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Original scientific paper

Analysis on Supply Chain Risk Factors of Prefabricated Buildings Using AHP-DEMATEL-ISM Model

Qiang CAI, Yunchao DU, Renxiang WANG*

Abstract: Given the numerous participants in the supply chain of prefabricated buildings and the great difficulty in improving risk management and control level, influencing factors through the literature review method were identified. Then, 7 first-level indexes and 23 second-level indexes were extracted. An influence index system for supply chain risks of prefabricated buildings was established. Comprehensively considering the importance and correlation of various influencing factors, the AHP-DEMATEL (Analytic Hierarchy Process and Decision-making Trial and Evaluation Laboratory) combined model was constructed, which solved the one-sided problem of the weight result of a single model. Then, the ISM (Interpretative Structural Modelling) model could be used to show the characteristics of the structural relationship of influencing factors hierarchically, and the fundamental supply chain risk factors were more accurately and clearly explored using the AHP-DEMATEL-ISM model. Results show that: (1) Logistics transportation distance, damage to prefabricated components during transportation, and unreasonable control of assembly period are the fundamental factors affecting the risk of prefabricated buildings, among which logistics transportation distance and damage to prefabricated components during transportation are the resulting factors, and the unreasonable control of the assembly period is the causal factor, but the factor weight is low because of the difficulty in short-term improvement. (2) Component production technology and equipment, transportation distance, and punctuality of product supply account for a high weight in the supply chain risk assessment index system of prefabricated buildings. (3) A total of 11 factors, such as inconformity of product design and standard, immature design technology level, component production technology and equipment, and quality of purchased materials, affect the supply chain risk of prefabricated buildings and are also causal factors with high weights. Conclusions obtained in the study provide a theoretical basis for the supply chain risk control of prefabricated buildings to a certain extent and also present a new perspective for the supply chain risk assessment of prefabricated buildings.

Keywords: AHP-DEMATEL-ISM; prefabricated buildings; risk assessment; supply chain

1 INTRODUCTION

Prefabricated buildings are manufactured through factory prefabrication and on site assembly, which significantly shortens the construction period; reduces energy consumption; saves resources; mitigates environmental pollution such as dust, noise, and construction waste; and brings remarkable energy conservation and environmental protection effects. Prefabricated buildings are becoming more popular because of the ever-increasing energy efficiency and environmental requirements of the construction industry. In recent years, the Chinese governments at all levels have successively issued incentive policies to promote the construction industrialization and development of prefabricated buildings. These policies have defined industry standards and formulated development goals and relevant subsidy and incentive policies. Green building in construction industry complies with the sustainable development concept; prefabricated buildings have ushered in new development opportunities.

Prefabricated buildings represent a new industrialized mode of construction. Production, processing, and transportation of prefabricated components resemble the production and operation process of the manufacturing industry, not only needing factory processing but also requiring onsite construction. Prefabricated buildings, which integrate the characteristics of the manufacturing industry and the traditional construction industry, have been vigorously promoted in China. In the entire life cycle, many non-negligible risks exist because their supply chain incorporates all business processes of planning, design, production, transportation, assembly, and operations management stages with a relatively complex construction process, numerous stakeholders, and intricate operation nodes. The difficulty in supply chain management has become a major issue in the development of prefabricated buildings. Thus, exploring an effective risk analysis and evaluation method is necessary to improve and perfect the operation level of the supply chain for prefabricated building projects.

2 LITERATURE REVIEW

In recent years, the steady economic growth in China has promoted the development of construction industrialization. This trend is driving the shift of building construction technology towards prefabricated construction technology. Today, the development of prefabricated buildings is restricted by high cost, low integration degree of industry chains, lack of information exchange between participants, and difficult risk management control. If introduced into prefabricated buildings, the concept of supply chain management not only effectively solves the aforementioned problems but also improves work efficiency, promotes exchange and cooperation, and maximizes benefits.

To date, many scholars have achieved robust research results in the supply chain risk management of prefabricated buildings. With the rise of prefabricated buildings in the construction field, several main supply chain risk analyses of prefabricated buildings have been published. Jiang et al. [1] summarized comprehensive risk factors, analyzed supply chain risks by constructing a risk network model, explored the internal relationship and transmission path between risks, and proposed the corresponding control measures. Lee et al. [2] obtained 49 risk factors leading to cost increase in the entire life cycle of prefabricated buildings in Korea using the failure mode and influence analysis method. Li et al. [3] comprehensively identified various risks in the investment stage of prefabricated buildings in China, established a risk identification feedback chart and a risk flow chart by using the system dynamics method, and quantitatively estimated the investment risk factors. Merschmann et al. [4] analyzed the influence of flexibility and uncertainty of prefabricated building supply chain on the performance of construction enterprises, performed an empirical analysis of German manufacturing enterprises, and drew relevant conclusions. Ratick et al. [5] stated that supply chain resilience could be enhanced by providing emergency inventories and storage equipment. Hosseini et al. [6] believed that factors, such as the reliability of supply chain enterprises and the product recovery rate, would affect the resilience of the supply chain. Mancheri et al. [7] pointed out that the flexibility and resilience of the supply chain itself would positively influence the resilience of the supply chain. To sum up, the process of supply chain risk analysis and evaluation of prefabricated buildings mainly focuses on a certain link in the supply chain, such as cost, investment, and supply chain resilience. However, no complete supply chain risk assessment system has been formed yet.

The supply chain of prefabricated buildings is an overall network structure with the general contractor at its core and is composed of design units, material and equipment suppliers, component manufacturers, subcontractors, and owners [8]. All units are connected by logistics, capital flow, and information flow [9]. At present, the current research on the risks of prefabricated buildings mostly focuses on quality [10], safety [11], schedule [12], and cost [13], while the research on the overall supply chain risks stays at the development stage. Koc et al. [14] related risk factors with stakeholders, and identified the key stakeholders that affected supply chain risks at all stages of the project life cycle. Zhang et al. [15] summarized the factors affecting the resilience of the supply chain, established a structural equation model, and confirmed that the production and construction of parts were the key factors affecting the supply chain resilience. Hsu et al. [16] discussed the influence of the schedule deviation on the supply chain of prefabricated buildings, and established a mathematical model that could choose the optimal production and transportation scheme. Yang et al. [17] adopted the fuzzy set qualitative comparative analysis method to analyze the green supply chain risk of prefabricated buildings from a holistic perspective, and fully considered internal and external links to help all participants in the supply chain to avoid risks. Sun et al. [18] analyzed the risk transmission effect, established a risk network model combining the complex network theory, and proposed the risk immunization strategy.

To sum up, certain research results regarding the supply chain of prefabricated buildings have been achieved. However, such problems as unclear risk factors and inaccurate evaluation results induced by single-mode construction exist because of the not inadequate application of prefabricated buildings in China. In this study, therefore, high-frequency risk factors were summarized and analyzed by looking up relevant literature based on the existing research results. A risk factor index system was established, and the supply chain risk factors of prefabricated buildings were explored by establishing an AHP-DEMATEL (Analytic Hierarchy Process and Decision-making Trial and Evaluation Laboratory) composite model. With this model, the weight of each factor was calculated and adjusted, the influencing degree of each factor in the supply chain on prefabrication risks in China was deeply analyzed, and the corresponding risk avoidance strategies were formulated.

3 METHODOLOGY

The weight of each influencing factor was calculated by AHP to measure its importance in the supply chain risk of prefabricated buildings, but this method ignored the interaction between two factors. However, the DEMATEL method [19], which was based on the graph theory and matrix, considered the causal relationship between the risk factors and their mutual influencing degree and effectively analyzed the logical relationship between the key factors that affected the supply chain risk of prefabricated buildings. In this study, the AHP and DEMATEL methods were combined, and the importance of each influencing factor and the correlation between the factors were comprehensively considered. On this basis, the ISM method exhibited a systematic structure of key factors influencing the supply chain risk of prefabricated buildings in the form of layered and directed topology, which could divide a complex architecture into a clearly visible multilayered structure; mine the fundamental, transitional, and surface-layer factors influencing the supply chain risk of prefabricated buildings; and help supply chain risk managers of prefabricated buildings master the source of risks.

3.1 Establishment of Risk Assessment Index System

By looking up the literature related to the supply chain of prefabricated buildings, we screened out related risk factors by combining the questionnaire survey results and interview results with the findings of experts in prefabricated buildings according to the basic principle of scientificity and reasonability. Then, a supply chain risk evaluation index system of prefabricated buildings was constructed, including seven first-level indexes, namely, design risk, procurement risk, production risk, transportation risk, assembly risk, external environmental risk, and compatibility risk, as well as 23 second-level indexes such as the feasibility of schematic design and the inconformity of product design with the standard.

(1) Design risk. The feasibility of schematic design determines the overall operation of the supply chain. The reasonable component splitting design is an important guarantee for producing qualified components in the production stage and completing assembly on time in the assembly stage, so the risk in the design stage is related to the success or failure of the entire project.

(2) Procurement risk. The price of purchased products is also associated with the cost control of the prefabricated building supply chain. Therefore, reducing the procurement risk of prefabricated buildings not only strengthens the management of the supply chain operation of prefabricated buildings but also reduces the cost risk of the supply chain of prefabricated buildings.

(3) Production risk. The key difference between prefabricated building projects and traditional building projects is that the production and processing of components are carried out in the factory. The production risk of prefabricated buildings directly affects the quality and safety of the entire construction project. Component manufacturers play a central role in the supply chain of prefabricated buildings, so reducing the risk in the production stage can fundamentally improve the toughness and resilience of the supply chain of prefabricated buildings when it is affected.

(4) Logistics risk. The traffic situation in the logistics process of assembled building components is uncertain, and ensuring the punctuality of logistics is difficult. Any traffic accident causes extra losses of personnel and

properties [20]. The lack of adequate protective measures in the logistics process of prefabricated building components also leads to damage that makes components unusable.

(5) Assembly risk. For prefabricated buildings, prefabricated components are often hoisted using mechanical equipment. The improper storage of spare parts increases the difficulty of hoisting, reduces work efficiency, and increases the schedule risk of the supply chain. The shortage of construction technologies and construction personnel gives rise to quality problems and even safety accidents, which seriously threaten the supply chain operations.

(6) External environmental risks. National policy regulation refers to the fact that the government regulates and intervenes with the operating state and relation of the supply chain of prefabricated buildings by means of policies, regulations, and plans, thus ensuring the sustainable, rapid, coordinated, and healthy development of the supply chain of prefabricated buildings. National policy regulation decides the supply chain risk of prefabricated buildings to a certain extent. At present, the public has not completely accepted the concept of prefabricated buildings; this impedes the market acceptance of prefabricated building projects. Therefore, the influence of market environmental risks on the supply chain is non negligible [21].

(7) Compatibility risk. Compatibility refers to the degree of mutual coordination between the modules of prefabricated buildings, and the compatibility risk is also an important constituent of the supply chain risk management of prefabricated buildings. In terms of the compatibility risk, two second-level indexes, namely, product standardization and forward or backward compatibility, were designed. Product standardization was the foundation for the supply chain of prefabricated buildings, and forward or backward compatibility was also a key index measuring the expansibility of prefabricated buildings.

Based on the preceding analysis, a supply chain risk evaluation index system containing 7 first-level indexes and 23 second-level indexes was established, as shown in Tab. 1.

Table 1 Prefabricated buildings supply chain risk evaluation index system

First-level indexes	Second-level indexes	Symbols
Design Risk B_1	Scheme design feasibility	B_{11}
	Product design does not comply with standards	B_{12}
	Design changes	B_{13}
	Immature design technology level	B_{14}
Procurement Risk B_2	Procurement product price	B_{21}
	Quality of purchased materials	B_{22}
	Timeliness of supply products	B_{23}
Production Risk B_3	Component production process and equipment	B_{31}
	Component quality	B_{32}
	On time production completion	B_{33}
	Lack of suppliers of prefabricated components that meet standards	B_{34}
Logistics Risk B_4	Logistics distance	B_{41}
	Damaged prefabricated components during logistics	B_{42}
	Logistics punctuality	B_{43}
Assembly Risk B_5	Immature assembly technology	B_{51}
	Unreasonable control of assembly schedule	B_{52}
	Safety accident risk	B_{53}
	Rework risk	B_{54}
	Mechanical failure	B_{55}
External Risk B_6	Government policy regulation	B_{61}
	Market environment impact	B_{62}
Compatibility Risk B_7	Product standardization	B_{71}
	Forward or backward compatibility	B_{72}

3.2 AHP Method

According to Tab. 1, the key factor system A was constructed for the first-level indexes affecting the supply chain risk of prefabricated buildings. The decision-making objective was divided into several second-level indexes B_1, B_2, …, B_n, and the comparative judgment matrix B between every two second-level indexes was obtained, as shown in the following equation:

$$B=\begin{bmatrix} b_{11} & b_{12} & \cdots & b_{1y} & \cdots & b_{1n} \\ b_{21} & b_{22} & \cdots & b_{2i} & \cdots & b_{2n} \\ b_{11} & b_{12} & \cdots & b_{ij} & \cdots & b_{n} \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ b_{n1} & b_{n2} & \cdots & b_{ni} & \cdots & b_{nn} \end{bmatrix} \quad (1)$$

where b_{ij} indicates the importance of factor B_i to factor B_j, which is usually expressed by the scale 1-9, as shown in Eq. (2).

$$b_{ij}=\frac{1}{b_{ji}}(b_{ij}>0) \quad (2)$$

The maximum characteristic root and weight vector of the pairwise judgment comparison matrix at each level were solved, followed by the consistency check. The weight vector of each layer needs to meet nonnegativity and consistency requirements, namely, $\sum_{i}^{n}W_i=1$ and $W_i\geq 0$, $\sum_{j}^{m}W_{ij}=1$, and $W_{ij}\geq 0$; $i=1, 2, 3, \ldots, n$; $j=1, 2, 3, \ldots, m$.

3.3 DEMATEL Method

DEMATEL is an effective factor analysis and identification method that is effective in dealing with complex social problems, especially index systems characterized by uncertain relations between factors. This method has been widely used in many fields. By observing the mutual influencing degree between two key factors that affect the supply chain risk of prefabricated buildings, the DEMATEL method uses matrices and related mathematical theories to calculate the structural relationship and influence intensity among the factors, and establishes the system structure model among the factors.

The Likert scale was used to quantify the strength of the direct relationship between various factors. 0 indicates that one factor has no influence on another, 1 indicates that one factor has a weak influence on another, 3 indicates that one factor has a moderate influence on another, and 5 indicates that one factor has a strong influence on another. The direct influence matrix $\boldsymbol{A}$ was established, as shown in the Eq. (3).

$$\boldsymbol{A}=(a_{ij})_{n\times n}=\begin{bmatrix} a_{11} & \cdots & a_{1n} \\ \vdots & \ddots & \vdots \\ a_{n1} & \cdots & a_{nn} \end{bmatrix} \tag{3}$$

where a_{ij} denotes the influencing degree of the i^{th} factor on the j^{th} factor.

After normalization, the values of the elements that directly affect matrix $\boldsymbol{A}$ are between 0 and 1, and the calculation formula is shown as follows:

$$X=(x_{ij})_{n\times n}=\frac{\boldsymbol{A}}{\max\left[\max\limits_{1\le i\leqslant n}\sum_{j=1}^{n}a_{ij},\max\limits_{1\le j\le n}\sum_{i\ne 1}^{n}a_{ij}\right]} \tag{4}$$

where X represents the normalized direct influence matrix. Then, a comprehensive influence matrix $\boldsymbol{T}$ was constructed as shown in Eq. (5), where $\boldsymbol{E}$ stands for the unit matrix.

$$\boldsymbol{T}=X\left(\boldsymbol{E}-X\right)^{-1} \tag{5}$$

The influencing degree D of each influencing factor and the influenced degree C are displayed in Eq. (6) and Eq. (7):

$$D=\left(t_i\right)_{n\times 1}=\left(\sum_{j=1}^{n}t_{ij}\right)_{n\times 1} \tag{6}$$

$$C=\left(t_j\right)_{1\times n}=\left(\sum_{i=1}^{n}t_{ij}\right)_{1\times n} \tag{7}$$

where t_i represents the value of the influencing degree of the i^{th} influencing factor, and t_j is the value of the influenced degree of the j^{th} influencing factor.

The cause degree $v_i = D_i - C_i$ of each influencing factor was calculated. If the cause degree of the i^{th} factor was smaller than 0, it was a result factor, and if the cause degree was greater than 0, it was a cause factor. Result factors were the influencing results of the cause factors.

The centrality $h_i = D_i + C_i$ of each influencing factor was calculated and sorted in descending order, and a greater value of h_i indicated the greater influence of these influencing factors on the quality of animal husbandry products during the production process. The weight w_i of each influencing factor acquired through AHP was combined with their centrality h_i obtained through the DEMATEL method to calculate the comprehensive weight z_i of influencing factors as shown in Eq. (8).

$$z_i=\frac{h_iW_i}{\sum\limits_{i=1}^{n}h_iW_i}\quad (i=1,\ 2,\cdots,\ n) \tag{8}$$

3.4 ISM Method

A reachability matrix of ISM was established. In most of the traditional research literature, the overall influence matrix was generally simplified by setting a threshold. In the present study, the threshold λ was calculated on the basis of Eq. (9), which could reduce human intervention and improve the research accuracy.

$$\lambda=\sum_{i,j=1}^{n}T_{i,j}\Big/n^2+\sqrt{\frac{\sum\limits_{i,j=1}^{n}\left(T_{i,j}-\overline{T_{i,j}}\right)^2}{n^2-1}} \tag{9}$$

where λ is the sum of the average value and standard deviation of the comprehensive influence matrix. Thus, the reachability matrix in the ISM model was calculated as shown in the Eq. (10).

$$\boldsymbol{K_{ij}}=\begin{cases}1, & T_{ij}>\lambda \\ 0, & T_{ij}<\lambda\end{cases} \tag{10}$$

Then, based on the reachability matrix $\boldsymbol{K}_{ij}$, the reachable set $R(S_i)$ and antecedent set $A(S_i)$ were obtained. $R(S_i)$ is the set of columns containing element 1 of factors in row i of reachability matrix $\boldsymbol{K}_{ij}$, and $A(S_i)$ is the set of rows containing element 1 of factors in column i of the reachability matrix. When $R(S_i) = R(S_i)\cap A(S_i)$,$R(S_i)$ was taken as the top-layer factor, and the results of all top-layer factors were divided according to this principle. This operation was repeated after already layered elements were deleted until all layers of influencing factors were divided.

4 RESULT ANALYSIS AND DISCUSSION

4.1 Weight Solving of Influencing Factors Based on AHP

According to the aforementioned steps of the AHP algorithm, 15 employees, including R&D, design, production management, and marketing personnel of a prefabricated building enterprise, were invited as experts to score the key influencing factors of the supply chain risk of prefabricated buildings. The experts compared the importance of the key factors affecting the supply chain risk of prefabricated buildings, calculated the average value, and constructed the judgment matrix of each decision-making goal, and the judgment matrix is consistent. The weight of supply chain risk influencing factors of prefabricated buildings was summarized, and the results are listed in Tab. 2.

Table 2 The weight of supply chain risk influencing factors of prefabricated buildings

First-level indexes	First-level indexes weight	Second-level indexes	Second-level indexes weight	Comprehensive weight of Secondary indexes
Design Risk B_1	0.1577	Scheme design feasibility	0.4106	0.0648
		Product design does not comply with standards	0.2898	0.0457
		Design changes	0.0925	0.0146
		Immature design technology level	0.2071	0.0327
Procurement Risk B_2	0.1945	Procurement product price	0.1962	0.0382
		Quality of purchased materials	0.4008	0.0780
		Timeliness of supply products	0.4030	0.0784
Production Risk B_3	0.2204	Component production process and equipment	0.4365	0.0962
		Component quality	0.1502	0.0331
		On time production completion	0.1383	0.0305
		Lack of suppliers of prefabricated components that meet standards	0.2750	0.0606
Logistics Risk B_4	0.2346	Logistics distance	0.4626	0.1085
		Damaged prefabricated components during logistics	0.4158	0.0975
		Logistics punctuality	0.1216	0.0285
Assembly Risk B_5	0.0455	Immature assembly technology	0.1620	0.0074
		Unreasonable control of assembly schedule	0.2586	0.0118
		Safety accident risk	0.1496	0.0068
		Rework risk	0.0953	0.0043
		Mechanical failure	0.3344	0.0152
External Risk B_6	0.0605	Government policy regulation	0.5435	0.0329
		Market environment impact	0.4565	0.0276
Compatibility Risk B_7	0.0868	Product standardization	0.4553	0.0395
		Forward or backward compatibility	0.5447	0.0473

4.2 Centrality Calculation of Key Factors Based on DEMATEL Method

Using the Likert scale, the 15 experts were asked to judge whether a direct relationship existed between the influencing factors and the strength of the relationship. The value with the highest frequency in the results was taken as the value in the direct influence matrix to obtain the direct influence matrix ***A***, which was normalized according to a certain formula to obtain the comprehensive influence matrix ***T***, as shown in Tab. 3.

Table 3 Comprehensive influence matrix ***T*** of prefabricated buildings' supply chain risk

	B_{11}	B_{12}	B_{13}	B_{14}	B_{21}	B_{22}	B_{23}	B_{31}	B_{32}	B_{33}	B_{34}	B_{41}	B_{42}	B_{43}	B_{51}	B_{52}	B_{53}	B_{54}	B_{55}	B_{61}	B_{62}	B_{71}	B_{72}
B_{11}	0.036	0.162	0.057	0.028	0.037	0.012	0.006	0.014	0.095	0.007	0.007	0.008	0.012	0.005	0.055	0.006	0.016	0.018	0.007	0.004	0.008	0.102	0.122
B_{12}	0.077	0.037	0.079	0.065	0.118	0.022	0.015	0.020	0.063	0.019	0.017	0.017	0.017	0.012	0.026	0.003	0.011	0.012	0.004	0.014	0.016	0.095	0.093
B_{13}	0.157	0.177	0.034	0.085	0.060	0.013	0.010	0.015	0.046	0.010	0.009	0.009	0.010	0.007	0.014	0.002	0.008	0.008	0.003	0.007	0.008	0.083	0.173
B_{14}	0.116	0.081	0.050	0.024	0.107	0.037	0.058	0.080	0.043	0.024	0.021	0.023	0.019	0.017	0.015	0.002	0.022	0.013	0.005	0.013	0.016	0.028	0.048
B_{21}	0.030	0.027	0.018	0.026	0.022	0.161	0.095	0.107	0.202	0.149	0.136	0.131	0.119	0.097	0.042	0.005	0.027	0.043	0.010	0.122	0.121	0.029	0.039
B_{22}	0.028	0.025	0.018	0.024	0.010	0.017	0.063	0.100	0.160	0.052	0.058	0.063	0.052	0.024	0.009	0.001	0.018	0.029	0.006	0.002	0.008	0.037	0.056
B_{23}	0.025	0.023	0.016	0.023	0.011	0.015	0.041	0.123	0.093	0.159	0.109	0.143	0.083	0.136	0.007	0.001	0.012	0.025	0.005	0.003	0.017	0.023	0.028
B_{31}	0.146	0.149	0.109	0.154	0.080	0.077	0.020	0.027	0.051	0.017	0.017	0.019	0.016	0.011	0.021	0.002	0.014	0.056	0.009	0.010	0.016	0.112	0.114
B_{32}	0.073	0.054	0.033	0.053	0.017	0.072	0.015	0.105	0.061	0.013	0.015	0.029	0.087	0.009	0.042	0.005	0.113	0.145	0.032	0.002	0.028	0.055	0.061
B_{33}	0.005	0.005	0.004	0.005	0.002	0.003	0.088	0.016	0.021	0.036	0.100	0.021	0.010	0.140	0.002	0.000	0.003	0.010	0.002	0.002	0.014	0.008	0.012
B_{34}	0.040	0.035	0.025	0.033	0.013	0.016	0.094	0.072	0.149	0.131	0.025	0.026	0.022	0.103	0.018	0.002	0.023	0.086	0.014	0.017	0.021	0.069	0.115
B_{41}	0.004	0.004	0.003	0.004	0.002	0.003	0.134	0.017	0.023	0.109	0.022	0.037	0.102	0.148	0.001	0.000	0.003	0.005	0.001	0.001	0.014	0.004	0.005
B_{42}	0.008	0.006	0.004	0.006	0.002	0.008	0.017	0.013	0.112	0.014	0.004	0.125	0.021	0.018	0.004	0.001	0.012	0.016	0.003	0.000	0.005	0.006	0.007
B_{43}	0.001	0.001	0.001	0.001	0.000	0.001	0.027	0.004	0.005	0.108	0.012	0.065	0.013	0.024	0.000	0.000	0.001	0.002	0.000	0.000	0.091	0.001	0.002
B_{51}	0.034	0.029	0.015	0.030	0.007	0.004	0.018	0.009	0.040	0.022	0.022	0.021	0.016	0.020	0.052	0.124	0.126	0.096	0.078	0.001	0.029	0.009	0.012
B_{52}	0.047	0.040	0.022	0.041	0.011	0.010	0.097	0.028	0.098	0.137	0.120	0.088	0.084	0.134	0.165	0.019	0.148	0.125	0.084	0.003	0.044	0.019	0.027
B_{53}	0.183	0.156	0.080	0.162	0.037	0.020	0.039	0.035	0.180	0.033	0.048	0.068	0.033	0.022	0.184	0.022	0.064	0.134	0.150	0.005	0.125	0.042	0.054
B_{54}	0.183	0.156	0.080	0.162	0.037	0.020	0.039	0.035	0.180	0.033	0.048	0.068	0.033	0.022	0.184	0.022	0.133	0.065	0.150	0.005	0.125	0.042	0.054
B_{55}	0.046	0.039	0.020	0.041	0.009	0.005	0.022	0.010	0.047	0.019	0.015	0.020	0.015	0.009	0.121	0.014	0.150	0.149	0.041	0.001	0.120	0.011	0.014
B_{61}	0.005	0.005	0.003	0.005	0.091	0.075	0.058	0.021	0.031	0.023	0.020	0.022	0.017	0.016	0.005	0.001	0.004	0.007	0.001	0.011	0.012	0.006	0.008
B_{62}	0.004	0.004	0.002	0.004	0.002	0.002	0.131	0.017	0.019	0.111	0.022	0.026	0.071	0.029	0.001	0.000	0.002	0.005	0.001	0.001	0.003	0.004	0.005
B_{71}	0.075	0.090	0.078	0.076	0.020	0.005	0.006	0.008	0.014	0.004	0.003	0.004	0.004	0.003	0.006	0.001	0.003	0.003	0.001	0.002	0.003	0.024	0.115
B_{72}	0.098	0.077	0.075	0.060	0.017	0.005	0.005	0.007	0.015	0.003	0.003	0.003	0.003	0.002	0.007	0.001	0.003	0.003	0.001	0.002	0.003	0.078	0.032

The value of each index was calculated using the comprehensive influence matrix, including the influencing degree (D), influenced degree (C), centrality ($D + C$), and cause degree ($D - C$). The weight of each factor obtained by the AHP method and the centrality of each factor acquired through the DEMATEL method were comprehensively calculated to obtain the final weight of each influencing factor, as shown in Tab. 4.

Table 4 D_i, C_i, $D + C_i$, $D - C_i$, AHP weight and final weight of prefabricated buildings' supply chain risk factors

	Influencing degree *D* value	Influenced degree *C* value	Centrality *D* + C value	Cause degree *D* − *C* value (*R*)	Attribute	AHP weight	Final weight	Sorting
B_{11}	0.825	1.424	2.250	−0.599	Resultant factor	0.0648	0.080	4
B_{12}	0.852	1.380	2.232	−0.527	Resultant factor	0.0457	0.056	8
B_{13}	0.949	0.827	1.776	0.122	Causal factor	0.0146	0.014	17
B_{14}	0.861	1.109	1.970	−0.248	Resultant factor	0.0327	0.035	12
B_{21}	1.759	0.712	2.471	1.047	Causal factor	0.0382	0.052	10
B_{22}	0.860	0.602	1.462	0.257	Causal factor	0.0780	0.062	7
B_{23}	1.119	1.098	2.217	0.021	Causal factor	0.0784	0.095	3
B_{31}	1.247	0.883	2.130	0.364	Causal factor	0.0962	0.112	1
B_{32}	1.120	1.750	2.870	−0.630	Resultant factor	0.0331	0.052	9
B_{33}	0.505	1.234	1.740	−0.729	Resultant factor	0.0305	0.029	14
B_{34}	1.151	0.855	2.005	0.296	Causal factor	0.0606	0.066	6
B_{41}	0.644	1.035	1.679	−0.390	Resultant factor	0.1085	0.100	2
B_{42}	0.412	0.859	1.271	−0.448	Resultant factor	0.0975	0.068	5
B_{43}	0.359	1.008	1.367	−0.649	Resultant factor	0.0285	0.021	15
B_{51}	0.814	0.981	1.795	−0.167	Resultant factor	0.0074	0.007	22
B_{52}	1.592	0.233	1.825	1.359	Causal factor	0.0118	0.012	20
B_{53}	1.877	0.916	2.793	0.962	Causal factor	0.0068	0.010	21
B_{54}	1.877	1.053	2.930	0.825	Causal factor	0.0043	0.007	23
B_{55}	0.940	0.609	1.548	0.331	Causal factor	0.0152	0.013	18
B_{61}	0.446	0.229	0.675	0.218	Causal factor	0.0329	0.012	19
B_{62}	0.465	0.846	1.311	−0.380	Resultant factor	0.0276	0.020	16
B_{71}	0.546	0.888	1.434	−0.341	Resultant factor	0.0395	0.031	13
B_{72}	0.504	1.196	1.699	−0.692	Resultant factor	0.0473	0.044	11

4.3 Calculation and Analysis Based on ISM Model

The ISM model for the key factors influencing the supply chain risk of prefabricated buildings was established. Through multiple trials, the threshold λ was taken as 0.15, and the reachability matrix in the above step was decomposed, as shown in Tab. 4.

Then, the reachable set *R*, antecedent set *Q*, and intersection *A* of the reachability matrix *M* were calculated using MATLAB, as reported in Tab. 5.

Table 5 Reachable set, antecedent set, and their intersection table

	Reachable set *R*	Antecedent set *Q*	Intersection set *A* = *R*∩*Q*
B_{11}	1, 2	1, 3, 12, 13, 16, 17, 18, 19	1
B_{12}	2	1, 2, 3, 12, 13, 16, 17, 18, 19	2
B_{13}	1, 2, 3, 23	3, 13	3
B_{14}	4	4, 7, 12, 16, 17, 18, 19	4
B_{21}	5, 6, 9, 20	5	5
B_{22}	6, 9	5, 6	6
B_{23}	4, 7, 10	7	7
B_{31}	8	8	8
B_{32}	9	5, 6, 9, 12, 16, 17, 18, 19	9
B_{33}	10	7, 10	10
B_{34}	11	11	11
B_{41}	1, 2, 4, 9, 12, 14, 15, 16, 17, 18, 19, 21	12	12
B_{42}	1, 2, 3, 13, 22, 23	13	13
B_{43}	14	12, 14, 16, 17, 18, 19, 21	14
B_{51}	15	12, 15, 16, 17, 18, 19	15
B_{52}	1, 2, 4, 9, 14, 15, 16, 17, 18, 19, 21	12, 16	16
B_{53}	1, 2, 4, 9, 14, 15, 17, 18, 19, 21	12, 16, 17, 18, 19	17, 18, 19
B_{54}	1, 2, 4, 9, 14, 15, 17, 18, 19, 21	12, 16, 17, 18, 19	17, 18, 19
B_{55}	1, 2, 4, 9, 14, 15, 17, 18, 19, 21	12, 16, 17, 18, 19	17, 18, 19
B_{61}	20	5, 20	20
B_{62}	14, 21	12, 16, 17, 18, 19, 21	21
B_{71}	22	13, 22	22
B_{72}	23	3, 13, 23	23

Note: Numbers represent a certain factor, such as 2 representing the second factor

Table 6 Hierarchical decomposition of influencing factors of prefabricated buildings' supply chain risk

Hierarchy	Influencing factors
Layer 1(top layer)	B_{12}, B_{14}, B_{31}, B_{32}, B_{33}, B_{34}, B_{43}, B_{51}, B_{61}, B_{71}, B_{72}
Layer 2	B_{11}, B_{22}, B_{23}, B_{62}
Layer 3	B_{13}, B_{21}, B_{53}, B_{54}, B_{55}
Layer 4	B_{42}, B_{52}
Layer 5 (bottom layer)	B_{41}

According to Tab. 5, the hierarchical decomposition table for the influencing factors of the supply chain risk of prefabricated buildings was acquired (Tab. 6).

It shows that the logistics transportation distance, damage to prefabricated components during transportation, and unreasonable control of the assembly period were among the fundamental factors in the fifth and fourth layers.

(1) Logistics transportation distance. A very important link in the supply chain of prefabricated buildings is logistics transportation, and the problems in this link lead to the supply chain risk. In practice, the material transportation for prefabricated buildings is analyzed to avoid the possible risks in logistics transportation and the specific reasons for the risks are explained to improve the risk control level of the supply chain of prefabricated buildings.

(2) Damage to prefabricated components during transportation. Prefabricated buildings are subjected to risks because of various factors during transportation, and such risks increase with the increase of transportation distance, which exerts a great impact on the supply chain risk of prefabricated buildings. The damage to goods during the logistics transportation of prefabricated components should be better controlled to reduce the supply chain risk. To ensure the safety transportation of prefabricated parts, the consignors should take the corresponding measures according to the inherent and potential defects of prefabricated parts, formulate an appropriate mode of transportation and a scientific loading method, fully integrate all kinds of transportation resources, reduce the damage to prefabricated parts during transportation, and provide a convenient environment for the development of prefabricated buildings.

(3) Unreasonable control of the assembly period. The unreasonable factors affecting the progress of prefabricated buildings are analyzed. On the premise of ensuring the construction quality and sustainability, the control of the construction progress is strengthened by changing the hoisting time of the prefabricated components, strengthening the connection of key processes in the standard floor plan, adjusting the hoisting mode of the prefabricated components, and optimizing the team configuration. The practical problems affecting the time limit control of the standard assembly floor are solved to improve the risk control level of the supply chain of prefabricated buildings.

5 CONCLUSIONS

At present, the building supply chain system is at the development stage, and the supply chain risk management of prefabricated buildings is facing great challenges. Establishing a systematic risk assessment model is necessary to better identify and manage risks of prefabricated building supply chain. This model, combined with the previous analysis, leads to the following conclusions:

(1) Many stakeholders are involved in the prefabricated building supply chain, each operation node is complex, and many risks may occur in the entire life cycle. Cooperation among all participants is crucial to the stable operation of the prefabricated building supply chain.

(2) Logistics transportation distance, damage to prefabricated components during transportation, and unreasonable control of the assembly period are the fundamental factors that affect the risks of prefabricated buildings. Therefore, the supply chain risk of prefabricated buildings can be effectively reduced by reasonably controlling the transportation distance, improving the safety transportation efficiency of prefabricated components, and elevating the control level of the assembly period.

(3) Using the AHP-DEMATEL-ISM combined model, we determined the risk levels and comprehensive risk levels at different stages, and the main factors affecting the supply chain risk of prefabricated buildings were identified to effectively perform a reasonable risk assessment of the supply chain of prefabricated buildings with many participants, thereby improving the risk control level.

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6 REFERENCES

[1] Jiang, R., Mao, C., Hou, L., Wu, C. K., & Tan, J. J. (2018). A SWOT analysis for promoting off-site construction under the backdrop of China's new urbanisation. *Journal of Cleaner Production*, *173*, 225-234. https://doi.org/10.1016/j.jclepro.2017.06.147

[2] Lee, J. S. & Kim, Y. S. (2016). Analysis of cost increasing risk factors in modular construction in Korea using FMEA. *Ksce Journal of Civil Engineering*, *21*, 1999-2010. https://doi.org/10.1007/s12205-016-0194-1

[3] Li, M., Li, G., Huang, Y., & Deng, L. Y. (2017). Research on investment risk management of Chinese prefabricated construction projects based on a system dynamics model. *Buildings*, *7*(3), 599-613. https://doi.org/10.3390/buildings7030083

[4] Merschmann, U. & Thonemann, U. W. (2011). Supply chain flexibility, uncertainty and firm performance: An empirical analysis of German manufacturing firms. *International Journal of Production Economics*, *13*(1), 43-53. https://doi.org/10.1016/j.ijpe.2010.10.013

[5] Raick. S., Meacham, B., & Aoyama, Y. (2010). Locating backup faclities to enhance supply chain disaster resilience. *Growth & Change*, *39*(4), 642-666. https://doi.org/10.1111/j.1468-2257.2008.00450.x

[6] Hosseini, S. & Khaled, A. A. (2016). A hybrid ensemble and AHP approach for resilient supplier selection. *Journal of Intelligent Manufacturing*, *30*(1), 207-228. https://doi.org/10.1007/s10845-016-1241-y

[7] Mancheri, N. A., Sprecher, B., Deetman, S. Young, S. B., Bleischwitz, R., Dong, L., Kleijn, R., & Tukker, A. (2018). A hybrid ensemble and AHP approach for resilient supplier selection. *Resources, Conservation and Recycling*, *30*(1), 207-228. https://doi.org/10.1016/j.resconrec.2017.10.018

[8] Huang, G. L. & Zhang, C. (2020). Green supply chain risk of prefabricated buildings based on SNA. *Journal of Civil Engineering and Management*, *37*(2), 41-49.

[9] Zhang, F. Y. & Xie, J. Y. (2020). Risk assessment of assembly construction supply chain based on cloud model. *Intelligent Building & Smart City*, *3*, 123-124. https://doi.org/10.1016/j.resconrec.2017.10.018

[10] Qu, F. Q., Chen, C. Y., & Yan, W. (2019). Quality risk assessment of prefabricated building components based on ANP-FUZZY. *Journal of Civil Engineering and Management*, *36*(3), 92-98.

[11] Chang, C. G. & Wu, X. (2018). Research on the safety risk assessment of assembly building construction. *Construction Economy*, *39*(8), 49-52.

[12] Li, C. Z., Zhong, R. Y., Xue, F., Xu, G., Chen, K., Huang, G. G., & Shen, G. Q. (2017). Integrating RFID and BIM technologies for mitigating risks and improving schedule performance of prefabricated house construction. *Journal of Cleaner Production*, *165*, 1048-1062. https://doi.org/10.1016/j.jclepro.2017.07.156

[13] Xun, Z. Y., Zhang, L. M., Zhao, Z. Y., & Xu, Y. L. (2020). Cost risk evaluation of prefabricated buildings based on combined weighted cloud model. *Journal of Civil Engineering and Management*, *37*(6), 8-13.

[14] Koc, K. & Gurgun, A. P. (2021). Stakeholder-associated life cycle risks in construction supply chain. *Journal of Management in Engineering*, *37*(1), 4020107-4020101. https://doi.org/10.1061/(ASCE)ME.1943-5479.0000881

[15] Zhang, M., Liu, Y., & Ji, B. (2021). Influencing factors of resilience of PBSC based on empirical analysis. *Buildings*, *11*(10), 467.

[16] Hsu, P., Aurisicchio, M., & Angeloudis, P. (2019). Risk-averse supply chain for modular construction projects. *Automation in Construction*, *106*, 102898. https://doi.org/10.1016/j.autcon.2019.102898

[17] Yang, H. & Ren, M. (2021). Research on risk management of green supply chain of prefabricated buildings based on QCA. *E3S Web of Conferences*, *248*(4), 03041. https://doi.org/10.1051/e3sconf/202124803041

[18] Sun, Y. Q. & Tian, Y. (2020). Research on key risks of prefabricated building supply chain based on complex network theory. *Construction Economy*, *41*(11), 79-83.

[19] Azmoodeh, M., Haghighi, F., & Motieyan, H. (2023). Capability Index: Applying a Fuzzy-Based Decision-Making Method to Evaluate Social Inclusion in Urban Areas Using the Capability Approach. *Social Indicators Research*, *165*(1), 77-105. https://doi.org/10.1007/s11205-022-03005-5

[20] Zhang, D., Wang, L., Xu, J., & Chen, K. (2021). Simulation analysis of the evolutionary mechanism of low-carbon rural logistics. *Dyna*, *96*(5), 484-491. https://doi.org/10.6036/10236

[21] Liu, X. J. & Li, D. D. (2019).Research on the influencing factors and promotion policies of assembly building development intention. *Mathematics in Practice and Theory*, *49*(1), 88-98. https://doi.org/10.1051/e3sconf/202124803041

Contact information:

Qiang CAI, PhD, Lecturer
Ningbo University of Technology,
No. 201, Fenghua Road, Jiangbei District, Ningbo, Zhejiang, 315211, China
E-mail: caiqiang@nbut.edu.cn

Yunchao DU, PhD, Associate Professor
Ningbo University of Technology,
No. 201, Fenghua Road, Jiangbei District, Ningbo, Zhejiang, 315211, China
E-mail: du_yunchao@nbut.edu.cn

Renxiang WANG, MD, Professor
(Corresponding author)
Ningbo University of Technology,
No. 201, Fenghua Road, Jiangbei District, Ningbo, Zhejiang, 315211, China
E-mail: wrx@nbut.edu.cn