



# Analysis of Carbon Emission Reduction Pathways in the Physicochemical Stage Using the DEMATEL-ISM Method for Prefabricated Building Construction

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**Abstract.** To clarify the longitudinal influence relationships and hierarchical structure among carbon emission reduction driving factors and achieve quantitative analysis, this study first identified 18 carbon reduction drivers through grounded theory methodology across five dimensions: resources and energy, project profile, transportation and warehousing, construction and management, and ecological environment. Subsequently, based on the integrated DEMATEL-ISM approach, a multi-level hierarchical ISM model of carbon reduction drivers during the embodied phase of prefabricated buildings was constructed to determine their hierarchical structure. By analyzing the centrality metrics and weight distributions of these drivers, critical carbon reduction factors were identified, while pathway weights were derived through structural modeling, ultimately establishing key carbon reduction pathways. Finally, an empirical validation was conducted using a prefabricated high-rise residential building project. The results demonstrate that material selection constitutes the pivotal carbon reduction factor, with the pathway "Low-carbon project design → Construction organization optimization → Material selection → Transportation planning → Energy structure adjustment → Dust control" emerging as the most significant implementation route for carbon mitigation.

**Keywords:** Prefabricated building; Physicochemical stage; Grounded theory; Carbon emission reduction path; DEMATEL-ISM model; Carbon emission reduction driver weights ;Path weight

## 1 Introduction

"China Building Energy Consumption Research Report 2023" points out that in 2021, the total energy consumption of the whole building process in China will account for 44.7% of the total energy consumption of the country, and the total carbon emission of the whole building process will account for 47.1% of the national carbon emission<sup>[1]</sup>. In this context, prefabricated buildings have attracted much attention due to their low carbon energy saving and green environmental protection characteristics. According to the 14th Five-Year Plan, by 2025, it is expected that the proportion of prefabricated buildings in new urban buildings will reach 30%<sup>[2]</sup>. However, some scholars have found

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[3-5] that the carbon emissions of prefabricated buildings in the physicochemical stage are relatively concentrated, with high intensity, numerous influencing factors and complex influencing relationships, and significant short-term impacts on the environment.

In the study of carbon emission in the physical and chemical stage of buildings, some scholars mainly adopted carbon emission coefficient method, fuzzy hierarchical comprehensive evaluation method, cloud model, machine learning algorithm, social network analysis method and structural equation model to carry out relevant research on carbon emission measurement, evaluation, prediction and influencing factors. For example, Cao Xi et al.<sup>[6]</sup> used the carbon emission coefficient method to establish a carbon emission calculation model for prefabricated components. Compared with cast-in-place buildings, prefabricated buildings in the physical and chemical stage can reduce carbon emissions by about 7.67kg per unit area. Yu Z et al.<sup>[7]</sup> combined carbon emission factor and energy analysis method to build an Em-CEF accounting model, and calculated and compared carbon emissions in the physical and chemical stages of green material buildings, prefabricated buildings and traditional buildings. Through case studies, they found that the carbon emissions of prefabricated buildings were higher than those of traditional buildings. Li Zhengdao et al.<sup>[8]</sup> adopted the fuzzy hierarchical comprehensive evaluation method to construct the evaluation model of emission reduction efficiency in the physical and chemical stage of modular buildings, and found through case analysis that the consumption of building materials has the most significant impact on carbon emission reduction efficiency. Sun S et al.<sup>[9]</sup> built an assessment model of carbon emission reduction effect in the physical and chemical stage of buildings based on the cloud model, and comprehensively evaluated the carbon reduction effect from the perspective of the building supply chain. Wang Zhiqiang et al.<sup>[10]</sup> established a practical model for calculating carbon emissions in the physical and physical stage of buildings based on machine learning algorithms to help designers predict carbon emissions in the early design stage. Based on the 3E system theory, Rui Z et al.<sup>[11]</sup> used structural equation model to analyze the influencing factors of carbon emission in the physical and chemical stage of prefabricated buildings from five dimensions: government policy, management mode, technical level, economic input and energy structure, and the results showed that management mode had the greatest impact on carbon emission reduction. Liu Jian et al.<sup>[12]</sup> used social network analysis to explore the influencing factors of carbon emissions in the physical and chemical stage of modular integrated buildings from the perspective of stakeholders, identified 11 key influencing factors, and proposed corresponding emission reduction measures. On the basis of calculating carbon emissions, Cheng S et al.<sup>[13]</sup> determined the main factors affecting carbon emissions in the physical and chemical stage of residential buildings by analyzing the carbon emission composition of the model buildings, and proposed corresponding carbon reduction strategies.

In summary, while existing studies have provided some theoretical support for carbon reduction in the embodied phase of prefabricated buildings, research specifically addressing carbon reduction pathways during this phase remains scarce. Furthermore, the methodological framework for investigating carbon reduction pathways has yet to establish comprehensive theoretical foundations, necessitating further research and exploration. In light of these gaps, this study first defines the research boundaries for carbon emissions in the embodied phase of prefabricated buildings. Subsequently,

considering critical characteristics such as high complexity, intensive resource and energy consumption, and compressed construction timelines, the paper selects the embodied phase carbon emissions of Building 4 in a prefabricated residential project in Ningbo as the research subject for systematic analysis.

## **2 Index System of Driving Factors for Carbon Emission Reduction in the Physical and Chemical Stage of Prefabricated Buildings**

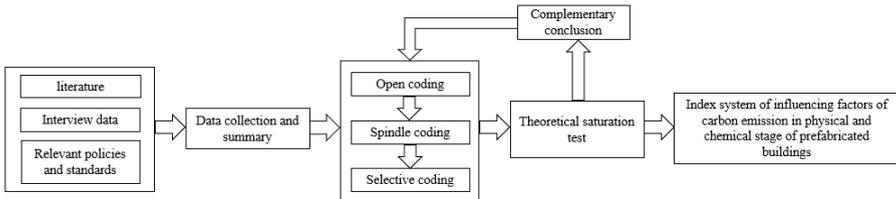
### **2.1 Research Boundary Definition**

The life cycle of a building consists of three system boundaries: cradle to gate, cradle to site, and cradle to grave system boundaries<sup>[14]</sup>. From cradle to site system boundary, in addition to on-site assembly, construction and waste disposal, it also includes all processes from the production of building materials to the transportation of finished products to the construction site<sup>[15]</sup>. The cradle to gate system boundary includes the upstream process from the production of building materials to the moment the finished product leaves the factory gate; The cradle-to-grave system boundary focuses on the life cycle of the building, from resource extraction of building components to utilization and disposal at the end of the life cycle<sup>[16]</sup>. To holistically assess resource inputs, energy consumption, and environmental impacts in construction, this study defines the research boundary for embodied carbon emissions in prefabricated buildings as a cradle-to-site system encompassing five critical phases: material production, material transportation, component fabrication, component transportation, and on-site assembly. The building materials production stage includes raw material mining and processing, and the main carbon emissions come from the energy and building materials consumption in the production process. The carbon emissions of building materials transportation and component transportation are mainly derived from the energy consumption of transport vehicles during transportation. Component manufacturing stage includes the process of building materials being processed into components or other forms of processing. Carbon emissions in this stage mainly come from energy consumption, building materials consumption and waste emissions in the processing process. The on-site assembly stage includes the process of assembly at the construction site according to the design requirements to form a complete building. The carbon emissions in this stage mainly come from the energy consumption of construction machinery and equipment at the construction site, the consumption of building materials and waste emissions.

### **2.2 Grounded Theory**

Grounded theory is one of the most influential research paradigms in the current social sciences. It is a qualitative research method that carries out theoretical modeling from the bottom up, and its core lies in connecting theoretical construction and empirical research, collecting and analyzing data, and gradually extracting concepts and categories<sup>[17]</sup>. This study implemented a systematic grounded theory protocol (following

Corbin & Strauss' three-stage coding framework) to construct the driver index system for carbon emission reduction during the materialization phase of prefabricated buildings. Through iterative open coding, axial coding, and theoretical coding, the methodology enabled comprehensive identification of critical decarbonization drivers. As shown in Figure 1.



**Fig. 1.** Flow chart of grounded theory research

The rooted theoretical data in this paper include (1) literature review: Among the literatures retrieved by CNKI with the main topics of "Building materialization stage", "carbon emission" and "carbon emission reduction", the restrictive conditions are the core journals and above, and there are a total of 82 literatures by 2023. In the core database of Web of Science (WOS), with "prefabricated buildings", "carbon emission" and "carbon reduction" as the main inscriptions, there are 202 articles as of 2023. After a comprehensive collection of 284 articles, Further screening, summary and induction were conducted around the keywords of "influencing factors", "evaluation", "in Building Materialization Stage", "influencing factors", "evaluation" and "carbon reduction". (2) Policy standards: "14th Five-Year Plan" Green Building and Building Energy Conservation Development Plan, "Accelerate the promotion of building energy conservation and carbon reduction work Plan," building carbon emission calculation standards, "green building evaluation standards," building energy conservation and renewable energy utilization general Code "and other policies and building standards. (3) Interview data: The interview data mainly come from semi-structured interviews. 25 relevant experts and scholars were invited to participate in the interview, mainly from the management and technical personnel of construction, supervision, construction and material suppliers and other units, as well as relevant scientific researchers in universities. Among them, 56% are between 30 and 50 years old; Managers accounted for 36%; Bachelor degree or above 68%; 72% have worked for more than 5 years. The above three types of data were preliminarily sorted out and analyzed, 8 worthless interview records were deleted, 75% of which were selected as sample data, and 25% were used for theoretical saturation verification.

## 2.3 Analysis of Grounded Theory Results

### 2.3.1 Open Coding to Determine the Initial Category.

In order to ensure the independence of the indicators, repetitive concepts and meaningless concepts are eliminated, and the remaining concepts are semantic screened,

classified and summarized to form an initial category. A total of 96 initial categories were identified in this paper.

### 2.3.2 Spindle Coding to Determine the Main Category.

The relationship between the 96 initial categories is deeply analyzed, the closely related initial codes are aggregated, and the 18 main categories finally extracted are shown in Table 1.

**Table 1.** Main category encoding result

encoding	Principal category	encoding	Principal category
$X_1$	Selection of building materials	$X_{10}$	Low carbon construction organization design and management
$X_2$	Energy structure selection	$X_{11}$	Use of advanced construction machinery
$X_3$	Project low carbon design and planning	$X_{12}$	Low-carbon construction publicity training
$X_4$	Total investment in project construction	$X_{13}$	The application of new technology and new process
$X_5$	Prefabricated building features	$X_{14}$	Construction efficiency of construction personnel
$X_6$	Low-carbon system building	$X_{15}$	Construction waste management
$X_7$	Transportation scheme	$X_{16}$	Degree of land reclamation and protection
$X_8$	Warehouse location selection	$X_{17}$	Greening systems sequester carbon
$X_9$	Warehouse management	$X_{18}$	Dust control

### 2.3.3 Theoretical Coding to Determine the Core Category.

After re-analyzing the original data and coding comparison with the initial category and main category, further refining and integrating the 18 main categories obtained by the spindle coding, it is concluded that the driving factors for carbon emission reduction in the physical and chemical stage of prefabricated buildings cover five aspects: resources and energy, project overview, transportation and storage, construction and management, and ecological environment, as shown in Table 2.

**Table 2.** Theoretical coding result

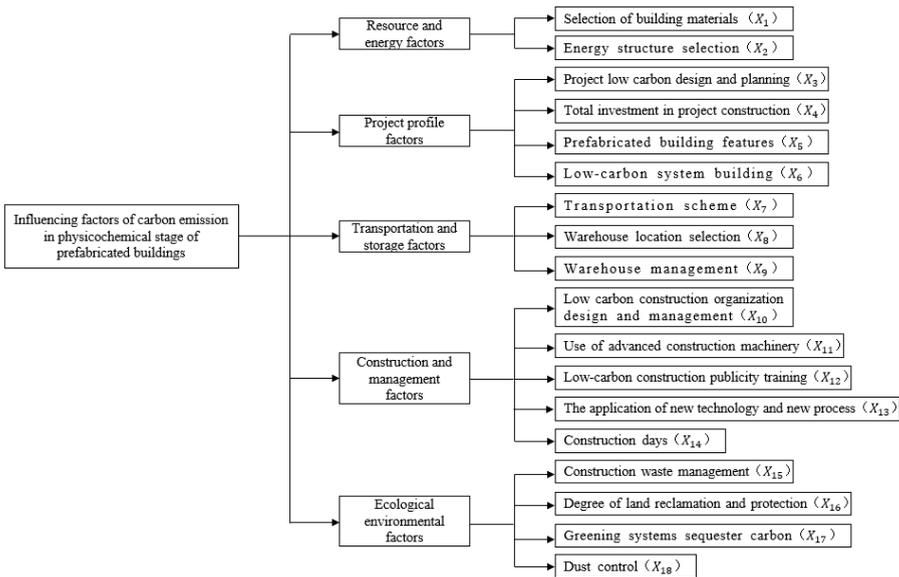
Core category	Principal category
Resource and energy factors	$X_1, X_2$
Project profile factors	$X_3, X_4, X_5, X_6$
Transportation and storage factors	$X_7, X_8, X_9$
Construction and management factors	$X_{10}, X_{11}, X_{12}, X_{13}, X_{14}$
Ecological environmental factors	$X_{15}, X_{16}, X_{17}, X_{18}$

**2.3.4 Saturation Test.**

In order to ensure the reliability and effectiveness of the research, the coding analysis of the remaining 25% data shows that no new concepts, categories or relationships are found, indicating that the driving factors of carbon emission reduction in the physical and chemical stage of prefabricated buildings obtained by the grounded theory applied in this paper have reached a saturation state, indicating that the data obtained in this paper is credible and complete.

**2.4 Establishment of Index System**

The index system of driving factors for carbon emission reduction in the physical and chemical stage of prefabricated buildings is formed according to the rooted theory, as shown in Figure 2.



**Fig. 2.** List of influencing factors of carbon emission in physical and chemical stage of prefabricated buildings

**3 Method Introduction**

**3.1 Integrated Analysis Method Based on DEMATEL-ISM**

Decision testing and evaluation laboratory analysis (DEMATEL method) is a method that combines causality diagram and matrix operation to analyze causality among factors and identify key factors in complex systems<sup>[18]</sup>. Interpretive structure model (ISM) is a qualitative method to analyze multiple influencing factors in a complex system. By establishing the structural relationship diagram among factors, the hierarchical

structure and correlation relationship of all factors in the system are revealed<sup>[19]</sup>. Combining the DEMATEL method with ISM, the Dematel-ISM model is established to analyze the driving factors of carbon emission reduction in the physical and chemical stage of prefabricated buildings. On the one hand, the key driving factors of carbon emission reduction and the causal relationship among them can be defined; on the other hand, the hierarchical structure and interrelation among driving factors of carbon emission reduction can be obtained. Thus, the complex factors are standardized and ordered, which provides some help for further quantitative analysis of carbon emission reduction path.

The integrated DEMATEL/ISM method is implemented as follows:

Step 1: Identify the driver set  $X=\{X_1, X_2, \dots, X_n\}$ , where  $n$  is the number of drivers.

Step 2: Create the initial direct influence Matrix  $A$ .

According to the experience of experts, the interaction and influence degree of each driving factor are compared in pairwise, and the direct influence matrix  $A^k=[r_{ij}^k]_{n \times n}$  is obtained by scoring method.  $r_{ij}^k$  indicates the degree of direct influence of factor  $r_i$  on  $r_j$  given by the KTH expert. The values are 0, 1, 2, 3 and 4 according to the 5 grades of no, weak, average, strong and very strong. When  $i=j, r_{ij}^k=0$ . In order to eliminate the subjective errors of experts, the results of each expert score are summarized and averaged, and then rounded (rounded) to obtain the direct influence matrix  $A$ .

$$A = \begin{bmatrix} 0 & \dots & r_{1n} \\ \vdots & \ddots & \vdots \\ r_{n1} & \dots & 0 \end{bmatrix} = [r_{ij}]_{n \times n} \tag{1}$$

Formula,  $r_{ij} = \frac{1}{m} \sum_{k=1}^m r_{ij}^k, k=1,2, \dots, m$ ;  $m$  and  $n$  represent the number of experts and the number of driving factors respectively.

Step 3: Determine the direct influence matrix  $B$  and the comprehensive influence matrix  $T$ .

By normalizing the direct influence matrix  $A$ , we get matrix  $B=[b_{ij}]_{n \times n}$  and matrix  $T=[t_{ij}]_{n \times n}$ .

$$B = \frac{1}{\max_{1 \leq i \leq n} \sum_{j=1}^n r_{ij}} A \tag{2}$$

$$T = (B + B^2 + \dots + B^k) = \sum_{k=1}^n B^k = B(I - B)^{-1} \tag{3}$$

Where:  $I$  is the identity matrix.

Step 4: Calculate impact level  $E_i$ , impact level  $E'_i$ , center level  $C_i$ , cause level  $Y_i$ , and relative weight  $W_i$  of the driver.

The impact degree  $E_i$  is obtained by summing the rows of the comprehensive impact matrix  $T$ , and the impact degree  $E'_i$  is obtained by summing the columns of the comprehensive impact matrix  $T$ . The central degree  $C_i$  is obtained by adding the impact degree  $E_i$  and the impact degree  $E'_i$ , and the cause degree  $Y_i$  is obtained by subtracting the impact degree  $E_i$  and the impact degree  $E'_i$ . The relative weight  $W_i$  is obtained by normalizing the centrality  $C_i$  of each factor.

$$E_i = \sum_{j=1}^n t_{ij} \quad (i=1,2,\dots,n) \tag{4}$$

$$E'_i = \sum_{j=1}^n t_{ji} \quad (i=1,2,\dots,n) \tag{5}$$

$$C_i = E_i + E'_i \quad (i=1,2,\dots,n) \tag{6}$$

$$Y_i = E_i - E'_i \quad (i=1,2,\dots,n) \tag{7}$$

$$W_i = \frac{C_i}{\sum_{i=1}^n C_i} \quad (i=1,2,\dots,n) \tag{8}$$

Step 5: Calculate the global influence matrix **D** and the reachability matrix **G**.

Since the matrix **T** cannot prove the influence of factors on itself, the identity matrix **I** is introduced to obtain the overall influence matrix  $D=[d_{ij}]_{n \times n}$  on the basis of the comprehensive influence matrix  $T=[t_{ij}]_{n \times n}$ . The matrix **D** is transformed into the reachable matrix  $G=[g_{ij}]_{n \times n}$  by introducing a suitable threshold  $\lambda$ . In order to obtain an objective and true threshold  $\lambda$ , this study first used the sum of mean  $\alpha$  and standard deviation  $\beta$  to obtain the initial threshold  $\lambda$ , and then determined the final threshold  $\lambda$  through repeated simulation and combined with expert opinions.

$$D = T + I \tag{9}$$

$$g_{ij} = \begin{cases} 1, & d_{ij} \geq \lambda \quad (i,j=1,2,\dots,n) \\ 0, & d_{ij} < \lambda \quad (i,j=1,2,\dots,n) \end{cases} \tag{10}$$

Where: **I** is the identity matrix,  $\lambda = \alpha + \beta$ ,  $\alpha$  represents the mean value of all elements in the matrix **T**,  $\beta$  represents the standard deviation of all elements in the matrix **T**.

Step 6: Construct the reachable set  $P(x_i)$ , antecedent set  $Q(x_i)$ , and common set  $R(x_i)$  for each driver.

The reachability set  $P(x_i)$  refers to the set of factors in the corresponding row of factor  $x_i$ , consisting of entries with a value of 1 in the reachability matrix **G**. The antecedent set  $Q(x_i)$  denotes the set of factors in the corresponding column of factor  $x_i$ , comprising entries with a value of 1 in the reachability matrix **G**. The common set  $R(x_i)$  is defined as the intersection of the reachability set  $P(x_i)$  and the antecedent set  $Q(x_i)$ .

$$P(x_i) = \{x_j | x_j \in X, g_{ij} = 1\} \tag{11}$$

$$(i = 1, 2, \dots, n)$$

$$Q(x_i) = \{x_j | x_j \in X, g_{ji} = 1\} \tag{12}$$

$$(i = 1, 2, \dots, n)$$

$$R(x_i) = \{x_i | x_i \in X, P(x_i) \cap Q(x_i) = P(x_i)\} \tag{13}$$

$$(i = 1, 2, \dots, n)$$

Step 7: Determine the hierarchical structure model.

By using equations (11) ~ (13), the discovered common set  $R(x_i)$  is first set as the topmost level of the ISM model, and then the rows and columns corresponding to the already layered factors are gradually removed from the reachable matrix  $G$ . This process is then repeated until all rows and columns of the reachable matrix  $G$  are removed, and finally a multi-level hierarchical structure model can be drawn.

### 3.2 Overview of the MICMAC Method

MICMAC (Matrix-based Multiplication Applied to a Classification) was proposed by French scholars Duperrin and Godet in 1973. It is a method used to analyze the interaction and influence of variables in complex systems<sup>[20]</sup>.

At present, in order to verify the scientificity of DEMATEL-ISM integration method in the classification of influencing factors and hierarchical analysis, many scholars have introduced MICMAC method as a supplementary analysis method. For example, Huo Yuyu et al. used MICMAC method to prove that the results of DEMATEL-ISM method's correlation analysis on the factors affecting the resource conflict in the technical interface process of Larin Railway are logical<sup>[21]</sup>. Xing Y et al have analyzed the interaction between pathogenic factors and logical structure of self-built house fire accidents based on the DEMATEL-AISM method, and have verified the rationality of the anti-stratified topological model of pathogenic factors of self-built house fire accidents analyzed by the DEMATEL-AISM method using MICMAC<sup>[22]</sup>. Therefore, the MICMAC method was used in this study to verify the scientificity of DEMATEL-ISM method in the analysis of influencing factors of carbon emission in the physicochemical stage of prefabricated buildings. The implementation steps are as follows:

Based on the reachability matrix  $G$ , the driving forced  $DF(X_i)$  and dependence  $DP(X_i)$  of the influencing factors can be calculated. The formula is as follows:

$$DF(X_i) = \sum_{j=1}^n g_{ij} \quad (i = 1, 2, \dots, n) \quad (14)$$

$$DP(X_i) = \sum_{j=1}^n g_{ji} \quad (i = 1, 2, \dots, n) \quad (15)$$

## 4 Case Study

### 4.1 Project Overview

The prefabricated residential building No. 4 of a project in Cixi City of Ningbo City is selected as the research object for analysis. The residential building is a high-rise residential building with concrete shear wall structure, with a total construction area of 12,389.71 square meters and a height of 84.4 meters. Among them, 5-28 floors are standard floors, and the assembly rate is 43%. The first floor is used as a garage, the impact of which is not considered in this study. This case has the characteristics of high complexity, relatively difficult construction and many participating departments, resulting in a large amount of building materials and energy consumption in the project. At the same time, the construction period is short and the waste disposal method is unreasonable, which makes the short-term impact on the environment obvious.

### 4.2 Correlation Analysis of Driving Factors for Carbon Emission Reduction

According to the index system of driving factors for carbon emission reduction in the materialization stage of prefabricated buildings established in Figure 2, 5 experienced vice president of the construction unit, project manager of the construction unit, technical personnel of the construction unit, supervision unit and material supplier of the prefabricated high-rise residential building project were invited to give expert scores on the 18 driving factors according to the criteria determined in step 2. The results scored by each expert are summarized and averaged, and then rounded (rounded) to establish the direct influence matrix  $A$ .

$$A = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 4 & 4 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 4 & 3 & 3 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 3 \\ 4 & 4 & 0 & 4 & 0 & 0 & 3 & 4 & 0 & 3 & 3 & 0 & 3 & 0 & 0 & 0 & 0 & 0 \\ 4 & 4 & 0 & 0 & 0 & 0 & 0 & 0 & 2 & 0 & 3 & 0 & 3 & 3 & 3 & 3 & 3 & 3 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 3 \\ 4 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 3 & 0 & 0 & 0 & 0 & 0 & 4 & 0 & 0 & 0 \\ 3 & 4 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \\ 0 & 4 & 0 & 0 & 0 & 0 & 2 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 3 \\ 4 & 3 & 0 & 0 & 0 & 0 & 2 & 0 & 0 & 0 & 3 & 3 & 3 & 3 & 3 & 2 & 3 & 3 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 3 & 0 & 2 & 1 & 0 \\ 2 & 2 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 2 & 0 & 2 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 2 & 0 & 0 & 3 & 0 & 3 & 2 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 3 & 2 & 4 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 3 & 3 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 3 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}$$

Based on the direct impact matrix  $A$ , the canonical direct impact matrix  $B$  and the comprehensive impact matrix  $T$  are calculated according to equations (2) ~ (3) in Step 3. Based on the matrix  $T$ , impact level  $E_i$ , impact level  $E'_i$ , centrality degree  $C_i$ , cause degree  $Y_i$  and relative weight  $W_i$  of each driving factor were calculated according to formulas (4) to (8), as shown in Table 3.

**Table 3.** DEMATEL modeling analysis results

Driving factor	Influence degree $E_i$	Influence degree $E'_i$	centrality $C_i$	Causation degree $Y_i$	relative weight $W_i/\%$	weight sort
$X_1$	0.706	0.733	1.44	-0.027	9.8	1
$X_2$	0.135	0.788	0.922	-0.653	6.3	7
$X_3$	1.357	0.000	1.357	1.357	9.2	2
$X_4$	1.187	0.125	1.312	1.062	8.9	4
$X_5$	0.094	0.000	0.094	0.094	0.6	18
$X_6$	0.479	0.000	0.479	0.479	3.3	14
$X_7$	0.333	0.463	0.796	-0.13	5.4	9

$X_8$	0.225	0.342	0.567	-0.117	3.9	13
$X_9$	0.094	0.164	0.258	-0.07	1.8	17
$X_{10}$	1.255	0.094	1.349	1.161	9.2	3
$X_{11}$	0.202	0.456	0.659	-0.254	4.5	12
$X_{12}$	0.337	0.103	0.44	0.235	3.0	16
$X_{13}$	0.349	0.371	0.72	-0.021	4.9	11
$X_{14}$	0.000	0.473	0.473	-0.473	3.2	15
$X_{15}$	0.306	0.443	0.749	-0.138	5.1	10
$X_{16}$	0.196	0.745	0.942	-0.549	6.4	6
$X_{17}$	0.094	0.756	0.849	-0.662	5.8	8
$X_{18}$	0.000	1.295	1.295	-1.295	8.8	5

Impact degree  $E_i$  indicates the impact of factor  $X_i$  on other factor  $X_j$  in the system. A larger value indicates a larger impact. The influence  $E'_i$  indicates the influence of other factors  $X_j$  on the factor  $X_i$ , and a larger value indicates that the factor  $X_i$  is more susceptible to the influence of other factors $X_j$ <sup>[23]</sup>. It can be seen from Table 3 that  $X_3$  has the largest influence  $E_i$  value, indicating that it has the greatest influence on other factors. The influence  $E_i$  values of  $X_{14}$  and  $X_{18}$  are the smallest, indicating that they have the least influence on other factors. The influence degree of  $X_{18}$   $E'_i$  is the largest, indicating that it is susceptible to other factors.  $X_3$ ,  $X_5$  and  $X_6$  have the smallest impact  $E'_i$ , which indicates that they are not easily affected by other factors.

Centrality  $C_i$  describes the importance and status of factor  $X_i$  in the system. The greater  $C_i$  is, the closer factor  $X_i$  is to the core status and the greater its role<sup>[24]</sup>. It can be seen from Table 3 that the building material selected  $X_1$  has the largest centrality value, indicating that it has the greatest direct impact on carbon emissions in the physical and chemical stage of the No. 4 prefabricated residential building project, and is the most important carbon reduction factor, which should be focused on control. Cause degree  $Y_i$  is the main index to evaluate the effect of a certain factor  $X_i$  on other factors  $X_j$ , and its value is negative, reflecting that this factor  $X_i$  is the result factor, and the opposite is the cause factor<sup>[25]</sup>. As can be seen from Table 3,  $X_3$ ,  $X_4$ ,  $X_5$ ,  $X_6$ ,  $X_{10}$  and  $X_{12}$  are the causes of carbon emission reduction in the physicochemical stage of the No. 4 prefabricated residential building project, and will affect other factors in various ways. Among them, the reason degree of project low-carbon design and planning  $X_3$  is greater than 1 and ranks first, indicating that  $X_3$  is more likely to affect other carbon reduction factors and lead to the increase of carbon emissions, which is the fundamental factor of carbon emission reduction and indirectly affects carbon emission reduction.  $X_1$ ,  $X_2$ ,  $X_7$ ,  $X_8$ ,  $X_9$ ,  $X_{11}$ ,  $X_{13}$ ,  $X_{14}$ ,  $X_{15}$ ,  $X_{16}$ ,  $X_{17}$  and  $X_{18}$  are the result factors of carbon emission reduction in the physical and chemical stage of prefabricated high-rise residential building projects, which are easily affected by other factors. Among them, the absolute reason degree of dust removal  $X_{18}$  is ranked first, which is the most direct factor for carbon emission reduction in the physicochemical stage of the No. 4 prefabricated residential building project.

By normalizing the center degree  $C_i$ , the weight  $W_i$  of each driving factor of carbon reduction is obtained. As can be seen from the weight  $W_i$  in Table 3, the weight of building materials selection ranks first, indicating that this factor plays an important

role in carbon emission reduction in the physical and chemical stage of the prefabricated residential building project No. 4. Therefore, the choice of building materials is the most critical factor for carbon reduction.

### 4.3 Hierarchical Structure Analysis of Driving Factors for Carbon Emission Reduction

Calculate the overall influence matrix  $D$  according to equation (9) in Step 5. The selection of threshold  $\lambda$  will affect the hierarchy division of ISM model. The initial threshold  $\lambda = \alpha + \beta = 0.022 + 0.043 = 0.066$  is calculated according to the sum of mean  $\alpha$  and standard deviation  $\beta$ . After repeated simulation and expert opinion, the threshold  $\lambda$  is selected as 0.066. On this basis, the reachability matrix  $G$  of driving factors of carbon reduction is obtained according to equation (10). Based on matrix  $G$ , the reachability set  $P(x_i)$  and the precursor set  $Q(x_i)$  of each carbon reduction driving factor are established through (11) ~ (13) in Step 6. As shown in Table 4, reachability set  $P(x_i)$  represents the set of all factors that can be reached by factor  $X_i$ . The antecedent set  $Q(x_i)$  represents the set of all factors that other factors can reach the factor  $X_i$ .

**Table 4.** Reachable set  $P(x_i)$  and antecedent set  $Q(x_i)$

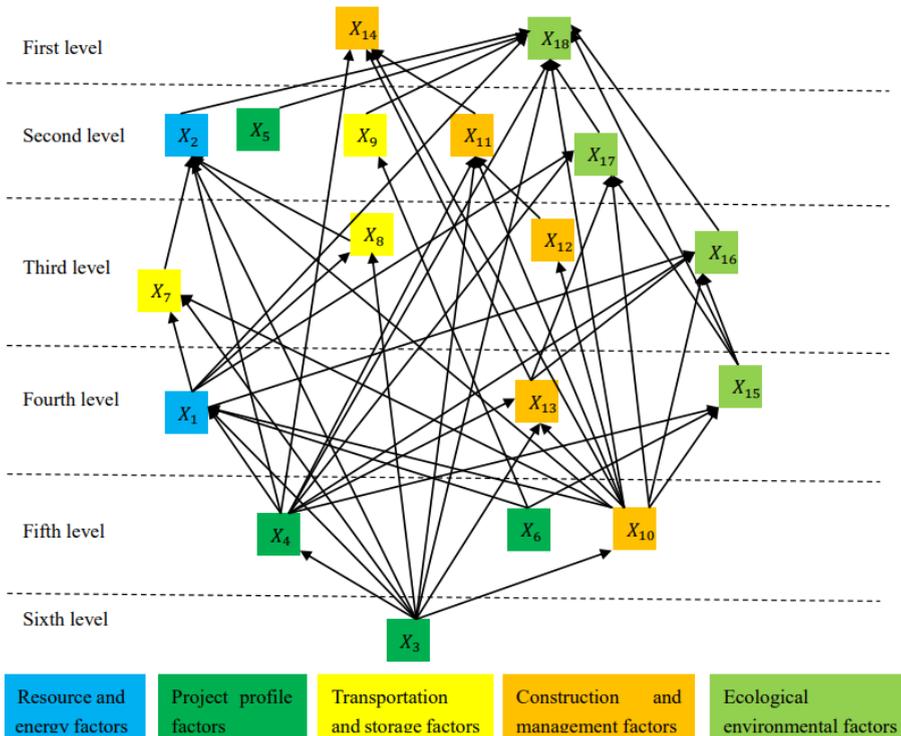
Factor	Reachable set $P(x_i)$	Precedence set $Q(x_i)$
$X_1$	$X_1, X_7, X_8, X_{16}, X_{17}, X_{18}$	$X_1, X_3, X_4, X_6, X_7, X_{10}$
$X_2$	$X_2, X_{18}$	$X_2, X_3, X_4, X_7, X_8, X_{10}$
$X_3$	$X_1, X_2, X_3, X_4, X_7, X_8, X_{10}, X_{11}, X_{13}, X_{18}$	$X_3$
$X_4$	$X_1, X_2, X_4, X_{11}, X_{13}, X_{14}, X_{15}, X_{16}, X_{17}, X_{18}$	$X_3, X_4$
$X_5$	$X_5, X_{18}$	$X_5$
$X_6$	$X_1, X_6, X_9, X_{15}$	$X_6$
$X_7$	$X_1, X_2, X_7$	$X_1, X_3, X_7, X_{10}$
$X_8$	$X_2, X_8$	$X_1, X_3, X_8$
$X_9$	$X_9, X_{18}$	$X_6, X_9$
$X_{10}$	$X_1, X_2, X_7, X_{10}, X_{11}, X_{12}, X_{13}, X_{14}, X_{15}, X_{16}, X_{17}, X_{18}$	$X_3, X_{10}$
$X_{11}$	$X_{11}, X_{14}$	$X_3, X_4, X_{10}, X_{11}, X_{12}$
$X_{12}$	$X_{11}, X_{12}$	$X_{10}, X_{12}$
$X_{13}$	$X_{13}, X_{14}, X_{16}, X_{17}$	$X_3, X_4, X_{10}, X_{13}$
$X_{14}$	$X_{14}$	$X_4, X_{10}, X_{11}, X_{13}, X_{14}$
$X_{15}$	$X_{15}, X_{16}, X_{17}, X_{18}$	$X_4, X_6, X_{10}, X_{15}$
$X_{16}$	$X_{16}, X_{18}$	$X_1, X_4, X_{10}, X_{13}, X_{15}, X_{16}$
$X_{17}$	$X_{17}, X_{18}$	$X_1, X_4, X_{10}, X_{13}, X_{15}, X_{17}$
$X_{18}$	$X_{18}$	$X_1, X_2, X_3, X_4, X_5, X_9, X_{10}, X_{15}, X_{16}, X_{17}, X_{18}$

According to the reachability set  $P(x_i)$  and antecedent set  $Q(x_i)$  of each carbon emission reduction driving factor established in Table 4, the carbon emission reduction driving factors in the physical and chemical stage of the No. 4 prefabricated residential building project are divided into 6 levels, as shown in Table 5.

**Table 5.** Hierarchical classification of driving factors for carbon reduction

Hierarchical rank	Factor set	Hierarchy declaration
First level	$X_{14}$ 、 $X_{18}$	Shallow drivers
Second level	$X_2$ 、 $X_5$ 、 $X_9$ 、 $X_{11}$ 、 $X_{17}$	Shallow drivers
Third level	$X_7$ 、 $X_8$ 、 $X_{12}$ 、 $X_{16}$	Transition driver
Fourth level	$X_1$ 、 $X_{13}$ 、 $X_{15}$	Transition driver
Fifth level	$X_4$ 、 $X_6$ 、 $X_{10}$	Deep driving factor
Sixth level	$X_3$	Underlying driver

According to Table 4 and Table 5, a multi-level hierarchical ISM model is drawn for the driving factors of carbon emission reduction in the physical and chemical stage of the No. 4 prefabricated residential building project, as shown in Figure 3.



**Fig. 3.** ISM model of driving factors of carbon emission reduction in physicochemical stage of No. 4 prefabricated residential building project

Figure 3 shows the relationship between the factors and the hierarchical structure of each factor. As can be seen from the figure, the driving factors of carbon emission reduction in the physical and chemical stage of the No.4 prefabricated residential building project are divided into four categories: shallow driving factors, transitional driving factors, deep driving factors and fundamental driving factors.  $X_2$ ,  $X_5$ ,  $X_9$ ,  $X_{11}$ ,  $X_{17}$ ,  $X_{14}$  and  $X_{18}$  are the most direct driving factors of carbon emission reduction in the physicochemical stage of the No. 4 prefabricated residential building project, and the lower factors have effects and influences on carbon emission reduction in the physicochemical stage.  $X_1$ ,  $X_7$ ,  $X_8$ ,  $X_{12}$ ,  $X_{13}$ ,  $X_{15}$  and  $X_{16}$  are the transitional driving factors of carbon emission reduction in the physical and chemical stage of the prefabricated residential building project No. 4, and the indirect driving factors of carbon emission reduction in the physical and chemical stage of the prefabricated building. They are not only affected by the underlying factors, but also have an impact on the upper factors.  $X_3$ ,  $X_4$ ,  $X_6$  and  $X_{10}$  are the most fundamental and deep driving factors of carbon emission reduction in the physical and chemical stage of the No. 4 prefabricated residential building project, which have a high driving force and have a greater influence on other factors. Among them,  $X_3$  is the most fundamental driving factor of carbon emission reduction in the physicochemical stage of the No. 4 prefabricated residential building project, and influences the upper carbon emission reduction driving factors in various ways.

#### 4.4 Analysis of Carbon Emission Reduction Path

By synthesizing Figure 3 and Table 3, we can see that there are 20 carbon reduction paths in the materialization stage of the prefabricated residential building project No. 4, centered on the key carbon reduction factor "building materials selection  $X_1$ ". In order to quantitatively analyze which of the "building materials selection" carbon reduction paths are of high importance and have a significant effect on carbon emission reduction in the physical and chemical stage of prefabricated high-rise residential building projects, it is necessary to consider the weight of carbon emission reduction paths. Therefore, based on the driving factor weight of carbon reduction, the concept of path weight is proposed. Path weight refers to the sum of the weight  $W_i$  of each carbon reduction driving factor in the carbon reduction path (the weight is from Table 3), and the normalization process is carried out to obtain the path weight of each carbon reduction path.

On the basis of the multi-level hierarchical ISM model of carbon emission reduction driving factors in the physical and chemical stage of No. 4 prefabricated residential building project constructed by DEMATEL-ISM method, from the perspective of carbon emission reduction driving factor weight  $W_i$ , the weight of various factors in the carbon emission reduction path is summed and normalized, and the path weight of each carbon emission reduction path is obtained. The path weight of the carbon reduction path is arranged from large to small, and the path weight table of the carbon reduction path of "building materials selection" is obtained, as shown in Table 6.

**Table 6.** The path weight of "Building materials selection" carbon emission reduction path

Serial number	Carbon reduction path	Path weight /%	Cumulative path weight /%
1	$X_3 \rightarrow X_{10} \rightarrow X_1 \rightarrow X_7 \rightarrow X_2 \rightarrow X_{18}$	6.46	6.46
2	$X_3 \rightarrow X_4 \rightarrow X_1 \rightarrow X_7 \rightarrow X_2 \rightarrow X_{18}$	6.42	12.88
3	$X_3 \rightarrow X_{10} \rightarrow X_1 \rightarrow X_8 \rightarrow X_2 \rightarrow X_{18}$	6.26	19.14
4	$X_3 \rightarrow X_4 \rightarrow X_1 \rightarrow X_8 \rightarrow X_2 \rightarrow X_{18}$	6.23	25.37
5	$X_3 \rightarrow X_{10} \rightarrow X_1 \rightarrow X_{16} \rightarrow X_{18}$	5.76	31.13
6	$X_3 \rightarrow X_4 \rightarrow X_1 \rightarrow X_{16} \rightarrow X_{18}$	5.72	36.85
7	$X_3 \rightarrow X_{10} \rightarrow X_1 \rightarrow X_{17} \rightarrow X_{18}$	5.68	42.53
8	$X_3 \rightarrow X_4 \rightarrow X_1 \rightarrow X_{17} \rightarrow X_{18}$	5.64	48.17
9	$X_3 \rightarrow X_1 \rightarrow X_7 \rightarrow X_2 \rightarrow X_{18}$	5.24	53.41
10	$X_3 \rightarrow X_1 \rightarrow X_8 \rightarrow X_2 \rightarrow X_{18}$	5.04	58.45
11	$X_3 \rightarrow X_{10} \rightarrow X_1 \rightarrow X_{18}$	4.91	63.36
12	$X_3 \rightarrow X_4 \rightarrow X_1 \rightarrow X_{18}$	4.87	68.23
13	$X_3 \rightarrow X_1 \rightarrow X_{16} \rightarrow X_{18}$	4.54	72.77
14	$X_3 \rightarrow X_1 \rightarrow X_{17} \rightarrow X_{18}$	4.46	77.23
15	$X_6 \rightarrow X_1 \rightarrow X_7 \rightarrow X_2 \rightarrow X_{18}$	4.46	81.69
16	$X_6 \rightarrow X_1 \rightarrow X_8 \rightarrow X_2 \rightarrow X_{18}$	4.26	85.95
17	$X_6 \rightarrow X_1 \rightarrow X_{16} \rightarrow X_{18}$	3.76	89.71
18	$X_3 \rightarrow X_1 \rightarrow X_{18}$	3.69	93.40
19	$X_6 \rightarrow X_1 \rightarrow X_{17} \rightarrow X_{18}$	3.68	97.08
20	$X_6 \rightarrow X_1 \rightarrow X_{18}$	2.91	99.99

As can be seen from Table 6, only from the perspective of path weights of carbon reduction paths, the weight of carbon reduction paths numbered 1-4 is greater than 6 and ranks the top four, indicating that these paths have a significant impact on carbon reduction in the materialization stage of the prefabricated residential building project No. 4. Among them, the path weight value of No. 1 "Project low-carbon design and planning → low-carbon construction organization design and management → building materials selection → transportation scheme → energy structure selection → dust control" is the largest, indicating that it plays an important role in carbon emission reduction in the physical and chemical stage of the No.4 prefabricated residential building project, and is the key carbon emission reduction path. The carbon reduction path involves five factors, such as project overview, construction and management, transportation and storage, resources and energy and ecological environment, which interact with each other and have the greatest impact on carbon emission reduction in the materialization stage of the No. 4 prefabricated residential building project, and should be paid more attention to. The path weight of No. 20 "low-carbon system construction → selection of building materials → dust removal control" is less than 3 and the least, indicating that it has the least influence on carbon emission reduction in the physical and chemical stage of the prefabricated high-rise residential building project No. 4.

The carbon emission reduction path distribution in the physicochemical stage of the No. 4 prefabricated residential building does not conform to the "80:20 law", and the path weight ratio of the carbon emission reduction path is evenly distributed, indicating that the influencing factors of carbon emission in the physicochemical stage of the No.

4 prefabricated residential building project do not exist in isolation, but interact and influence each other. The influence of factors at different levels is passed layer by layer, resulting in cumulative effects. This can have a significant impact on the environment. Sequence number 1-14 and 18 carbon emission reduction paths, the intrinsic drivers directly affect the deep drivers, and then affect the transition drivers and shallow drivers; Sequence number 15 ~ 17 and 19 ~ 20 carbon emission reduction paths, deep drivers directly affect the transition drivers, and then affect the shallow drivers. In order to achieve energy saving and emission reduction in the materialization stage of the prefabricated building and reduce the short-term impact on the environment, four aspects can be considered: essential driving factors, deep driving factors, transitional driving factors and shallow driving factors. The essential and deep driving factors are the starting points of the carbon emission reduction path, and such factors have strong driving forces and are not easily affected by other factors. However, the impact on other factors is strong, which should be the top priority of management and control. Transitional driving factors play a connecting role in the path of carbon reduction. Such factors need comprehensive and multi-angle joint control and should be the focus of control. Shallow driving factors are the end of the carbon emission reduction path and are easily affected by other factors, which have a direct impact on carbon emission reduction in the physical and chemical stage of buildings, and should be strengthened.

**4.5 Discuss**

The DEMATEL method relies on subjective judgments and scores by experts, which can lead to higher subjectivity in the results. Experts in different positions may have different understandings and views on the same issue, which may affect the accuracy and reliability of the survey information.

The results of this study are applicable to energy conservation and emission reduction of prefabricated buildings in different geographical regions.

**5 MICMAC Model Validation Analysis of Key Drivers**

The results of MICMAC analysis can be calculated based on the reachable matrix G. The driving force  $DF(X_i)$  is obtained by adding rows in the reachable matrix G, and the dependency  $DP(X_i)$  is obtained by adding vertical columns in the reachable matrix G. The results are shown in Table 7. Based on these data, the driving force - dependence diagram of carbon emissions in the physical and chemical stage of prefabricated buildings can be further drawn, as shown in Figure 4, so as to more intuitively analyze the relationship between various factors and their impact on carbon emissions.

**Table 7.** Influencing factors Driving force and dependence

factor	Driving force	Degree of dependency	factor	Driving force	Degree of dependency
$X_1$	6	5	$X_{10}$	12	2
$X_2$	2	7	$X_{11}$	2	7

$X_4$	10	2	$X_{13}$	4	4
$X_5$	2	2	$X_{14}$	1	7
$X_6$	6	1	$X_{15}$	4	4
$X_7$	3	4	$X_{16}$	3	6
$X_8$	2	3	$X_{17}$	2	7
$X_9$	3	7	$X_{18}$	1	11

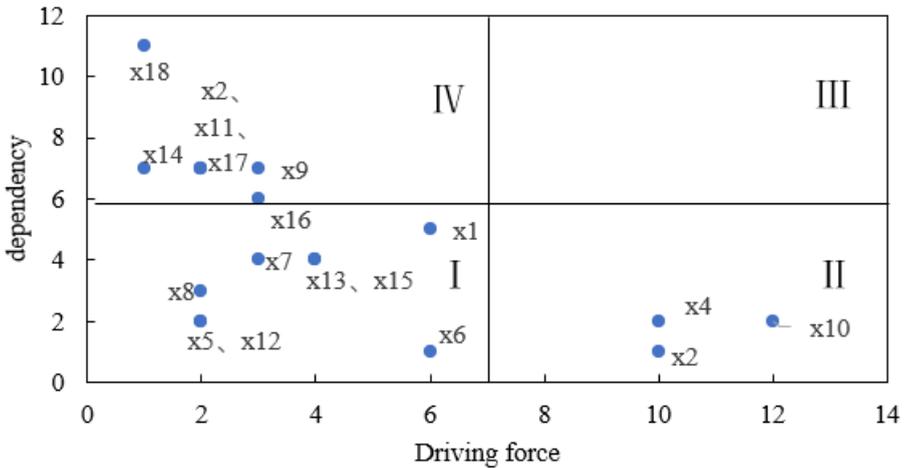


Fig. 4. Driving force - dependence diagram of influencing factors

According to Table 7 and Fig. 4, the selection of energy structure  $X_2$ , warehouse management  $X_9$ , use of advanced construction machinery  $X_{11}$ , carbon sequestration of greening system  $X_{17}$ , construction days  $X_{14}$  and dust removal  $X_{18}$  are dependent factors, which are in the top two layers of ISM model and are easily affected by other factors. It is the most direct driving factor of carbon emission reduction in the physical and chemical stage of prefabricated residential building projects, and exerts an effect and influence on carbon emission reduction through the lower factors.

The selection of building materials  $X_1$ , transportation scheme  $X_7$ , warehouse location  $X_8$ , publicity and training of low-carbon construction  $X_{12}$ , application of new technology and new process  $X_{13}$  and construction waste management  $X_{15}$  belong to autonomous factors, which are in the middle two layers of ISM model, and are the transitional driving factors of carbon emission reduction in the materialization stage of prefabricated residential building projects. It plays an indirect role in carbon emission reduction in the physical and chemical stage of prefabricated buildings, which is influenced by both the underlying factors and the upper factors.

Project low-carbon design and planning  $X_3$ , total investment in project construction  $X_4$ , low-carbon system construction  $X_6$ , and low-carbon construction organization design and management  $X_{10}$  are independent factors, which are in the bottom two layers of ISM model. They are the most fundamental and deep driving factors for carbon

emission reduction in the materialization stage of prefabricated residential building projects, with high driving force and greater influence on other factors. Among them, it is the most fundamental driving factor of carbon emission reduction in the physical and chemical stage of prefabricated residential building projects, and influences the upper carbon emission influencing factors in a variety of ways.

In summary, the autonomous, dependent, and independent factors of carbon reduction drivers in the embodied phase of prefabricated buildings derived from MICMAC analysis exhibit high consistency in their influence characteristics with the direct, shallow, middle, deep, and root drivers identified through the DEMATEL-ISM method. This congruence further substantiates the scientific validity and analytical effectiveness of the DEMATEL-ISM approach in classifying influencing factors, conducting hierarchical analysis, and elucidating carbon reduction pathways.

## 6 Conclusion

Through the application of grounded theory, open coding, axial coding, and theoretical coding were conducted on literature, policies, relevant standards, and interview data. This process systematically established a driving factor index system for carbon emission reduction during the physical and chemical stages of prefabricated buildings. The index system comprises five core categories and eighteen subcategories, encompassing resource and energy factors, project profile factors, transportation and storage factors, construction and management factors, and ecological environment factors.

The carbon emission reduction driving factors in the materialization stage of prefabricated high-rise residential building projects can be divided into 6 levels and 4 categories, and there is a clear progressive relationship between the carbon reduction driving factors at each level and category. With the gradual progression of shallow driving factors, transitional driving factors, deep driving factors and fundamental driving factors, The influence of various factors on carbon emission reduction in the physicochemical stage of prefabricated buildings is gradually deepening.

Build a carbon emission reduction path centered on the key carbon reduction factor "building materials selection". From the perspective of path weight of the carbon reduction path, the key carbon reduction path "project low-carbon design and planning → low-carbon construction organization design and management → building materials selection → transportation plan → energy structure selection → dust control" is obtained. Among them, the low-carbon design and planning of the project and the design and management of the low-carbon construction organization are important factors, and the selection of building materials, transportation scheme, energy structure and dust control are important outcome factors, which should be paid attention to when formulating carbon emission reduction strategies.

By analyzing and mining the driving factors of carbon emission reduction in the physical and chemical stage of prefabricated buildings, this study studies the interaction relationship, influence degree and hierarchical structure among various factors, and defines the key carbon emission reduction path, which not only provides theoretical support for the government to formulate scientific policies to effectively reduce the carbon

emission of the construction industry, but also has great significance for promoting the sustainable development of the prefabricated building industry.

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