applied sciences

MDPI

Article

Research on Carbon Footprint Accounting in the Materialization Stage of Prefabricated Housing Based on DEMATEL-ISM-MICMAC

Wei Liu and Qingcheng Huang *

School of Civil Engineering and Architecture, East China Jiaotong University, Nanchang 330013, China
* Correspondence: huangqc0616@163.com

Abstract: This work employs the carbon emission factor method to offer real-world instances for carbon footprint accounting, allowing for a thorough analysis of the carbon footprint and important influencing elements throughout the materialization stage of prefabricated housing. To identify the 18 important influencing factors that need to be examined from the five stages of building material production, conveyance of building materials, component manufacturing, component transportation, and building, this paper applies the DEMATEL-ISM-MICMAC (Decision-Making Trial and Evaluation Laboratory–Interpretive Structure Modeling–Cross-Influence Matrix Multiplication) model based on data quantification. Following the findings, the case project's physical phase generated a carbon footprint of approximately 4.68 $\times$ 10^6 kg CO_2. The building materials' production and processing phase contributed the highest carbon footprint of the entire physical phase, totaling 4,005,935.99 kg CO_2, or 88.24% of the total carbon footprint. To determine the centrality and causality of the influencing factors, four major influencing factors—energy consumption of raw materials (S_4), construction planning and organization (S_{15}), transportation energy type (S_6), and waste disposal (S_2)—were identified using the DEMATEL approach. The influencing factor system hierarchy was divided into six levels using the ISM technique. Level L6, which comprises one influencing factor for organizing and planning, is construction planning and organization (S_{15}). Utilizing the MICMAC technique, it was possible to identify the energy consumption of raw materials (S_4) as the primary cause of the materialization phase of built dwellings' carbon footprint. The building material production phases have the largest influence on carbon footprints, according to both case accounting and modeling research. The study's findings can offer some conceptual guidance for the creation of low-carbon emission reduction schemes.

Keywords: prefabricated housing; materialization stage; carbon footprint; carbon emission factor method; DEMATEL-ISM-MICMAC

Citation: Liu, W.; Huang, Q. Research on Carbon Footprint Accounting in the Materialization Stage of Prefabricated Housing Based on DEMATEL-ISM-MICMAC. *Appl. Sci.* **2023**, *13*, 13148. https://doi.org/10.3390/app132413148

Academic Editors: Carlos Morón Fernández and Daniel Ferrández Vega

Received: 6 November 2023
Revised: 6 December 2023
Accepted: 7 December 2023
Published: 11 December 2023

1. Introduction

With the rapid development of the construction industry, the environmental impact of construction is not to be underestimated. In terms of worldwide energy consumption and CO_2 emissions, buildings are one of the three primary sectors (together with industry and transportation). In China, building carbon emissions makeup between 2/5 and 1/2 of all carbon emissions. The IPCC Sixth Assessment Report (AR6) Working Group III Report [1], which was made public in April 2022, states that Chapter 9 offers a thorough analysis of the world's greenhouse gas emissions from the building industry. The building industry is on track to attain net-zero greenhouse gas emissions by 2050 if robust policy measures are put in place to support rational demand, increase efficiency in energy consumption, and stimulate the use of alternative sources of energy. This is one of the key conclusions. Existing and new constructions have enormous potential to cut emissions, and implementing climate change mitigation measures will aid in achieving the Sustainable Development Goals (SDGs) of the United Nations, as well as enhancing the building industry's ability to respond to climate change in the future. Thus, it is thought that cutting construction emissions will be essential to reaching the long-term objective of keeping the rise in global temperature at 2 °C.

The "14th Five-Year Plan" for the development of the construction industry was released in January 2022 by the Ministry of Housing and Urban–Rural Development. It placed a strong emphasis on the rapid development of assembled buildings and the promotion of green construction techniques. It is obvious that the industrialized construction of assembled buildings, as opposed to traditional construction methods, will result in energy savings and reduced emissions. According to the "In-depth Research and Development Trend Analysis Report on the Current Situation of China's Construction Industry (2023–2030)", the completed residential area accounts for the largest share of the total, accounting for 66.26% of the total in 2021, followed by the completed area of factories and buildings, with a share of 13.81%, as shown in Figure 1. As a result, China views lowering the energy usage and carbon emissions of assembled homes as a crucial first step toward achieving energy savings and emission reduction [2]. In order to develop appropriate emission reduction strategies and methods to meet the goal of reducing emissions from building, carbon footprint accounting and research into factors impacting the carbon footprint can be used to evaluate the size and trend of the carbon footprint. A carbon footprint analysis of assembled homes is therefore pertinent.

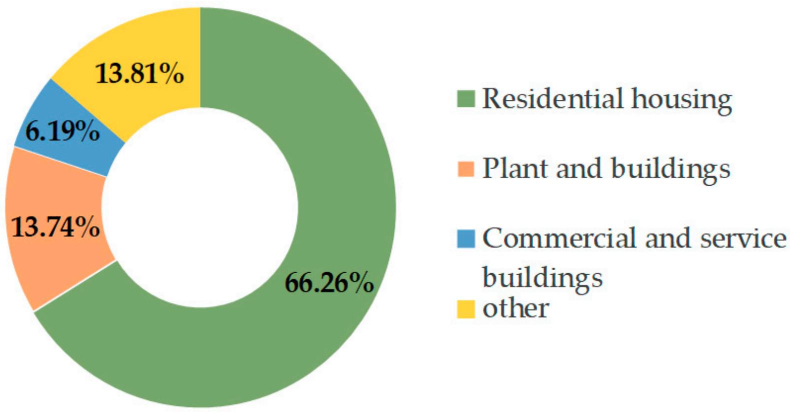

Figure 1. Percentage of housing completions by national construction firms, 2021.

This paper focuses on the carbon footprint accounting and influencing factors of assembled homes in the materialization stage. First, the research boundary of the materialization stage of prefabricated housing is clarified. Secondly, the carbon footprint accounting model in this stage is constructed by adopting the carbon emission factor method. From an engineering management perspective, the factors that impact carbon footprints are thoroughly examined, and the internal structure of these factors is analyzed with the DEMATEL-ISM-MICMAC model, and then actual cases are introduced to verify the feasibility of the method. The study proposes a systematic carbon footprint model and influencing factors analysis method for the materialization stage of prefabricated housing, which provides a reference for low-carbon decision-making in assembled buildings. It also provides theoretical support for the administration's empirically established policies to reduce greenhouse gas emissions from the building industry.

2. Literature Review

2.1. Carbon Footprint Accounting Methods

Globally, many cities have committed to modernizing their structures. Complexes with a small carbon footprint [3] and constructed buildings have drawn significant interest from academics both domestically and internationally as a crucial method to minimize carbon. Carbon footprint accounting is an effective way to evaluate greenhouse gases, but there is no uniform measurement standard yet. Based on the real measurement technique, Wang [4] created an online real-time CO_2 in thermal power unit monitoring model, making use of the system's online detection approach and using data from on-site inspections to account for carbon emissions from thermal power units. To determine the nation's proportionate share of carbon emissions from the building industry, Jonas [5] evaluated the energy use and emissions of carbon in the Irish building industry using the substance regulation approach. Meng [6] calculated the net production of CO_2 from wastewater treatment data based on the treatment process of photosynthetic bacteria and the material balance principle. Zhang [7], Jiang [8], Sun [9], and Lou [10] used the emissions of the carbon dioxide coefficient to calculate the carbon footprint of existing buildings at the emergence stage.

For studies on carbon footprint accounting, Matilainen [11] evaluated the carbon emissions of various options using a commercial structure as a case study, examined the patterns of consumption of energy and carbon emissions of various building design options, and examined the connection between energy expenditure and carbon emissions. Jeong [12] estimated the carbon emissions coming from the building components used during construction after studying six apartments of varying sizes, with the building size acting as a variable. Dodoo [13] examined the carbon emissions produced by an eight-story wooden frame structure across its entire life cycle. Biswas [14], utilizing the life cycle assessment (LCA) method, found that implementing an academic construction management strategy reduced the structure's energy use and emissions of greenhouse gases. Sim [15] compared the energy usage of steel-frame, concrete-frame, and wood-frame buildings to examine the connection between energy use and carbon emissions. Yi [16] presented a technique known as stochastic carbon estimation for estimating the unpredictable nature of GHG emissions. The emissions of carbon dioxide from building materials were examined by Arrigoni [17]. Among other things, Kanafani [18] examined the carbon emissions of 61 Danish construction sites according to how much energy they used.

Upon reviewing the findings of worldwide research on the calculation of carbon footprints, while there are several ways to account for the carbon footprint of construction, the field survey method, structural balance method, and carbon emission coefficient method are the ones with the greatest application range.

2.2. Carbon Footprint Accounting Boundary

Currently, the majority of academics, both domestically and internationally, use the complete life cycle concept to calculate the building's carbon emissions, investigate the sources of the emissions for the building's entire life cycle or just a particular stage, and evaluate the building's environmental impact. For research on the full life cycle, Bonamente [19] examined the stages of pre-production, manufacture, assembly, use, and service life, adopting a parametric model and the whole life cycle approach. Cho [20] conducted a comparative study comparing conventional and low-carbon buildings, breaking down the building's entire life cycle into four phases: the manufacture of materials for building, onsite development, operation, and demolition, employing a life cycle assessment methodology. Tumminia [21] investigated the energy efficiency and environmental effects of prefabricated construction modules in Italy. Dong [22] produced an LCA model driven by carbon emission reductions for each of the six phases in the life cycle of prefabricated temporary housing. Teng [23] provided evidence of prefabrication to reduce carbon emissions through a case study based on the whole life cycle theory. Mei [24] separated a building's complete life cycle into five phases: designing and planning the structure, collecting the building resources, construction, operation, and demolition. Gao [25] quantified a building in Shenzhen by establishing a full life cycle evaluation model for assembly buildings. Zheng [26] developed a framework for accounting for carbon dioxide during the construction, use, and abandonment phases of the construction process, using a complete life cycle methodology to assess its impact on the total amount of carbon emissions from the structure. For research on the physical phase aspect, to make carbon emission calculations, Tavares [27] separated the construction phase of prefabricated elements into three phases: material manufacturing and transit, component fabrication and delivery to the spot, and on-site assembly. Gao [28] used the process inventory analysis method, combined with the characteristics of assembled concrete buildings, to divide the materialization phase into building material extraction and production, factory production, transportation, and assembly construction phases. Liu [29] divided the materialization stage into prefabricated component production and processing, logistics and transportation, and on-site construction and installation stages, and then carried out carbon footprint analysis. Ma [30] calculated the carbon footprint after looking at the variables influencing the greenhouse gas emissions of completed structures during the various phases of industrial manufacturing, transportation and shipping, and assembly construction. Wang [31] established a carbon emission model for metro civil engineering to quantify the carbon emissions in each physical stage.

Scholarly investigations on assembled houses have progressively garnered prominence, coinciding with the rapidly expanding assembled building industry in China. When deciding the border of the carbon footprint calculation, the majority of academics employ all facets of the life cycle philosophy to compute carbon emissions for the whole life cycle of assembled houses. They neglect to take into account the fact that the materialization stage, which is a critical stage in determining carbon emissions, can roughly replace the entire life cycle while lowering the computation amount. Subsequent examination of the literature reveals that the materialization phase can be further subdivided into the following: the building material production phase, the conveyance of building materials phase, the component manufacturing phase, the component phase of transportation, and the building phase.

2.3. Carbon Footprint Impact Factors

Regarding the impact factors of the carbon footprint, Li [32] employed structural equation modeling to examine the pertinent influencing components and adopted the carbon dioxide emission factor approach to account for greenhouse gas emissions throughout the assembly construction civilization phase. Shang [33] utilized BIM technology to achieve the completion of the building's carbon balance. Before building the corresponding BIM model, the influencing variables for material mobility were identified. Using BIM technology, these factors were categorized, which allowed for the resolution of the issues of inadequate carbon storage and inadequate carbon balance following carbon balance. Zhao [34] identified 23 factors affecting carbon emissions of assembled buildings and calculated the importance of these factors and their relationship with each other using the DEMATEL-ISM model. Ding [35] used the DPSIR model to construct an assessment system for the factors affecting carbon emissions of assembled buildings, which included identifying drivers, applying pressure, observing the state, evaluating the impact, and taking response measures. Then, the improved TOPSIS model was applied to empirically study the carbon emission-influencing factors of assembled buildings in Jilin province. To examine the greenhouse gas -financing elements of assembled buildings in various stages, Wang [36] separated the building into five stages, such as deciding, arranging, and construction, based on every phase of the cycle. Zheng [37] utilized the entropy weight method in conjunction with explanatory structural modeling to determine the primary factors influencing the greenhouse gas emissions of assembled buildings. The carbon dioxide emissions factors of formed buildings were examined from five perspectives, including social, economic, demographic, and environmental, to promote the environmentally conscious growth of collected buildings. Ding [38] took prefabricated components as the research object, established four core factor models, including policy, market, technology, and design, and used structural equation modeling to reveal the relationship between prefabricated components that are jointly influenced by multiple factors. Zhan [39] focused on the choice of components during the manufacturing phase of construction supplies, the use of energy, the storage of materials, and the emission of carbon dioxide, and proposed six fundamental assumptions. He used an empirical analysis and a review of the literature to study the construction and development of an apartment building in Beijing. Then, using structural equation modeling, the many variables that assembly buildings are subjected to during the building material production stage were theoretically justified. Du [40] In this paper, structural equation modeling is used to explore the key factors affecting carbon emissions from a supply chain perspective. Jiang [41] examined the primary causes of carbon dioxide emissions from the standpoint of stratified variability using an improved geodetic sensor tool.

Most scholars have studied the factors affecting carbon emissions either from the perspective of the entire construction industry, from the whole life cycle of a building, or from the operation stage. There are relatively limited studies on the factors that influence carbon emissions during the materialization stage, although this stage has the highest amount of carbon dioxide emissions throughout the building lifespan cycle. Without taking into account additional effects connected to carbon sources, most of the current research on the topic uses carbon emissions in both the physical and chemical phases to calculate the main impact factors.

3. Materials and Methods

3.1. Carbon Footprint Accounting Boundaries and Pathways

In this paper, we mainly account for the carbon footprint of the materialization stage of prefabricated housing, so we divide the materialization stage into four stages, namely, the processes involved in the building material production phase, conveyance of building materials phase, component manufacturing phase, component phase of transportation, and the building phase, as shown in Figure 2.

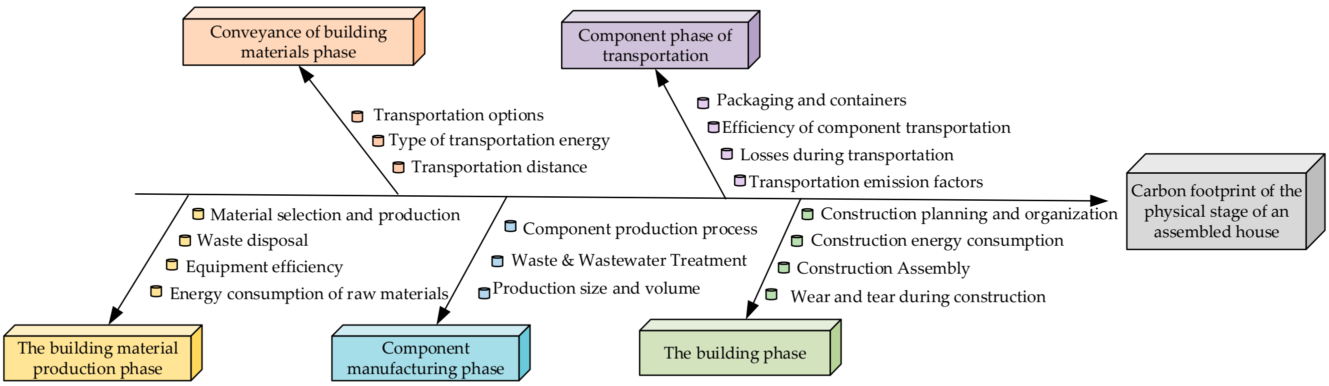

Figure 2. Cause-and-effect diagram for a carbon footprint.

3.2. Model of Accounting for Carbon Footprint in the Materialization Stage of Prefabricated Housing

CO_2 emissions make up the majority of the carbon footprint associated with the assembly phase of prefabricated structures. For this research, the carbon dioxide footprint is characterized as the amount of CO_2 emissions. Using the carbon emission coefficient approach and system boundary setup, the carbon dioxide and greenhouse gas emissions of the prefabricated building assembly phase were calculated.

$$E_c = E_{c1} + E_{c2} + E_{c3} + E_{c4} + E_{c5} \tag{1}$$

In Equation (1), E_c is the total carbon footprint, and E_{c1}, E_{c2}, E_{c3}, E_{c4}, E_{c5} are the carbon emissions of the building material production phase, conveyance of building materials phase, component manufacturing phase, component phase of transportation, and the building phase, respectively.

$$E_{c1} = \sum_{i=1}^{n} Q_i \bullet F_i \tag{2}$$

In Equation (2), Q_i represents the total mass of the i material and F_i represents the emission factor of the i material.

$$E_{c2} = \sum_{j=1}^{m} \left(\sum_{i=1}^{n} D_{i,j} \times Q_i \right) \times F_j \tag{3}$$

In Equation (3), The number of ways to carry construction supplies is represented by the symbol m, and $D_{i,j}$ denotes the transportation distance of transporting material i using transportation mode j. F_j represents the factor of carbon dioxide emissions for transportation mode j.

$$E_{c3} = \sum_{h=1}^{s} \sum_{g=1}^{r} \left(E^1_{g,h} \times V_g \right) \times F_h + \sum_{g=1}^{r} \left(L^1_g \times V_g \right) \times F_L \tag{4}$$

In Equation (4), r is the number of types of prefabricated components produced, S is the number of types of energy consumed, $E^1_{g,h}$ is the consumption of energy h for the production of prefabricated components g per unit volume, V_g is the volume of prefabricated components g, F_h is the carbon emission factor for energy h, L^1_g is the consumption of labor for the production of prefabricated components g, and F_L is the carbon emission factor for the activities of personnel.

$$E_{c4} = \sum_{j=1}^{p} \left(\sum_{g=1}^{r} D_{g,j} \times Q_g \right) \times F_j \tag{5}$$

In Equation (5), p is the number of types of modes of transportation used to transport the component to the construction site, $D_{g,j}$ is the distance transported by transporting the component g by mode j, and Q_g is the total mass of the g component.

$$E_{c5} = \sum_{h=1}^{w} \sum_{g=1}^{r} \left(E^2_{g,h} \times V_g \right) \times F_h + \sum_{g=1}^{r} \left(L^2_g \times V_k \right) \times F_L \tag{6}$$

In Equation (6), w is the number of energy types consumed, $E^2_{g,h}$ is the consumption of energy h for the construction of a unit volume of prefabricated g components, V_g is the volume of prefabricated g components, and L^2_g is the labor consumption for the construction of prefabricated g components.

3.3. A Model for Assessing the Impact Factors of Carbon Footprint Accounting in the Materialization Phase of Prefabricated Housing

In order to make clear the connections between the elements that influence the carbon footprint of prefabricated housing during the materialization stage, as well as the extent to which each component influences the carbon footprint of assembled houses during this stage, in this study, we propose to use the DEMATEL-ISM-MICMAC approach to build a model of the factors impacting the carbon footprint during this stage of prefabricated housing. First, we asked 12 experts from colleges and universities, design institutes, prefabricated component factories, and construction companies to screen the initial influencing factors and derive the indicator system based on the data and indicator system required by the DEMATEL-ISM-MICMAC method. Next, we invited 20 scholars of assembled buildings and carbon footprint researchers to score the indicators and derive the raw data. Additionally, then the DEMATEL method will be employed to determine the centrality and causality of each influencing factor. Secondly, the contextual link between the influencing factors provided the basis for the structural self-interaction matrix (SSIM), which was then transformed by SSIM to obtain the reachability matrix. Additionally, an ISM recursive model of influencing factors will be established to provide a structured representation of these disordered factors. Finally, based on the reachability matrix, the MICMAC model of influencing factors will be developed, and the driver-dependency diagram for each influencing factor will be generated. Each influencing factor will be categorized and analyzed based on its characteristics. Specific steps are illustrated in Figure 3.

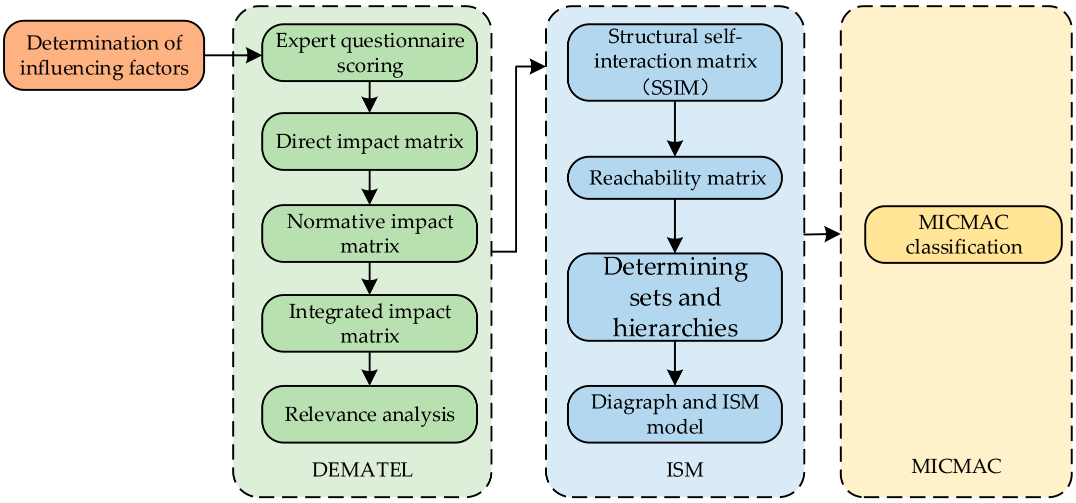

Figure 3. Impact factor assessment process.

3.3.1. Construction of an Indicator System for Impact Factors

Using the Web of Science and China Knowledge Network databases, the terms "prefabricated housing" and "carbon footprint" were first searched. Twenty-four influencing elements were first found concerning the physical stage of assembled houses, which were broken down into five dimensions. Second, twelve experts from prefabricated component factories, construction companies, design institutes, and universities were provided with the opportunity to screen the preliminary indicators of influencing factors using the Delphi method. Information on the group of experts is shown in Table 1.

Table 1. Specialist information.

Expert Type	Work Unit	Title	Access Time	Access Mode
Faculty Specialist A	Tongji University	Professor	November 2022	E-mail
Faculty Specialist B	Beijing Jiaotong University	Professor	November 2022	E-mail
Faculty Specialist C	Nanchang University	Professor	November 2022	On-site
Faculty Specialist D	East China Jiaotong University	Professor	November 2022	On-site
Operations Manager E	Jinhui Construction Group Co.	Senior Engineer	December 2022	On-site
Operations Manager F	China Construction 5th Engineering Bureau	Senior Engineer	December 2022	E-mail
Operations Manager G	China Construction 3rd Engineering Bureau	Senior Engineer	December 2022	On-site
PC Plant Manager H	Pinson New Building Materials Co.	Senior Engineer	December 2022	Telephone interview
PC Plant Manager I	Tonghua Building Materials Technology Co.	Senior Engineer	January 2023	Telephone interview
Operations Manager J	Housing and Urban-Rural Development Bureau	Senior Engineer	January 2023	On-site
PC Transportation Manager K	China Railway 25th Bureau Group	Senior Engineer	January 2023	E-mail
PC Transportation Manager L	Liouhe Xunjie Logistics Co.	Senior Engineer	January 2023	E-mail

After several rounds of discussion and research by the expert group, 18 influencing factors were identified, and an indicator system of carbon footprint-influencing factors for assembled housing was established, as shown in Table 2.

Table 2. Indicator system for the elements that affect the prefabricated home industry's ability to materialize its carbon footprint.

Dimension of Analysis	Factors	Explanation
The building material production stage	Material selection and production S_1	Different building materials have different carbon footprints. Choosing materials with a lower carbon footprint, such as recycled materials or low-carbon concrete, can reduce a building's carbon footprint.
	Waste disposal S_2	Waste materials generated during production and construction need to be disposed of. Proper waste management can reduce adverse environmental impacts, including carbon emissions.
	Equipment efficiency S_3	The energy efficiency and effectiveness of equipment used in the production and processing of building materials affect carbon emissions. The use of efficient equipment and tools can reduce energy consumption and carbon emissions.
	Energy consumption of raw materials S_4	The production and processing of construction raw materials requires energy, including electricity and fuel. The use of electricity from renewable sources and production processes that optimize energy consumption can reduce energy-related carbon emissions.
Conveyance of building materials phase	Transportation tool selection S_5	Different types of transportation generate different levels of carbon emissions. Choosing low-carbon means of transportation, such as electric vehicles and efficient trucks, can reduce carbon emissions during transportation.
	Type of transportation energy S_6	The use of different types of fuels or energy sources can also affect carbon emissions. Choosing to use renewable energy or low-carbon fuels can reduce carbon emissions during transportation.
	Transportation distance S_7	Longer transportation distances lead to more fuel consumption and carbon emissions. Optimizing the supply chain, choosing manufacturers close to construction sites, and reducing transport distances can reduce carbon emissions.
Component manufacturing phase	Component production process S_8	Different production processes can have an impact on carbon emissions. Some production processes may require high temperatures or chemical treatments, which can lead to higher carbon emissions.
	Waste and wastewater treatment S_9	The production of prefabricated components may generate waste materials and wastewater, and additional carbon emissions may be generated during the treatment and disposal of these wastes.
	Production size and volume S_{10}	Large-scale production may be more efficient than small-scale production, and appropriate mass production can reduce carbon emissions per component.
Components' phase of transportation	Packaging and containers S_{11}	Packaging and containers for precast components also affect carbon emissions. Excessive packaging increases energy consumption and waste generation, and choosing lightweight packaging materials can reduce carbon emissions.
	Efficiency of component transportation S_{12}	The efficiency of transportation has a direct impact on carbon emissions. Carbon emissions can be reduced by adopting rational transportation plans and routes to avoid unnecessary delays and waiting.
	Losses during transportation S_{13}	During transportation, building materials may be subject to wear and tear due to shocks and vibrations. This may result in the need for additional production and transportation, thus increasing carbon emissions.
	Transportation emission factors S_{14}	Emissions from transportation are also an important factor. For example, the emission standards and technical status of trucks and transport vehicles affect the level of carbon emissions.

Table 2. *Cont.*

Dimension of Analysis	Factors	Explanation
The building phase	Construction planning and organization S_{15}	Unreasonable construction planning and organization may lead to unnecessary duplication of work, additional energy consumption, and carbon emissions.
	Construction energy consumption S_{16}	On-site construction requires the use of energy, such as electricity and fuel, for mechanical equipment, lighting, heating, cooling, and so on. The use of non-renewable energy sources has a corresponding carbon footprint.
	Construction Assembly S_{17}	Assembly of prefabricated components is a critical process in the construction of assembled buildings, affecting the schedule and accuracy [42].
	Wear and tear during construction S_{18}	Losses may occur during on-site construction, such as wasted materials, energy, and time, which may result in the need for additional resources and energy, thus increasing carbon emissions.

3.3.2. DEMATEL-ISM-MICMAC Analysis

DEMATEL can visualize the complex relationships among the elements using icons, matrix tools, and scatter plots to clarify the importance of each element to the whole system. ISM is mainly used to summarize the binary relationships among the factors and explain the system hierarchy using concept mapping-directed topology diagrams. System elements are categorized using MICMAC analysis; in this paper, the MICMAC model of influencing factors is constructed based on the reachability matrix, the driving force-dependency diagram of each influencing factor is obtained, and each influencing factor is categorized and analyzed based on its features.

The following is the precise process of investigating carbon footprint-influencing variables during the materialization stage of prefabricated housing utilizing the DEMATEL-ISM-MICMAC approach.

Step 1. Using the system of carbon footprint-influencing elements in the materialization stage of prefabricated housing derived using the Delphi method, the direct impact relationship matrix is determined:

$$B = \left[b_{ij}\right]_{n\times n} \tag{7}$$

Step 2. Normalizing the matrix B yields the matrix C, such that C_{ij} lies in the interval [0, 1].

$$C = \frac{B}{\max_{(1\le i\le n)} \sum_{j=1}^{n} b_{ij}} \tag{8}$$

Step 3. The integrated impact matrix is solved to clarify the degree of influence that the influencing factors on the carbon footprint of the materialization phase of the assembled house have on each other, and to calculate the total influence, the category attributes, and the degree of importance of each influencing factor.

$$T = C^1 + C^2 \ldots + C^n = C\frac{I - C^{n-1}}{I - C} \tag{9}$$

where I is the unit matrix, and since C_{ij} lies in the interval [0, 1], $C^{n-1}\ n \to 0$ as $n \to \infty$. Therefore,

$$T = C(I - C)^{-1} \tag{10}$$

Step 4. In solving the structural self-interaction matrix (SSIM), by contrasting the elements with one another, a relationship between variables S_i and S_j is established. This indicates that it is unclear if S_i influences S_j, or vice versa, in terms of the relationship's importance. As seen in Table 3, we employed four notations to determine the contextual link between the two sub-variables (S_i and S_j) under investigation.

Table 3. ISM symbols for describing interrelationships between factors.

Symbolic	Connotation
O	Factor S_i and factor S_j are mutually unrelated.
X	Factor S_i and a reciprocal effect on factor S_j.
V	Factor S_i has a direct effect on factor S_j.
A	Factor S_j has a direct effect on factor S_i.

Step 5. In solving the reachability matrix F, which is created by extracting the reachability matrix from SSIM, the reachability matrix represents the final relationship between variables in binary form. The binary numbers 0 and 1 take on the role of the numerous relationships between variables that were formerly represented by the symbols V, A, X, and O in SSIM. The reachability matrix F can be obtained by applying the following criteria to the SSIM variables V, A, X, and O. The detailed steps may further be found in paper [43,44].

- If the SSIM's (S_i, S_j) entry is 'V', the reachability matrix's (S_i, S_j) entry becomes 1, and the (S_j, S_i) entry becomes 0.
- If the SSIM's (S_i, S_j) entry is 'A', the reachability matrix's (S_i, S_j) entry becomes 0, and the (S_j, S_i) entry becomes 1.
- If the SSIM's (S_j, S_i) entry is 'X', the reachability matrix's (S_i, S_j) entry becomes 1, and the (S_j, S_i) entry similarly becomes 1.
- If the SSIM's (S_i, S_j) entry is 'O', the reachability matrix's (S_i, S_j) entry becomes 0, and the (S_j, S_i) entry similarly becomes 0.

Step 6. $R(S_i)$ refers to the reachability set of S_i and $A(S_i)$ represents the antecedent set of S_i. The reachability set $R(S_i)$, the antecedent set $A(S_i)$, and the intersection set are identified through the reachability matrix F, and the matrix is hierarchically processed to construct a multilevel recursive structural model of the carbon footprint-influencing factors in the materialization stage of prefabricated housing.

$$R(S_i) \cap A(S_i) = R(S_i) \tag{11}$$

Step 7. The dependency and driving force are plotted. Equations (12) and (13) are applied to obtain the driving force and dependency of the matrix.

$$D_j = \sum_{j=1}^{n} a_j^m, (j = 1, 2, 3, \ldots, n) \tag{12}$$

$$R_j = \sum_{i=1}^{n} a_j^m, (j = 1, 2, 3, \ldots, n) \tag{13}$$

where a_{ij}^m is the i row and j column element of the reachability matrix F; D_i is the i row sum of the reachability matrix F, and R_j is the j column sum of the reachability matrix F.

4. Case Study

4.1. Project Synopsis

The project's location is depicted in Figure 4, and the study's sample was the assembled dwelling No. 4 of that project in Cixi, Ningbo City. The concrete shear barrier structure of this 28-story residential building has a total floor area of 12,389.71 square meters and a height of 84.4 m. This residential building is a high-rise residential building, of which floors 5–28 are standard floors. The assembly rate is 43%. It should be noted that the first floor is used as a garage, the impact of which is not considered in this study.

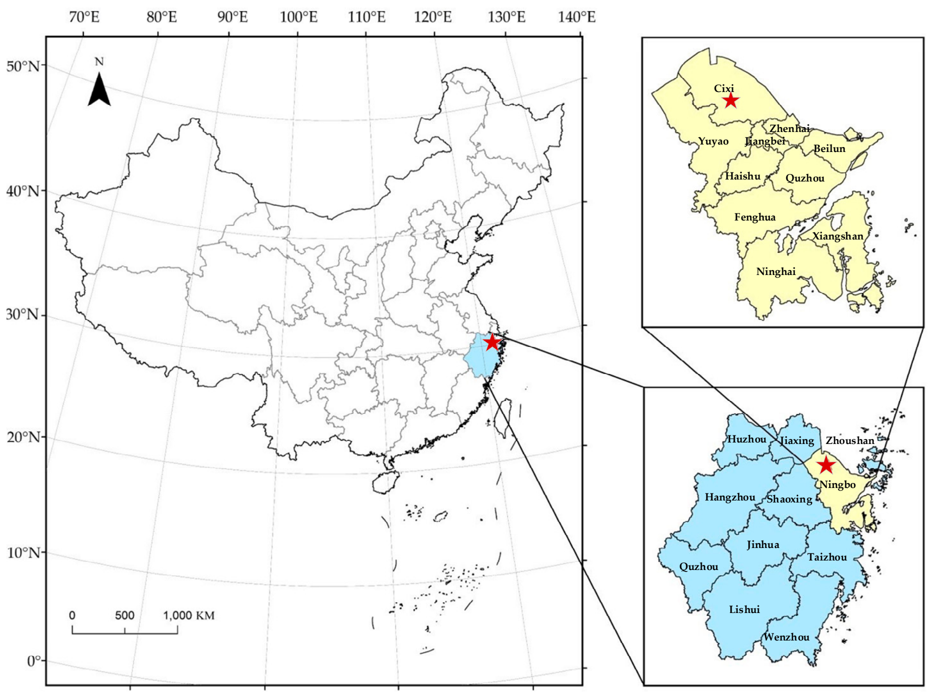

Figure 4. Geographic location of Cixi City.

4.2. Carbon Footprint Accounting

Equations (1)–(6) are used to compute each stage's carbon footprint. The results are shown in Table 4.

Table 4. Carbon footprint.

Point	Carbon Footprint/kg CO_2	Percentage
The building material production stage	4,005,935.99	88.24%
Conveyance of building materials phase	60,011.38	1.28%
Component manufacturing phase	18,451.3	0.39%
Components' phase of transportation	30,118.57	0.64%
The building phase	442,508.31	9.45%
Overall amount	4,683,025.55	100%

About 4.68×10^6 kg CO_2 was produced during the physical phase of this example, resulting in a 377.98 kg CO_2 carbon footprint on each square meter of floor surface. Construction material production and processing had the largest carbon footprint, followed by on-site construction, building material transportation, prefabricated component transportation, and prefabricated element processing. Upon examining solely the carbon footprint accounting of the materialization stage, we discovered that the manufacture and processing of building materials are the primary targets for reducing carbon emissions. The reinforcement of concrete and steel, two common building materials, currently accounts for each of the top two greenhouse gas emissions.

4.3. Carbon Footprint Influence Factor Analysis Based on DEMATEL-ISM-MICMAC

This study classifies the influential factors and assigns an assessment to each one. Five levels are identified for $S_i(i = 1, 2, \ldots, 4)$, and the values 0 to 4 assigned to each level quantitatively represent the degree of influence between the factors: 0 represents a very small influence, 1 represents a small influence, 2 represents a moderate influence, 3 represents a large influence, and 4 represents a very large influence. We invited 20 scholars and carbon footprint researchers in the field of assembled buildings to participate in scoring the influencing factors, comparing the influence of one factor on another, and evaluating the correlation between the carbon footprint factors of assembled homes. The arithmetic mean method was used to average expert scores and create an initial impact matrix for carbon footprint factors in assembled homes.

4.3.1. Analysis of DEMATEL Results

Applying Equations (9) and (10) to the direct impact matrix derived from the experts' scores yields an integrated impact matrix T, as shown in Table 5.

Table 5. The integrated impact matrix T.

Factors	S_1	S_2	S_3	S_4	S_5	S_6	S_7	S_8	S_9	S_{10}	S_{11}	S_{12}	S_{13}	S_{14}	S_{15}	S_{16}	S_{17}	S_{18}
S_1	0	2	0	0	1	2	0	0	0	3	2	0	0	0	0	0	0	0
S_2	0	0	0	0	0	3	0	0	0	0	3	1	1	0	0	1	0	0
S_3	3	3	0	0	3	3	2	1	1	1	4	1	2	0	0	0	0	0
S_4	3	3	1	0	4	3	3	4	3	3	3	3	3	0	0	2	3	2
S_5	3	4	1	0	0	4	3	2	3	1	2	0	2	0	0	1	0	0
S_6	0	3	0	0	0	0	0	0	0	0	2	1	1	0	0	1	0	0
S_7	3	3	0	0	4	3	0	2	4	1	2	0	2	0	0	3	0	2
S_8	2	2	0	2	4	2	4	0	3	3	2	0	2	0	0	3	1	0
S_9	2	0	0	0	2	0	2	0	0	3	1	1	0	0	0	0	0	0
S_{10}	4	0	0	0	0	0	0	0	0	0	1	0	3	0	0	3	3	0
S_{11}	3	4	1	0	2	4	3	1	1	0	0	1	2	0	0	1	0	2
S_{12}	0	2	0	0	0	3	0	0	0	0	0	0	3	0	0	0	0	0
S_{13}	0	1	0	0	0	1	1	0	0	0	0	1	0	0	0	3	0	0
S_{14}	2	2	0	0	1	2	0	0	0	0	3	0	3	0	0	2	1	0
S_{15}	2	3	1	4	3	3	3	4	3	1	2	3	1	0	0	4	1	2
S_{16}	2	2	0	0	3	2	2	0	0	0	2	0	3	0	0	0	0	1
S_{17}	1	1	0	3	1	1	3	3	1	1	0	0	0	0	0	3	0	4
S_{18}	3	3	0	0	3	3	4	0	2	0	1	3	1	0	0	2	3	0

The integrated impact matrix T was processed using MATLAB R2022b software to determine the degree of influence, degree of being affected, causality, and centrality. The centrality was then ranked. As shown in Table 6.

Table 6. Calculation results of influence, cause and centrality of impact factors, and centrality ranking.

Factors	Degree of Influence	Degree of Being Affected	Causality	Centrality	Centrality Ranking
S_1	0.361	1.261	−0.900	1.622	10
S_2	0.319	1.555	−1.235	1.874	5
S_3	0.894	0.154	0.740	1.048	16
S_4	1.675	0.264	1.412	1.939	4
S_5	0.949	1.158	−0.209	2.107	3
S_6	0.277	1.588	−1.311	1.866	6
S_7	1.085	1.130	−0.045	2.215	1
S_8	1.198	0.585	0.612	1.783	7
S_9	0.430	0.797	−0.367	1.227	14
S_{10}	0.512	0.664	−0.152	1.176	15
S_{11}	0.922	1.202	−0.280	2.123	2
S_{12}	0.238	0.551	−0.313	0.789	17
S_{13}	0.252	1.136	−0.884	1.388	13
S_{14}	0.574	0.000	0.574	0.574	18
S_{15}	1.657	0.000	1.657	1.657	9
S_{16}	0.641	1.110	−0.468	1.751	8
S_{17}	0.996	0.391	0.605	1.388	12
S_{18}	1.048	0.485	0.563	1.534	11

The centrality–causality diagram is depicted according to Table 6 (Figure 5).

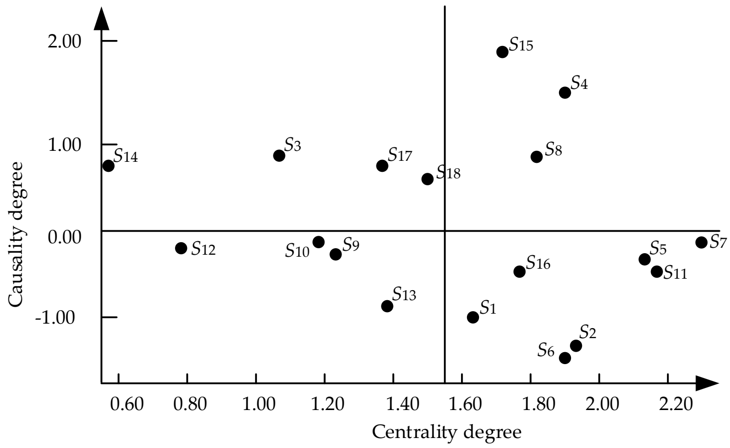

Figure 5. Centrality–causality degree diagram.

(1) Regarding the extent of impact, the top three factors are raw material energy consumption (S_4), construction planning and organization (S_{15}), transportation energy type (S_6), and waste disposal (S_2). This indicates that these three factors have the greatest importance in influencing the other factors.
(2) In terms of centrality, the three factors of transportation distance (S_7), packaging and containers (S_{11}), and transportation tool selection (S_5) have larger values of centrality. Therefore, the carbon footprint in the materialization stage of prefabricated housing should focus on the management of building material transportation.
(3) The causal factors are, in descending order, construction planning and organization (S_{15}), raw material energy consumption (S_4), packaging and containers (S_{11}), component production process (S_8), construction assembly (S_{17}), transportation emission factors (S_{14}), and losses during construction (S_{18}). These factors are the causal factors in the carbon footprint of the materialization phase of the assembled house, and should be given high priority. Among them, packaging and containers (S_{11}) belong to the prefabricated component processing stage, demonstrating that the carbon footprint of the materialization stage of constructed dwellings depends on packaging and containers.
(4) The top three resultant factors are material selection and production (S_1), waste disposal (S_2), and type of energy transportation (S_6), suggesting that at the materialization stage of completed houses, these three parameters are more likely to be modified by other aspects in the carbon footprint process.

4.3.2. Analysis of ISM Results

The contextual interactions among the identified carbon footprint-influencing variables may vary in degree. The contextual linkages between the carbon footprint-influencing elements yield SSIMs in accordance with step 4 of the ISM technique. Such links can be detected using ISM in order to derive a relationship model. According to expert comments and the impact of each piece on the other, contextual linkages are created.

For example, factor S_1 ("material selection and production"), is compared with factor S_{10} ("production size and volume") for their contextual relationship. S_{10} influences S_1, hence the contextual relationship of 'A' is considered. In a similar vein, other contextual linkages can be inferred, and the ensuing matrix can be filled by comparing the carbon footprint influencers S_1–S_{18}. The links between the effects of carbon footprints are displayed in Table 7.

Table 7. Structural self-interaction matrix (SSIM).

Factors	S_{18}	S_{17}	S_{16}	S_{15}	S_{14}	S_{13}	S_{12}	S_{11}	S_{10}	S_9	S_8	S_7	S_6	S_5	S_4	S_3	S_2
Material selection and production S_1	O	O	O	O	O	O	O	A	A	O	O	O	A	A	O	A	A
Waste disposal S_2	O	O	A	O	O	A	A	A	O	O	O	O	A	O	O	A	
Equipment efficiency S_3	O	O	O	O	O	A	A	V	A	A	A	A	V	V	O		
Energy consumption of raw materials S_4	A	A	X	O	O	V	V	V	V	V	V	V	V	V			
Transportation tool selection S_5	O	O	A	O	O	A	O	A	A	A	A	V	V				
Type of transportation energy S_6	O	O	A	O	O	A	A	A	O	O	O	O					
Transportation distance S_7	A	O	V	O	O	A	O	A	A	V	A						
Component production process S_8	O	A	V	O	O	A	O	X	V	V							
Waste and wastewater treatment S_9	O	O	O	O	O	O	A	A	A								
Production size and volume S_{10}	O	A	A	O	O	A	O	A									
Packaging and containers S_{11}	A	O	A	O	O	A	A										
Efficiency of component transportation S_{12}	O	O	O	O	O	A											
Losses during transportation S_{13}	O	O	A	O	O												
Transportation emission factors S_{14}	O	A	A	O													
Construction planning and organization S_{15}	A	A	V														
Construction energy consumption S_{16}	A	O															
Construction Assembly S_{17}	V																
Wear and tear during construction S_{18}																	

The reachable matrix F is formed using the binary numbers '1' and '0'. The different symbols used to represent contextual relationships ('V', 'A', 'X', and 'O') can be replaced by '1' and '0' in accordance with the previously established principles, as outlined in step 5. The reachability matrix F is shown in Table 8.

Table 8. The reachability matrix F.

Factors	S_1	S_2	S_3	S_4	S_5	S_6	S_7	S_8	S_9	S_{10}	S_{11}	S_{12}	S_{13}	S_{14}	S_{15}	S_{16}	S_{17}	S_{18}
S_1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
S_2	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
S_3	1	1	1	0	1	1	0	0	0	0	1	0	0	0	0	0	0	0
S_4	1	1	0	1	1	1	1	1	1	1	1	1	1	0	0	1	0	0
S_5	1	1	0	0	1	1	1	0	0	0	0	0	0	0	0	0	0	0
S_6	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
S_7	1	1	0	0	1	1	1	0	1	0	0	0	0	0	0	1	0	0
S_8	1	1	0	0	1	1	1	1	1	1	1	0	0	0	0	1	0	0
S_9	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0
S_{10}	1	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0
S_{11}	1	1	0	0	0	1	1	0	0	0	1	0	0	0	0	0	0	0
S_{12}	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0
S_{13}	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0
S_{14}	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0
S_{15}	1	1	0	1	1	1	1	1	1	0	1	1	0	0	1	1	0	0
S_{16}	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0
S_{17}	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1	1	1
S_{18}	1	1	0	0	1	1	1	0	0	0	0	0	0	0	0	0	0	1

The reachability series, the antecedent set, and the intersection set are determined from the reachability matrix F, as shown in Table 9.

To establish the carbon footprint influence factors of the stage of materialization of the prefabricated housing hierarchy framework, as depicted in Figure 6, the reachable matrix f processing is used to obtain the reachability set $R(S_i)$, the antecedent set $A(S_i)$, and the intersection set. Then, Formula (11) is applied based on the outcomes of the hierarchy's priority division to collect five layers.

Table 9. Collection list.

Factors	Reachability Set	Antecedent Set	Intersection Set
S_1	1	1,3,4,5,7,8,10,11,15,18	1
S_2	2	2,3,4,5,7,8,11,15,18	2
S_3	1,2,3,5,6,11	3	3
S_4	1,2,4,5,6,7,8,9,10,11,12,13,16	4,15	4
S_5	1,2,5,6,7	3,4,5,7,8,15,18	5,7
S_6	6	3,4,5,6,7,8,11,15,18	6
S_7	1,2,5,6,7,9,16	4,5,7,8,11,15,17,18	5,7
S_8	1,2,5,6,7,8,9,10,11,16	4,8,15	8
S_9	9	4,7,8,9,15	9
S_{10}	1,10	4,8,10	10
S_{11}	1,2,6,7,11	3,4,8,11,15	11
S_{12}	12	4,12,15	12
S_{13}	13	4,13	13
S_{14}	14	14	14
S_{15}	1,2,4,5,6,7,8,9,11,12,15,16	15	15
S_{16}	16	4,7,8,15,16,17	16
S_{17}	7,16,17,18	17	17
S_{18}	1,2,5,6,7,18	17,18	18

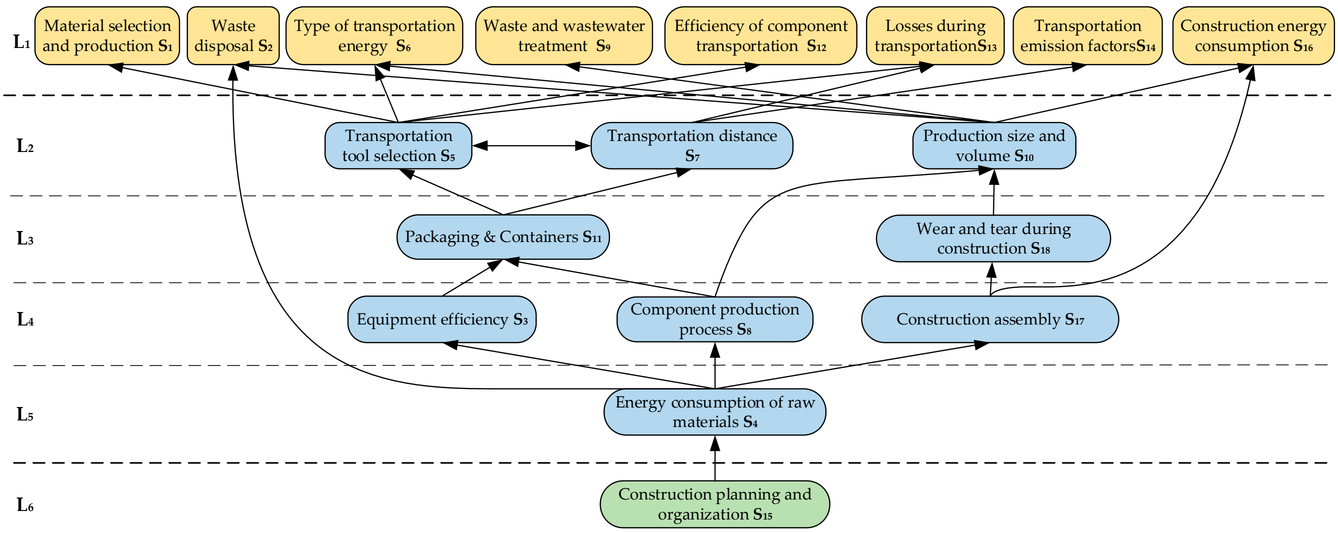

Figure 6. ISM recursive structure diagram of carbon footprint-influencing factors in the materialization stage of prefabricated housing.

(1) L6 belongs to the deep-level factor, which should pay great attention to construction planning and organization (S_{15}).

(2) L1 belongs to the shallow sub-factors, and the issues at this level primarily pertain to the delivery of prefabricated components and the production and processing of construction materials, indicating that these two phases will directly affect the manufactured home's carbon footprint.

(3) L2 to L4 belong to the middle-level factors, and they will have an impact on the shallower-level factors. Among them, transportation tool selection (S_5) and transportation distance (S_7) have a strong correlation. Therefore, in the greenhouse gas emissions investigation of the materialization stage of prefabricated housing, it is imperative to enhance the handling of building material transportation in order to reduce the carbon emissions of the building process.

4.3.3. Analysis of MICMAC Results

Based on the reachability matrices, the drivers and dependencies of the matrices were obtained using the application of Equations (12) and (13) (Table 10).

Table 10. Drivers and dependencies table.

Factors	Driving Force	Dependency
S_1	1	10
S_2	1	9
S_3	6	1
S_4	13	2
S_5	5	7
S_6	1	9
S_7	7	8
S_8	10	3
S_9	1	5
S_{10}	2	3
S_{11}	5	5
S_{12}	1	3
S_{13}	1	2
S_{14}	1	1
S_{15}	12	1
S_{16}	1	6
S_{17}	4	1
S_{18}	6	2

Dependency versus driver graphs were plotted according to Table 10 (Figure 7).

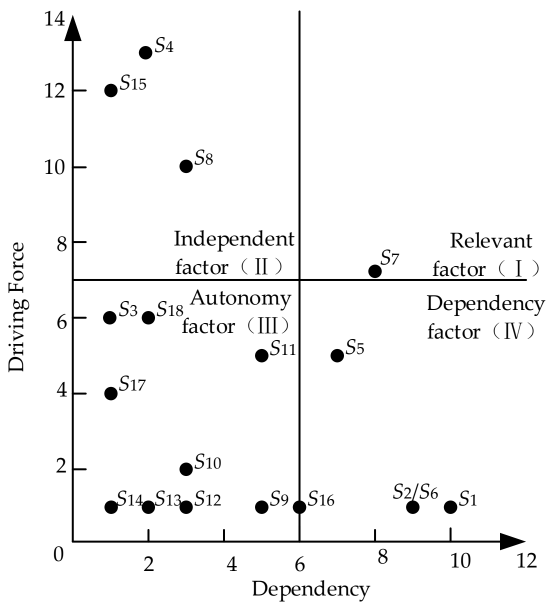

Figure 7. MICMAC classification chart of carbon footprint-influencing factors in the materialization phase of prefabricated housing.

(1) As illustrated in Figure 7, the first quadrant belongs to the correlation factors; only transportation distance (S_7) is on the border of the correlation and dependence factors, with a high driving force and a high degree of dependence, indicating that this factor has a considerable influence on the carbon footprint of the physical stage of prefabricated housing, but it is also susceptible to the influence of other factors. It is an unstable factor, and its change will cause strong changes in other factors in the system.

(2) the energy consumption of raw materials (S_4), component production process (S_8), and construction planning and organization (S_{15}) are located in the second quadrant, indicating that they have a high degree of drive and a low degree of dependence and are independent factor sets.
(3) These elements become the deep core factors driving the carbon footprint of the physical phase of constructed homes because they have a large impact on the other variables while being less impacted by them; the third quadrant belongs to the autonomous factors of equipment efficiency (S_3), waste and wastewater treatment (S_9), production size and volume (S_{10}), packaging and containers (S_{11}), efficiency of component transportation (S_{12}), losses during transportation (S_{13}), transportation emission factors (S_{14}), construction assembly (S_{17}), and wear and tear during construction (S_{18}). These are nine factors with low dependency and driving force, and although relatively independent, they directly affect the carbon footprint of the stage at which prefabricated housing is objectified, and are influential factors that cannot be ignored.
(4) The fourth quadrant belongs to dependent factors, including material selection and production (S_1), waste disposal (S_2), transportation tool selection (S_5), type of transportation energy (S_6), and construction energy consumption (S_{16}). They are classified as contingent variables because they are highly dependent on other variables yet lack a strong driving factor. These should be regulated by keeping an eye on changes in other factors that affect the carbon footprint of assembled dwellings as they occur.

5. Discussion

The creation of prefabricated housing is the primary path for potential construction development. As housing makes up a significant portion of a structure, calculating carbon footprints and investigating their effect factors is a crucial step in advancing the development of prefabricated housing. The carbon footprint-influencing factors have been identified in the five stages of the building material production phase, conveyance of building materials phase, component manufacturing phase, component phase of transportation, and the building phase. They are centered on the carbon footprint procedure in the materialization stage of gathered buildings from the perspective of engineering administration, incorporating the distinctive features of the materialization stage, and provide practical engineering initiatives that use the carbon dioxide emission factor approach to calculate carbon footprints. The findings of the real project are in line with the theoretical assessment.

It was discovered that the production and processing of building components primarily determined the objectification phase of the constructed home's carbon footprint. Building professionals will find this study very useful in swiftly identifying the aspects influencing the carbon footprint of prefabricated housing. Furthermore, the research findings can be used to determine priorities for corresponding reductions in emissions, and to direct the development of low-carbon buildings.

The carbon emission factor method, with its easily comprehensible principles and practical data collection, is a rather comprehensive and scientific procedure for accounting for carbon footprints. To determine the centrality and cause and effect of each influential element, the DEMATEL approach is utilized to identify the reasonable connection and degree of importance between the factors. To attempt to expand on the hierarchical arrangement and general connection of carbon dioxide footprint-influencing factors, the combined ISM and MICMAC method is applied to determine the deep essential factors, important over-factors, and project-influencing variables related to carbon footprint in the stage of the materialization of prefabricated housing.

6. Conclusions

The research object for this study's carbon footprint measurement was an apartment complex in Cixi City, Ningbo City, Zhejiang Province, China. The carbon footprint of the residence's materialization stage was calculated using the carbon emission factor method. To find out more about the factors influencing the carbon footprint when the prefabricated dwelling is materialized, the DEMATEL-ISM-MICMAC model was implemented. The study's particular findings are listed below.

(1) For the materialization stage of the prefabricated housing, the carbon footprint of a residential home in Cixi City is calculated using the carbon emission coefficient approach [43]. The carbon footprint of the house throughout its physical phase was approximately 4.68×10^6 kg CO_2, and it was 377.98 kg CO_2 per square meter of floor area. The building material production phase, the building phase, the conveyance of building materials phase, the component phase of transportation, and the component manufacturing phase are the phases in order of their carbon footprint. The stage of building material creation and processing is the key to minimizing carbon emissions, rather than the outputs of attention. At this point, actions can be taken to minimize material waste, such as giving priority to construction materials derived from low-carbon waste or raw materials, enhancing the productivity of manufacturing machinery, and implementing sensible low-carbon waste disposal techniques.
(2) By using DEMATEL analysis, it is determined that three factors—transport distance (S_7), packaging and containers (S_{11}), and transportation tool selection (S_5)—have large centrality values. As a result, the management of building material transport should be the primary focus of the materialization stage of prefabricated housing to minimize its carbon footprint. Construction planning and organization (S_{15}), the energy consumption of raw materials (S_4), packaging and containers (S_{11}), the component production process (S_8), construction assembly (S_{17}), transportation emission factors (S_{14}), and wear and tear during construction (S_{18}) are listed in order of causality. Among these, packing and containers (S_{11}) are associated with the prefabricated element-processing step, suggesting that they are necessary to minimize the environmental impact of the constructed house's materialization stage.
(3) The transportation tool selection (S_5) and transportation distance (S_7) of L2 were found to have a strong correlation using ISM analysis. It was also found that in the carbon footprint assessment of the manufacturing phase of prefabricated housing, the logistics for the transportation of building supplies needed to be strengthened to reduce the carbon emissions connected with the building procedure.
(4) The energy consumption of raw materials (S_4), component production process (S_8), and construction planning and organization (S_{15}) were found to have a strong drive and low reliance, respectively, and were classified as independent factors based on the results of the MICMAC study. They are the primary elements influencing the objectification phase of the prefabricated housing's carbon footprint, having a considerable impact on other aspects while being less influenced by them.

The production and processing of construction materials have the biggest influence on the carbon footprint of the objectification phase of constructed dwellings, according to both the simulation DEMATEL-ISM-MICMAC study of the contributing elements and the carbon footprint measurement of a construction endeavor in Cixi City. Construction planning and organization, equipment efficiency, and material generation and selection can all be emphasized to reduce carbon emissions. Even if the stages of prefabricated component manufacturing and shipping have less of an effect on the materialization stage's carbon footprint, they should not be disregarded. The materialization stage of prefabricated housing has a higher carbon footprint due to several factors, such as the construction assembly process, production scale and number of batches, component transportation packaging, and containers for shipping. These factors must be optimized to achieve carbon emission reduction effects.

It is important to acknowledge the limitations of this study, though. Only 18 influencing factor indications were retrieved for this research's evaluation of the materialization stage of prefabricated housing, which has five sub-stages with influencing variables comprising numerous aspects. It is important that future research take into account the influencing aspects of various materialization stages of prefabricated housing carbon footprints in an all-encompassing manner. Secondly, there are certain difficulties with the tiny sample of real cases in this research. In later research, additional instances are included to confirm the practical implementation of the model. The impact of the experts' preferences and their expertise level on the matrix acquisition results was disregarded when experts were invited to rank the numerous influencing elements in the direct influence matrix acquisition method. Future marking may take into account a mix of subjective and objective methods to address this problem.

Author Contributions: Conceptualization, W.L.; Methodology, W.L. and Q.H.; Funding acquisition, W.L.; Supervision, W.L. and Q.H.; Validation, W.L. and Q.H.; Writing—original draft, Q.H.; Writing—review and editing, W.L. and Q.H. All authors have read and agreed to the published version of the manuscript.

Funding: National Natural Science Foundation of China project (Project number: 72261012); Jiangxi Provincial Social Science "14th Five-Year" Fund Project (Project number: 22GL16); Jiangxi Provincial Department of Education Science and Technology Research Project (Project number: GJJ2200648).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

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: The authors declare no conflict of interest.

References

1. Climate Change 2022: Mitigation of Climate Change. Available online: https://www.ipcc.ch/report/sixth-assessment-report-working-group-3/ (accessed on 9 August 2023).
2. Liu, X.A. Analysis of energy saving and emission reduction benefits and strategy of whole life cycle energy saving and emission reduction of assembled buildings. *Build. Energy Effic.* **2021**, *49*, 70–74.
3. Francesco, C.; Anita, T.; Andrea, A. From Nearly Zero Energy to Carbon-Neutral: Case Study of a Hospitality Building. *Appl. Sci.* **2021**, *11*, 2–29.
4. Wang, M.; Zhou, Z.X.; Feng, M.M.; She, G.J.; Sun, R.Y. Modeling and accuracy validation of CO_2 emission monitoring by actual measurement method for thermal power units. *Coal Chem.* **2022**, *50*, 18–21+33.
5. Jonas, N.; John, H.; Anders, W.; Madeleine, N. Direct and indirect energy use and carbon emissions in the production phase of buildings: An input-output analysis. *Energy* **2007**, *32*, 1593–1602.
6. Meng, F.; Zhang, G.M. Study on carbon emission from wastewater resource utilization by photosynthetic bacteria based on material balance. *Ind. Water Treat.* **2022**, *42*, 74–78.
7. Zhang, R.Z.; Zhang, H.; Hei, R.G.; Ye, H.Y.; Cong, M. Research on the framework and process of automatic carbon emission calculation for dynamic modeling of assembled buildings. *Build. Technol.* **2023**, *54*, 2034–2039.
8. Jiang, Y.D.; Wang, R.Y.; Zheng, J.M. Calculation of Carbon Emission of Assembled Steel Structure Residential Buildings throughout their Lifetime. *Shanghai Energy Conserv.* **2022**, 1105–1111. [CrossRef]
9. Sun, Y.; Li, C. Measurement and analysis of carbon emissions from prefabricated buildings under the transition of new and old kinetic energy. *IOP Conf. Ser. Earth Environ. Sci.* **2021**, *813*, 2–7.
10. Lou, F.; Liu, L.J.; Qin, J.W.; Liu, N. Carbon Emission Calculation and Emission Reduction Optimization Strategies for Assembled Steel-Mixed Combined Structure Buildings. *Constr. Technol.* **2021**, *50*, 65–68+74.
11. Matilainen, P.; Airaksinen, M. A Carbon Footprint of an Office Building. *Energies* **2011**, *4*, 1197–1210.
12. Jeong, Y.; Lee, S.; Huh, J. Estimation of CO_2 emission of apartment buildings due to major construction materials in the Republic of Korea. *Energy Build.* **2012**, *49*, 437–442. [CrossRef]
13. Dodoo, A.; Gustavsson, L. Life cycle primary energy use and carbon footprint of wood-frame conventional and passive houses with biomass-based energy supply. *Appl. Energy* **2013**, *112*, 834–842. [CrossRef]
14. Biswas, K.W. Carbon footprint and embodied energy consumption assessment of building construction works in Western Australia. *Int. J. Sustain. Built Environ.* **2014**, *3*, 179–186. [CrossRef]
15. Sim, J.; Sim, J. The air emission assessment of a South Korean traditional building during its life cycle. *Build. Environ.* **2016**, *105*, 283–294. [CrossRef]
16. Yi, C.; Gwak, H.; Lee, D. Stochastic carbon emission estimation method for construction operation. *J. Civ. Eng. Manag.* **2017**, *23*, 137–149. [CrossRef]
17. Arrigoni, A.; Pelosato, R.; Melià, P.; Gianluca, R.; Sergio, S.; Giovanni, D. Life cycle assessment of natural building materials: The role of carbonation, mixture components and transport in the environmental impacts of hempcrete blocks. *J. Clean. Prod.* **2017**, *149*, 1051–1061. [CrossRef]

18. Kanafani, K.; Magnes, J.; Lindhard, M.S.; Balouktsi, M. Carbon Emissions during the Building Construction Phase: A Comprehensive Case Study of Construction Sites in Denmark. *Sustainability* **2023**, *15*, 10992. [CrossRef]
19. Bonamente, E.; Cotana, F. Carbon and Energy Footprints of Prefabricated Industrial Buildings: A Systematic Life Cycle Assessment Analysis. *Energies* **2015**, *8*, 12685–12701. [CrossRef]
20. Cho, S.; Chae, C. A Study on Life Cycle CO_2 Emissions of Low-Carbon Building in South Korea. *Sustainability* **2016**, *8*, 579. [CrossRef]
21. Tumminia, G.; Guarino, F.; Longo, S.; Ferraro, M.; Cellura, M.; Antonucci, V. Life cycle energy performances and environmental impacts of a prefabricated building module. *Renew. Sustain. Energy Rev.* **2018**, *92*, 272–283. [CrossRef]
22. Dong, L.; Wang, Y.; Li, X.H.; Jiang, B.Y.; Al-Hussein, M. Carbon Reduction Measures-Based LCA of Prefabricated Temporary Housing with Renewable Energy Systems. *Sustainability* **2018**, *10*, 718. [CrossRef]
23. Teng, Y.; Li, K.J.; Pan, W.; Thomas, N. Reducing building life cycle carbon emissions through prefabrication: Evidence from and gaps in empirical studies. *Build. Environ.* **2018**, *132*, 125–136. [CrossRef]
24. Shang, M.; Geng, H. A study on carbon emission calculation of residential buildings based on whole life cycle evaluation. *E3S Web Conf.* **2021**, *261*, 04013. [CrossRef]
25. Gao, Y.; Li, Z.D.; Zhang, H.; Yu, B.; Wang, J.Y. Carbon emission analysis of the whole process of assembly building construction based on LCA. *J. Eng. Manag.* **2018**, *32*, 30–34.
26. Zheng, X.Y.; Xu, J.X. LCA-based research on carbon emission in the whole life cycle of assembled buildings—Light steel assembled integrated villa in Chongqing City as an example. *Build. Econ.* **2019**, *40*, 107–111.
27. Tavares, V.; Lacerda, N.; Freire, F. Embodied energy and greenhouse gas emissions analysis of a prefabricated modular house: The "Moby" case study. *J. Clean. Prod.* **2019**, *212*, 1045–1053. [CrossRef]
28. Gao, X.; Zhu, J.J.; Xu, S.T. A case study on carbon footprint measurement of assembled monolithic concrete buildings at the chemicalization stage. *Build. Energy Effic.* **2020**, *48*, 131–137.
29. Liu, Y. Carbon Emission Measurement Research on the Stage of Assembled Building Mechanization. *North Build.* **2020**, *5*, 40–43.
30. Ma, W.D.; Sun, D.C.; Deng, Y.S.; Meng, X.Y.; Li, M. Analysis of Carbon Emissions of Prefabricated Buildings from the Views of Energy Conservation and Emission Reduction. *Nat. Environ. Pollut. Technol.* **2021**, *20*, 39–44. [CrossRef]
31. Wang, Y.S.; Yang, X.; Yan, H.; Zhang, Y.; Li, J.F. Measurement of Building Carbon Emissions Based on the Whole Life Cycle—An Example of a Campus Office Building Renovation and Expansion Project in Guangzhou. *J. Eng. Manag.* **2017**, *31*, 19–24.
32. Li, M.M.; Chen, W.G.; Li, L. Research on carbon emission calculation and influencing factors in the stage of assembled building fabrication. *J. Saf. Environ.* **2023**, 1–10. [CrossRef]
33. Shang, C.; Xu, X.; Bao, L.R.; Zhou, T.T. Simulation of Carbon Balanced BIM Models for Life Cycle Carbon Balance of Assembled Buildings. *Comput. Simul.* **2023**, *40*, 267–271.
34. Zhao, Y.; Sun, S.Y.; Liu, L. A study on carbon emission reduction drivers and pathways in assembled buildings. *Constr. Econ.* **2022**, *43*, 90–95.
35. Ding, X.X.; Xu, X.Z.; Wang, Q.; An, X.D. A Study on the Influencing Factors of Carbon Emission of Assembled Buildings Based on DPSIR and Improved TOPSIS Models. *J. Eng. Manag.* **2022**, *36*, 47–51.
36. Wang, J.; Song, Y.J.; Bian, X.R. Analysis of Carbon Emission Influencing Factors of Assembled Buildings under Whole Life Cycle. *Anhui Build.* **2020**, *27*, 146–147.
37. Zheng, Y.H.; Zhang, A.M.; Yu, C.Y.; Hou, L.C.; Yu, L.; Chen, G.L. Research on the Influencing Factors of Carbon Emission of Assembled Buildings Based on ISM-Entropy Weight Method. *Chongqing Build.* **2023**, *22*, 8–11.
38. Ding, X.X.; Xu, X.Z.; Wang, Q. SEM-based study on the influencing factors of carbon emission reduction of prefabricated components for assembled buildings. *Build. Energy Effic.* **2023**, *51*, 123–128.
39. Zhan, Z.J.; Xia, P.; Xia, D.T. Study on Carbon Emission Measurement and Influencing Factors for Prefabricated Buildings at the Materialization stage Based on LCA. *Sustainability* **2023**, *15*, 13648. [CrossRef]
40. Du, Q.; Pang, Q.Y.; Bao, T.N.; Guo, X.Q.; Deng, Y.G. Critical factors influencing carbon emissions of prefabricated building supply chains in China. *J. Clean. Prod.* **2020**, *280*, 124398. [CrossRef]
41. Jiang, X.T.; Wang, Q.; Li, R.R. Investigating factors affecting carbon emission in China and the USA: A perspective of stratified heterogeneity. *J. Clean. Prod.* **2018**, *199*, 85–92. [CrossRef]
42. Chippagiri, R.; Biswal, D.; Mandavgane, S.; Bras, A.; Ralegaonkar, R. Life Cycle Assessment of a Sustainable Prefabricated Housing System: A Cradle-to-Site Approach Based on a Small-Scale Experimental Model. *Buildings* **2023**, *13*, 964. [CrossRef]
43. Qureshi, K.M.; Mewada, B.G.; Alghamdi, S.Y.; Almakayeel, N.; Qureshi, M.R.N.; Mansour, M. Accomplishing Sustainability in Manufacturing System for Small and Medium-Sized Enterprises (SMEs) through Lean Implementation. *Sustainability* **2022**, *14*, 9732. [CrossRef]
44. Qureshi, K.M.; Mewada, B.G.; Alghamdi, S.Y.; Almakayeel, N.; Mansour, M.; Qureshi, M.R.N. Exploring the Lean Implementation Barriers in Small and Medium-Sized Enterprises Using Interpretive Structure Modeling and Interpretive Ranking Process. *Appl. Syst. Innov.* **2022**, *5*, 84. [CrossRef]