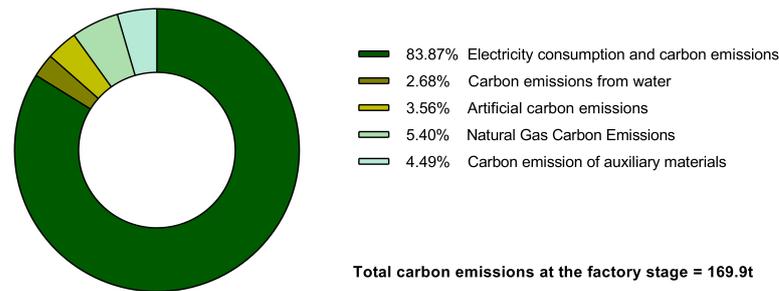


Figure 9. Emissions distribution in prefabrication stage of B1 building.

4.2. Comparison of Carbon Emissions in the Transportation Phase of Building B1

The carbon emissions associated with the prefabricated method in the transportation phase were 42.66 t lower, when compared to those under the reference building. The main reason for this is that the different construction methods affect the quality of the building materials and the transportation distance in the transportation phase, as shown in Figure 10. The prefabricated method itself requires transporting the building materials from the original material manufacturer to the prefabrication factory first, while the non-prefabricated method only needs transport from the material factory to the project base, such that, in the former, the increased transport distance will lead to higher carbon emissions with the same building materials; however, the reference building in this study, using the non-prefabricated method, requires a greatly increased amount of materials used for the same design. Ultimately, the impact of increased mass overshadows the impact of reduced distance.

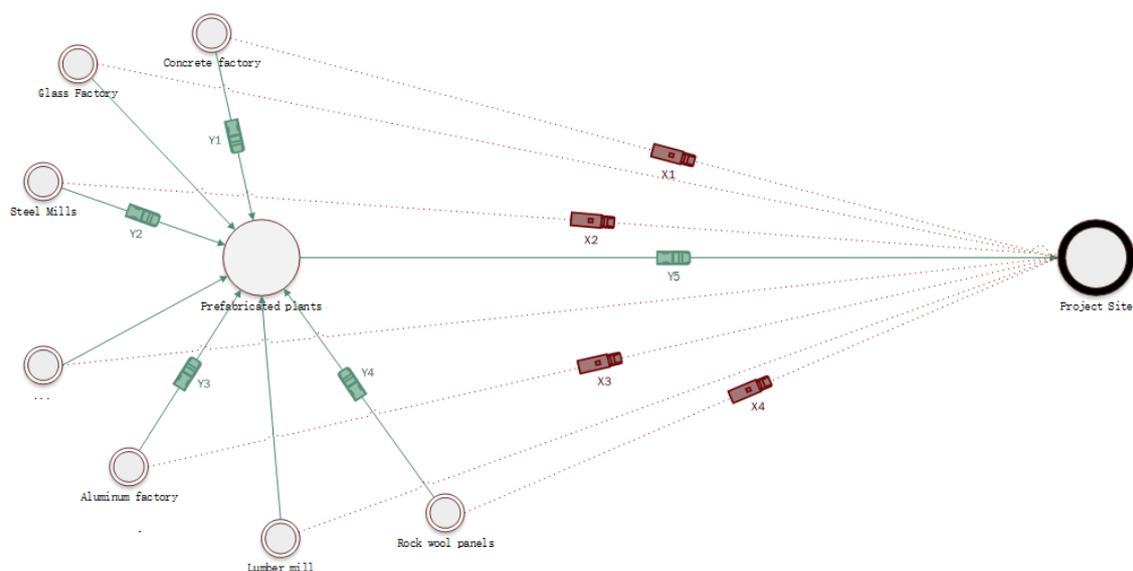


Figure 10. Comparison of transportation distance of B1 building.

4.3. Comparison of Carbon Emissions in the B1 Building Site

The on-site phase of the B1 building emitted 50.65 t less carbon than the reference building, as shown in Figure 11. The main reason for this is that the B1 building is nearly 100% prefabricated and the on-site assembly work takes up most of the on-site activities, while fabrication construction activities are minimal. Prefabricated assembly can save construction time while improving construction quality and efficiency. The B1 building design planned for site construction to start on 15 October 2019, with the main body and exterior walls completed on 15 December 2019, and the completion and acceptance completed by 30 May 2020, taking less than 8 months in total, greatly reducing the time for site construction. As a result, the total consumption of water and electricity, gasoline and diesel, and labor was reduced significantly.

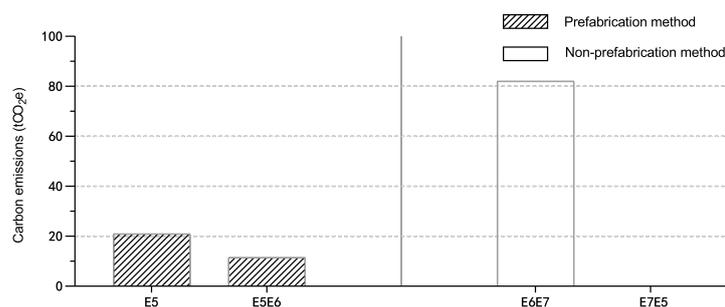


Figure 11. Comparison of carbon emissions during the construction phase of Building B1.

4.4. Analysis of the Technical Contribution of the B1 Building

The above B1 building method can be used to evaluate the carbon reduction associated to new buildings in the future. The new prefabricated construction area in Zhejiang Province reached 78.95 million square meters in 2019, accounting for 18.9% of the new prefabricated construction area in the country, and the new prefabricated office buildings in Zhejiang Province are expected to occupy 0.0378 billion square meters per year as shown in the Figure 12, according to this standard. Compared with the non-prefabricated method, the measured carbon emissions standard of Building B1 can allow for 531,090 tons of carbon emissions per year to be saved, thus saving nearly 5 million tons of carbon emissions by 2030.

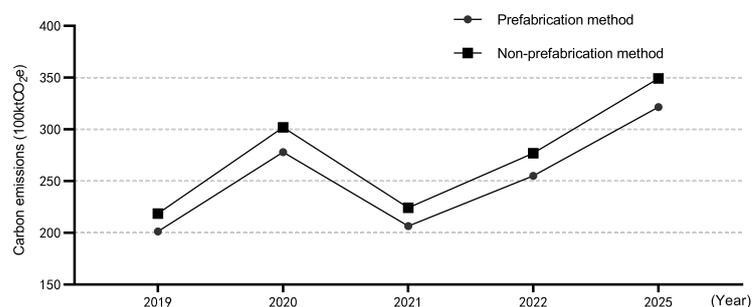


Figure 12. Schematic diagram of carbon emissions reduction in the production and construction stages of newly built prefabricated buildings in Zhejiang Province.

5. Conclusions

Under the background of carbon neutrality, China is in a period of vigorously developing prefabricated buildings. However, due to the problems of high cost, lagging production line, and poor water leakage and sound insulation, prefabricated buildings are not yet widely accepted, and their promotion is delayed at this stage. The carbon reduction effect shown in our research result is conducive to enhancing the public's perception of

prefabricated buildings. At the same time, designers can clearly understand the carbon emissions sources in the production and construction process, which is beneficial for control of the carbon emissions in the early design of buildings.

In this study, we investigated the difference in carbon emissions between two construction methods for Building B1 using a life-cycle boundary from cradle to end of construction. The results indicated that the physical phase of the prefabricated office building, with a high assembly rate, can significantly reduce the amount of carbon emissions: the total carbon emissions under the prefabricated construction method of the B1 building were 2265.73 tCO₂e, which was 22 kgCO₂e/m² less, when compared to the reference construction using the non-prefabricated method. The off-site part of the carbon emissions was reduced by 12.9 kgCO₂e/m², the transportation stage was reduced by 4.8 kgCO₂e/m², and the on-site part was reduced by 5.7 kgCO₂e/m². The reductions in carbon emissions are mainly due to the reduction in carbon emissions of building materials, including the advantages of steel, the good use of BIM design technology to avoid material waste, and the prefabricated system itself. Second, the carbon emissions reduction can be attributed to the on-site assembly construction, as prefabricated assembly can save construction time and improve construction quality and efficiency, such that the corresponding total consumption of water and electricity, gasoline and diesel, and labor is greatly reduced. In the future development of China's construction industry, through their whole life-cycle, prefabricated buildings can bring a lot of carbon emissions reduction benefits, and the implementation of prefabricated office buildings with PEC structure systems can effectively reduce carbon emissions and help China to achieve carbon-neutral and carbon peak goals as soon as possible.

Finally, there were some limitations to this study. The research results demonstrated that the carbon emissions associated with steel and concrete accounted for a large proportion, and the emissions reduction was really caused by prefabrication or the change of materials. However, we firmly believe that prefabrication can bring about carbon emissions reduction, and enhancement of the industrialization degree of prefabrication processes will also allow for the saving of raw materials. In other words, different construction processes and methods will bring about different quantities of raw materials. In addition, we did not compare the demolition stages of the B1 building, but the recovery rate of B1 building may be as high as 18% [58], in terms of the greenhouse gases produced by materials. Therefore, in the follow-up research, we intend to continue to study how much carbon emissions reduction can be achieved through the use of prefabricated steel structures, compared with steel structures built on-site, as well as visual analysis of carbon emissions in the operational stage of prefabricated public buildings using BIM technology. In the future, we also plan to investigate more real cases. Future research will continue to investigate office buildings with an assembly rate of about 60%, as well as the demolition stage of buildings, in order to further explore the possibility of carbon emissions reductions through prefabricated buildings.

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