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Study on Resilience Factors and Enhancement Strategies in Prefabricated Building Supply Chains

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Abstract: Prefabricated building holds promise for quality, efficiency, and sustainability when compared to traditional techniques. However, realizing prefabricated building work hinges on strengthening supply chain resilience. This research assesses interdependent risks undermining prefab network continuity during disruption. Questionnaire data from industry experts informed a structural equation model quantifying pathways between component production, construction, information, and other uncertainties. Findings confirm that project delays can be traced to manufacturing and on-site risks, with information gaps broadly propagating impacts. Meanwhile, organizational risks have an insignificant influence, suggesting partnership networks readily reconfigure around operational contingencies. Robust information infrastructures and coordination, therefore, offer crucial leverage. Accordingly, a multidimensional resilience enhancement strategy is formulated, prioritizing supply chain transparency, digital integration, inventory buffering, contingencies planning, and transportation flexibility. Our mixed-methods approach advances the construction literature by demonstrating the applicability of structural equation modeling for diagnostic resilience analytics. Industry leaders also gain actionable, evidence-based guidance on strategic investments to stabilize project flows. This dual theoretical and practical contribution underscores the versatility of tailored statistical assessments in furthering construction innovation objectives within complex, uncertain environments.

Keywords: prefabricated building; supply chain resilience; resilience enhancement strategy

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1. Introduction

The Earth's climate system is influenced by the emission of greenhouse gases resulting from human developmental activities. Presently, China stands as the world's largest emitter of greenhouse gases, facing substantial pressures and challenges in energy conservation and emissions reduction efforts. The construction industry, as a priority sector for advancing towards a low-carbon society, has garnered public attention [1]. China, as one of the world's major economies, has committed to achieving carbon neutrality by 2060 and reaching its emission peak by 2030 [2], as part of actively participating in global carbon reduction initiatives. In comparison to traditional construction, prefabricated building construction offers advantages such as lower resource consumption and reduced environmental pollution, positioning it as the future direction for the construction industry [3]. Meanwhile, in recent years, the construction industry has explicitly articulated the need for high-quality development, propelling the collaborative growth of intelligent construction and the industrialization of new building methods to facilitate transformative upgrades. In that spirit, and with climate targets also in mind, the vigorous development of prefabricated buildings stands out as a promising measure to enhance the level of industrialization in the construction sector [4].

The continuous and healthy development of industry, as well as the improvement of the modular construction industry chain, serve to be facilitated, thereby enhancing economic and societal standards [5]. Modular construction has taken shape in the industry chain under the impetus of policies and market guidance. However, as the industry develops nationwide, an increasing mismatch between management methods and production processes has become evident, leading to issues such as management disconnection. As a product of deep integration between the construction and manufacturing industries, prefabricated building works can leverage manufacturing experience to address bottlenecks in overall management during project construction, encompassing logistics, capital flow, and information flow, with the supply chain as the fundamental unit [6].

A resilient supply chain is characterized by its flexibility and agility, demonstrating the ability to swiftly adapt to and recover from disruptions in order to return to its original state or an even a more desirable state. Various scholars have provided nuanced definitions of supply chain resilience (SCR), as outlined in Table 1. It can be observed that resilience is defined in two dimensions: first, the system's ability to withstand risks and maintain stability, and second, the system's capacity to recover after being impacted by risks.

Table 1. The concepts of SCR.

Definitions	References
The supply chain's ability to minimize the likelihood of interruptions, reduce the consequences of these interruptions when they occur, and decrease the time required to restore normal performance.	[7–9]
The capability of the supply chain to achieve performance through adjustment strategies.	[10–12]
The supply chain's responsiveness to external or internal interruptions and vulnerabilities, coupled with its capacity to swiftly restore a state of high performance and efficiency.	[13,14]
The preparedness of the supply chain for unforeseen events, its ability to react to interruptions, and its capability to restore the structure and functionality of the supply chain through continuous strategies.	[15,16]
The ability of the supply chain to return to its original state in emergency risk environments.	[17]
The proactive planning and design capability of the supply chain network, enabling it to predict unexpected events, respond to interruptions, and sustain a robust state of operation.	[18,19]
The adaptive capability of the supply chain, which entails reducing the probability of disturbances, resisting the spread of disturbances by controlling the supply chain network, and effectively planning for recovery to a robust operational state.	[20]

To mitigate risk, the supply chain must be multidimensional and interdisciplinary, designed with the objectives of incorporating event preparedness, providing efficient and effective responses, and returning to or enhancing the original state after an interruption. In this paper, the resilience of prefabricated building supply chains (PBSCs) is defined as follows: under different types of risks, the prefabricated component supply system possesses the capability to resist, respond to, recover from, and adapt to interruptions in the supply chain [21]. Measurement metrics for the resilience of PBSCs are categorized into seven dimensions encompassing predictive capability, redundancy, robustness, and more, as detailed in Appendix A. Today, research shows that the supply chain of modular construction in China currently faces barriers like lack of coherence and slow promotion [22]. Moreover, global supply chains confront frequent disruptions and delays, posing obstacles to resilience [23]. Given these challenges, and aligned with the nascent state of domestic prefabrication networks, assessing and informing strategic priorities for resilience enhancement is critical.

Therefore, the objectives of this study were (1) to establish a model of factors influencing the resilience of PBSCs and identify key influencing factors; and (2) to explore strategies for enhancing the resilience of PBSCs. The remainder of this article is structured as follows to fulfill those aims—Section 2 establishes the theoretical background on PBSC resilience and reviews relevant scholarly literature, identifying limitations in the existing body of knowledge. Section 3 puts forward a hypothesized structural model based on proposed risk pathways and describes data collection and structural equation modeling (SEM) methodologies for assessment. Section 4 presents the analytical outcomes of testing the hypothetical model against survey data. Building on influential risks confirmed through the preceding SEM verification, Section 5 then discusses specific approaches construction firms can implement to bolster supply network continuity. Finally, Section 6 concludes by summarizing key findings and contributions.

2. Literature Review

A growing body of research has applied technological innovations in structural engineering [24,25] and construction methods. For example, robotic automation has been applied for modular tasks such as brick and rebar laying [26]. Photovoltaic glass curtain walls and adaptive facades allow for dynamic building–grid integration [27]. However, sustainability challenges persist, including substantial waste generation. Prefabricated building components made under controlled factory conditions offer advantages in precision, efficiency, and lower embedded emissions [3]. By integrating construction planning with off-site lean manufacturing principles, improved quality control is also enabled [28]. But investigations have predominantly centered around environmental analysis [29–31], lacking a focus on supply-side risks undermining the resilience and continuity crucial for scaling. This research addresses this gap, informing strategic priorities for smoothing project flows. Technical advancements in digital model coordination with suppliers, inventory optimization methods, and sensor-based logistics monitoring also show promise for further enhancing assembly supply chain stability [32].

Numerous scholars have conducted extensive research on PBSCs from diverse perspectives. Arshad et al. [33] explored the key influencing factors and their interactive relationships in the modular integrated building supply chain. They identified factors under four themes: dominant factors, symbiotic factors, external factors, and latent factors, emphasizing the need for further investigation into latent factors. Masood et al. [34], based on the driving nature of construction industry suppliers, employed expert surveys to determine the critical factors influencing supplier performance in PBSCs. Wang et al. [35] investigated the risk propagation mechanism in PBSCs and identified 17 key risk factors. Chang et al. [36] analyzed the advantages and disadvantages of Chinese assembly building from the perspectives of productivity, resources, and environmental sustainability, identifying green opportunities within the assembly supply chain—though in isolation from enhancing resilience capabilities.

As for the construction SCR, Liao et al. [37] established a framework for achieving resilience in the construction supply chain in three dimensions: organization, management, and technology. Chen et al. [38] investigated the resilience of construction supply chains under supply–demand uncertainty, considering uncertainties in supplier capacity and material demand. They proposed an optimization model for the construction supply chain. While extensive analysis exists of SCR, systematic assessment of vulnerability factors shaping prefab supply network resilience has been lacking. Furthermore, construction SCR research has grown but focused on traditional methods rather than prefabrication specifics [12,39].

SEM is a multivariate analysis model capable of precisely assessing the accuracy of influencing factor indicators while also examining the level of association among various influencing factors and measurement indicators [40]. Although SEM has demonstrated utility in construction risk evaluation, existing applications center on assessing factors like site safety [41], investment risks [42], and general supplier selection [43]. Implementations in specialized prefabrication contexts addressing supply chain issues remain sparse, though they are crucial given the intricacies and interdependencies involved.

By pioneering SEM-based resilience analysis tailored to prefab supply chain networks, this research bridges a significant methodological gap in addition to addressing thematic risk management limitations. The model development, structural testing, and targeted enhancement strategies offer a template for complementary future studies to build upon using robust statistical approaches. Practically, the methodical risk identification and mitigation guidance provides actionable steps for construction firms to adopt in strengthening project robustness.

3. Methodology

3.1. Modeling Process

3.1.1. Factors Influencing SCR

An extensive analysis of existing works on SCR and precursor risks in construction contexts [44–52] provided the basis for identifying relevant factors. Text mining techniques were applied to scan these articles in order to derive an initial set of keywords. A further manual review by two evaluators grouped these into categorical factors and selected 32 specific high-relevance variables based on consensus. The influencing factors identified in the PBSCs are presented in Table 2, classifying them into external environmental risks and internal risks. External environmental risks encompass considerations of the natural environment, policies and regulations, and industry standards, while internal risks within the supply chain include organizational relationships, information, management, design, component production, transportation, and construction risks.

Table 2. List of factors influencing PBSCs' resilience.

Primary Indicators	Items	Secondary Indicators	Descriptions
External environmental risks (EERs)	W1	Natural environment	The possibility of natural disasters.
	W2	Policies	The level of perfection of industrial policy.
	W3	Standard specification	The level of perfection of national standards.
Organizational relationship risks (ORRs)	H1	Communication and coordination	All participants in the supply chain can communicate and coordinate in a timely and effective manner.
	H2	Cooperation satisfaction	The level of satisfaction of the participants in the supply chain when cooperating.
	H3	Benefit distribution	The participants in the supply chain can achieve fairness and rationality in the distribution of benefits.
	H4	Target consistency	The consistency of the objectives of each participant in the supply chain with the project objectives.
	H5	Organizational mutual trust	Organizations can trust each other and have a high level of trust.
	H6	Cooperation mechanism	The risk sharing of all participants in the supply chain, cooperation, and establishment of relevant management systems.
Information risks (IRs)	X1	Information construction	The level of information construction of each participant in the supply chain.
	X2	Information platform	The perfection of the construction of an information interaction platform, which can provide the basis for information sharing.
	X3	Information sharing	The effect of information sharing among participants in the supply chain.
	X4	Information transmission	The accuracy and timeliness of information transmission between supply chain participants.
Management risks (MRs)	M1	Crisis consciousness	The management measures for coping with risks, such as setting up emergency plans and disaster recovery plans.
	M2	Risk response	Risk control measures can be carried out in times when risk events occur.
	M3	Experience summary	The ability to summarize experience and save data after a risk event occurs.

Table 2. *Cont.*

Primary Indicators	Items	Secondary Indicators	Descriptions
	M4	Resource integration and reconstruction	The ability to integrate resources and reconstruct processes after the occurrences of risk events.
	M5	Risk tolerance	The ability to bear economic losses after the occurrences of risk events.
Design risks (DRs)	D1	Component design	The technology of component design is innovative, and the standardization and modular design of components make it universal and interchangeable.
	D2	Change control	When a design change of the component occurs, it can respond quickly.
	D3	Number of personnel	The number of professional and technical personnel with the ability to deepen the design.
Component production risks (CPRs)	P1	Component redundancy	The overcapacity in component production and the ability to replace defective components in time.
	P2	Component manufacturing	The integration level of component production, component quality, manufacturing cost, and quantity.
	P3	Manufacturer management	The maturity of supplier management, supply plan, standardization, and specialization of the factory.
Transportation risks (TRs)	T1	Logistics company reliability	The transportation personnel have qualified skills and high quality, and the transportation company has a strong carrying capacity and can transport the components on time with reliability.
	T2	Transportation distance and cost	The distance of component transportation and the cost of transportation.
	T3	Transport flexibility	When supply chain disruption occurs, the transportation plan can be adjusted in time.
	T4	Level of transportation redundancy	Component transport has alternative routes and vehicles.
Construction risks (CRs)	S1	Construction capacity	The construction quality, methods and equipment, site layout management, and construction specialization.
	S2	Professional talents	The experience and ability of field personnel in the construction, cost, and safety of prefabricated buildings, and the base and plan setting of talent training.
	S3	Construction technology	Construction organization design, technical scheme formulation, and process flow arrangement.
	S4	Regulatory mechanisms	The number of personnel with construction site supervision experience.

3.1.2. PBSC Resilience Impact Factor Model

In the process of constructing a theoretical model, the initial step involves addressing specific research questions and building the model based on relevant theories and research assumptions. This approach aims to achieve an in-depth analysis of the elements of various potential and measured variables and their interrelationships. Similar to the measurement of SCR, the measurement of resilience in PBSCs primarily focuses on predictive capability, redundancy, robustness, agility, adaptability, recovery capability, and learning ability [21,53,54]. This paper utilizes SEM to analyze the research, with the goal of verifying the alignment between the constructed model and research assumptions and analyzing critical risk factors in PBSCs. A model depicting the influencing factors in PBSCs and their resilience is illustrated in Figure 1.

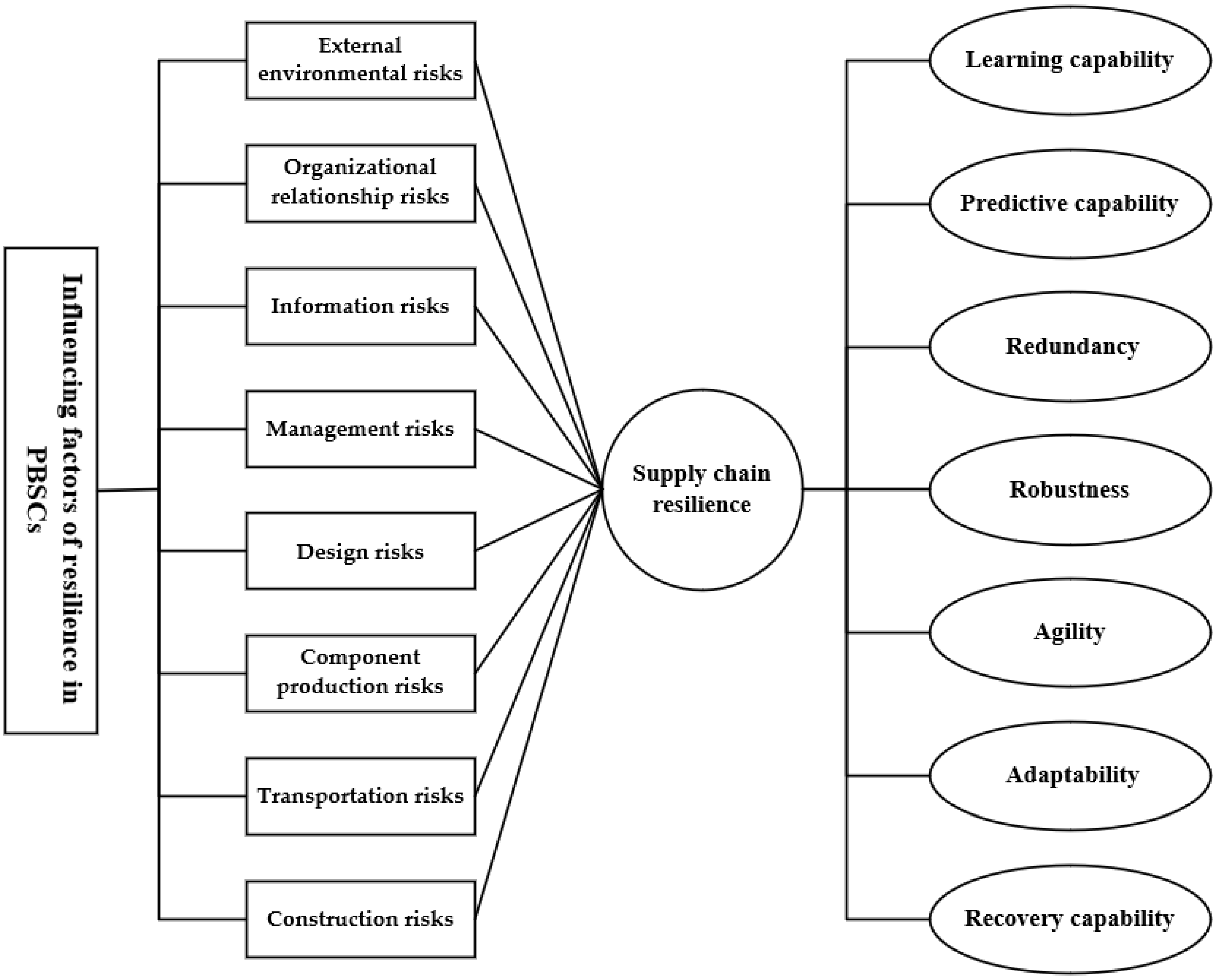

Figure 1. Influencing factors and SCR model of PBSCs.

Through the elucidation of the influencing factors above, we developed the following nine hypotheses:

H1. *'External environmental risks' have a significant positive impact on 'information risks'.*

H2. *'Transportation risks' have a significant positive impact on 'construction risks'.*

H3. *'Design risks' have a significant positive impact on 'component production risks'.*

H4. *'Information risks' have a significant positive impact on 'management risks'.*

H5. *'Information risks' have a significant positive impact on 'organizational relationship risks'.*

H6. *'Component production risks' have a significant positive impact on supply chain resilience.*

H7. *'Construction risks' have a significant positive impact on supply chain resilience.*

H8. *'Management risks' have a significant positive impact on supply chain resilience.*

H9. *'Organizational relationship risks' have a significant positive impact on supply chain resilience.*

3.2. Data Collection

In this study, we compiled a list of factors influencing the resilience of PBSCs based on literature analysis. Data collection was carried out through a questionnaire survey conducted online. The survey targeted experts with a certain knowledge background in prefabricated building projects. Participants were either currently involved in research or had completed prefabricated building projects. This approach ensured the credibility of the collected questionnaire data. The questionnaire consisted of three parts. The first part gathered basic information, including the workplace, educational background, and years of experience in the industry. The second part focused on investigating factors influencing the resilience of PBSCs, covering eight aspects such as external environmental risks, organizational relationship risks, and information risks. The third part aimed at measuring indicators of resilience in PBSCs, encompassing aspects like predictive ability, redundancy, and robustness, totaling seven aspects. A Likert five-point scale was employed to assess respondents' attitudes toward the survey options. A total of 205 sample data were collected for this research. After questionnaire cleaning, 174 valid data samples were obtained, resulting in an effective questionnaire recovery rate of 84.9%.

3.3. Data Analysis

This study employed the statistical analysis software SPSS and AMOS (IBM SPSS Statistics 28 and IBM SPSS Amos 28) for empirical analysis. First, reliability and validity of measurement items were assessed to purify scale quality. Subsequently, AMOS enabled confirmatory assessment of the measurement model, linking resilience dimensions to observed indicators. SEM was applied next to estimate the hypothesized causal pathways. Model fit indices determined the adequacy of model alignment with data trends. This iterative application of SEM analysis techniques resulted in an optimized model with satisfactory goodness of fit. Hypothesis testing was finally conducted to examine the identified risk interrelationships and their significance levels, informing strategic priorities.

4. Results

4.1. Description of Data

Descriptive statistical analysis was conducted on the demographic information of the 174 valid survey responses. From the statistical analysis of the basic information of the surveyed individuals in the questionnaire, it can be observed that 37.9% of the respondents are affiliated with research organizations, 20.1% with construction companies, 10.3% with design firms, and 8.0% with component production companies, indicating a diverse representation of professionals from different aspects of the construction field. The educational background of the respondents is predominantly master's degree holders, accounting for 59.2%, followed by bachelor's degree holders at 34.5%. As a high proportion of respondents possess postgraduate qualifications, the sample served to provide sound expertise. Regarding the years of experience in the industry, more than 75.9% of the surveyed individuals have been engaged in the industry for over 1 year. As all participants have a relevant industry background, we deemed that they were suitable to offer credible perspectives on the specific issues examined.

4.2. Reliability and Validity Test

Reliability, in the context of survey questionnaires, pertains to the dependability, consistency, or stability of the obtained results and serves as an indicator of the authenticity of respondents' responses. Cronbach's alpha coefficient is typically employed as a measure in internal consistency reliability assessments. A Cronbach's alpha between 0.6 and 0.8 indicates acceptable reliability, while a value higher than 0.8 represents good reliability. The reliability examination of the overall scale is illustrated in Table 3, while detailed statistics for various categories are presented in Table 4. The analysis reveals a high level of reliability in the collected questionnaire data, indicating robust consistency.

Table 3. Reliability test of the overall scale.

Cronbach's α	Cronbach's α Based on Standardized Items	Number of Items
0.971	0.971	39

Table 4. Reliability test of sample data.

Latent Variables	Items	Mean	Standard Deviation	CITC	Cronbach's α
EER	W1	133.93	619.468	0.462	0.817
	W2	133.72	619.369	0.523	
	W3	133.51	613.165	0.631	
ORR	H1	133.53	611.973	0.692	0.910
	H2	133.78	620.903	0.550	
	H3	133.62	613.532	0.635	
	H4	133.71	614.232	0.667	
	H5	133.65	613.373	0.709	
	H6	133.55	615.440	0.669	
IR	X1	133.66	614.179	0.653	0.891
	X2	133.64	615.573	0.690	
	X3	133.64	615.122	0.695	
	X4	133.51	611.488	0.687	
MR	M1	133.50	610.691	0.778	0.896
	M2	133.44	616.999	0.686	
	M3	133.58	612.881	0.710	
	M4	133.58	612.892	0.710	
	M5	133.53	613.499	0.699	
DR	D1	133.52	609.465	0.753	0.874
	D2	133.59	613.422	0.738	
	D3	133.74	609.964	0.728	
CPR	P1	133.61	613.128	0.740	0.880
	P2	133.66	609.879	0.766	
	P3	133.54	612.701	0.741	
TR	T1	133.74	615.245	0.689	0.896
	T2	133.93	614.157	0.706	
	T3	133.71	607.767	0.780	
	T4	133.89	612.981	0.697	
CR	S1	133.45	609.671	0.790	0.896
	S2	133.54	611.441	0.753	
	S3	133.52	613.893	0.742	
	S4	133.73	613.169	0.705	

CITC, corrected item-total correlation.

Validity primarily refers to the extent to which a measured variable accurately describes the factor being measured. Through AMOS statistical analysis software, the convergent validity of individual indicators, CR of latent variables, and AVE of the sample data were assessed. The specific results are presented in Table 5. The CR for all factors' measurement variables exceeds 0.7, and the standard loadings (i.e., individual indicator reliabilities) are all greater than 0.5. The AVE for each measurement term is greater than 0.6. Based on this comprehensive analysis, it is evident that the scale exhibits a high level of validity.

Table 5. Validity test (* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$).

Latent Variables	Items	Parameter Significance Estimation				Std.	SMC	CR	AVE
		Unstd.	SE	t-Value	*p*-Value				
EER	W1	1.454	0.183	7.954	***	0.930	0.865	0.834	0.634
	W2	1.000				0.820	0.672		
	W3	0.816	0.078	10.523	***	0.719	0.517		
ORR	H1	0.999	0.083	12.069	***	0.790	0.624	0.910	0.629
	H2	0.991	0.076	12.973	***	0.839	0.704		
	H3	0.905	0.076	11.915	***	0.791	0.626		
	H4	0.900	0.075	11.956	***	0.793	0.629		
	H5	1.006	0.082	12.316	***	0.788	0.621		
	H6	0.943	0.073	12.893	***	0.811	0.658		
IR	X1	1.000				0.854	0.729	0.892	0.675
	X2	1.096	0.081	13.509	***	0.832	0.692		
	X3	1.032	0.079	13.016	***	0.854	0.729		
	X4	0.864	0.077	11.275	***	0.765	0.585		
MR	M1	1.000				0.807	0.651	0.897	0.635
	M2	0.984	0.084	11.745	***	0.794	0.630		
	M3	0.939	0.085	11.019	***	0.760	0.578		
	M4	1.018	0.076	13.397	***	0.859	0.738		
	M5	0.889	0.070	12.659	***	0.821	0.674		
DR	D1	1.000				0.828	0.686	0.875	0.699
	D2	0.958	0.071	13.515	***	0.827	0.684		
	D3	1.039	0.074	14.117	***	0.847	0.717		
CPR	P1	1.000				0.853	0.728	0.880	0.710
	P2	0.845	0.062	13.735	***	0.811	0.658		
	P3	0.830	0.064	12.925	***	0.789	0.623		
TR	T1	1.000				0.877	0.769	0.897	0.685
	T2	0.915	0.064	14.330	***	0.830	0.689		
	T3	1.083	0.077	14.086	***	0.855	0.731		
	T4	1.025	0.079	12.902	***	0.811	0.658		
CR	S1	1.000				0.837	0.701	0.896	0.683
	S2	1.028	0.081	12.740	***	0.802	0.643		
	S3	1.000				0.801	0.642		
	S4	0.822	0.080	10.279	***	0.727	0.529		
SCR	R1	0.946	0.083	11.335	***	0.780	0.608	0.918	0.615
	R2	0.983	0.079	12.434	***	0.826	0.682		
	R3	0.893	0.075	11.919	***	0.808	0.653		
	R4	0.931	0.080	11.573	***	0.795	0.632		
	R5	0.882	0.082	10.757	***	0.749	0.561		
	R6	1.454	0.183	7.954	***	0.930	0.865		
	R7	1.000				0.820	0.672		

Unstd., unstandardized; SE, standard error; SMC, square multiple correlation; CR, composite reliability; AVE, average variance extracted.

4.3. Results of the Hypothesis Model

4.3.1. Measurement Model Analysis

The measurement model was composed of latent variables and measurement variables. As latent variables needed to be represented through the determination of observed variables, the accuracy of the observed indicators directly affected the relationships among latent variables. Therefore, the measurement model impacted the results of the SEM analysis. There were nine latent variables, including external environmental risk, organizational relationship risk, information risk, etc. The observation variables totaled 39. The constructed measurement model is illustrated in Figure 2.

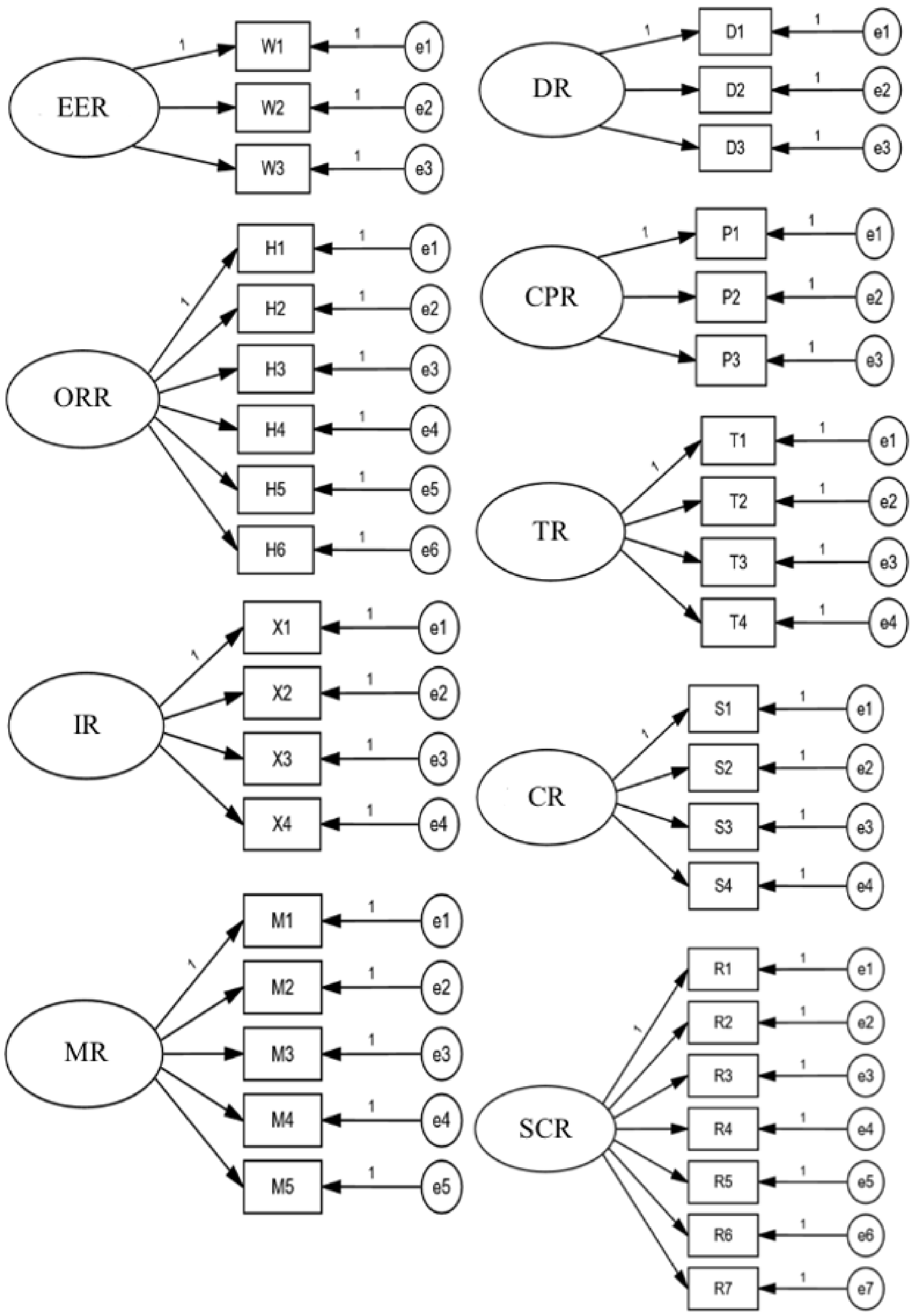

Figure 2. Measurement model.

In the process of carrying out SEM, the first step involves examining whether the model adequately captures the relationships between the measured variables and latent variables. The fit of the measurement model is presented in Figure 3, where the factor loading coefficient of W1 is < 0.6 and SMC is < 0.36. However, due to the requirement that each latent variable should be measured by at least three indicators, W1 is not excluded. The factor loading coefficients and SMC of other measurement models meet the criteria.

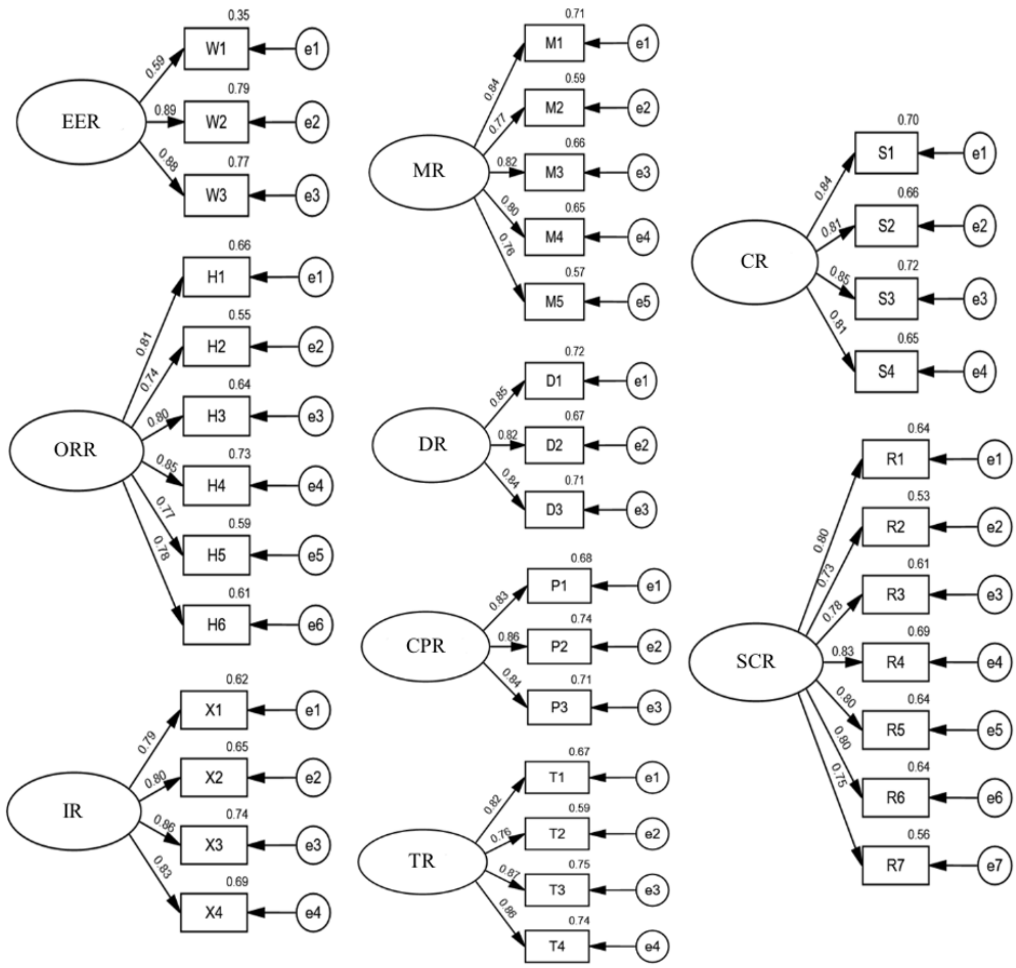

Figure 3. Measurement model verification analysis.

4.3.2. Structural Model Analysis

Based on the theoretical model and measurement model of the resilience impact factors in the prefabricated construction supply chain mentioned earlier, we carried out SEM in the AMOS statistical analysis software. Subsequently, the model underwent fit adjustments to determine the optimal evaluation model. To validate the assumed relationships among latent variables, the hypothesis model was executed. The resulting model diagram and parameter estimation table are presented in Figure 4 and Table 6, respectively.

Table 6. The fit indices.

Fit Indices [1]	Recommendations	Hypothesis Model
RMR	<0.05	0.039
RMSEA	<0.08	0.067
IFI	>0.90	0.908
CFI	>0.90	0.907
CMIN/DF	<3.00	1.769
PGFI	>0.05	0.636
PCFI	>0.05	0.815
PNFI	>0.05	0.729

[1] RMR, root mean square residual; RMSEA, root mean square error of approximation; IFI, incremental fit index; CFI, comparative fit index; PGFI, parsimonious goodness-of-fit index; PCFI, parsimonious comparative fit index; PNFI, parsimonious normed fit index.

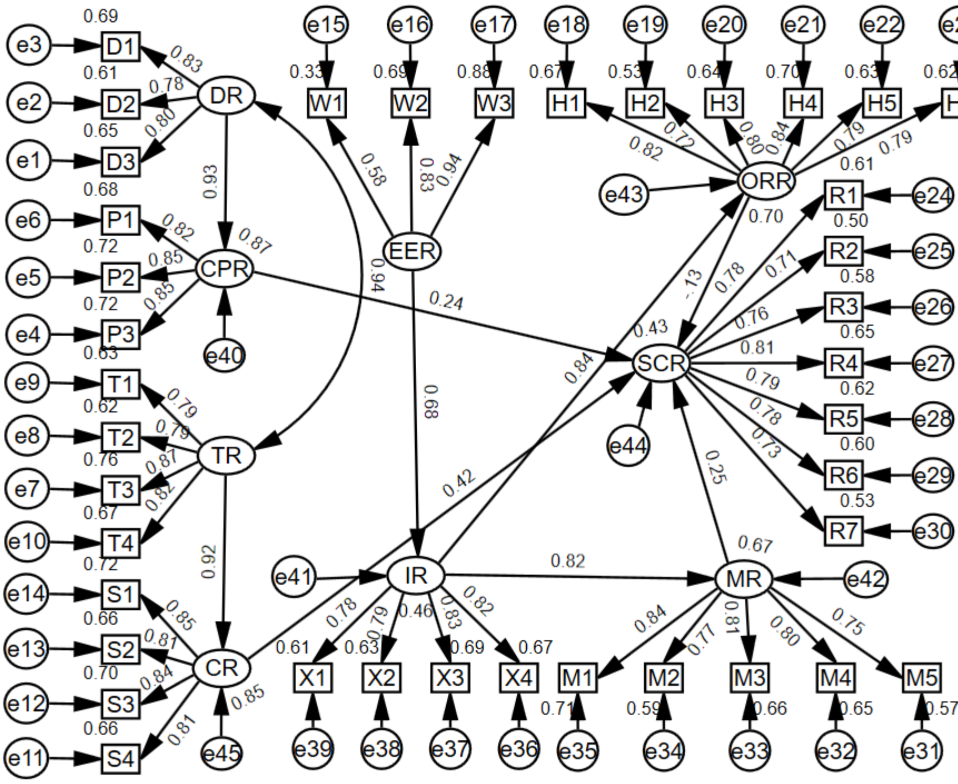

Figure 4. Structural model.

In the model diagram, each latent variable is represented by an elliptical shape, while observed variables are represented by rectangular shapes. The arrows in the diagram indicate the directions of relationships between variables, and the thicknesses of the arrows reflect the strengths of these relationships. As can be observed in Table 6, the fit indices of the proposed model in this study are satisfactory. Specifically, the commonly used fit indices, CFI and IFI, have values of 0.907 and 0.908, respectively, both exceeding 0.9. This indicates that the model fits the actual data well. Additionally, the RMSEA has a value of 0.067, which is less than 0.08, suggesting a high level of adaptability of the model to the questionnaire data. Considering these indices collectively, it can be concluded that the constructed model is acceptable for the data in this study, demonstrating a good performance in both structure and parameter estimation.

The hypothesis testing results of the structural model are presented in Table 7. As indicated, eight hypotheses were supported and one hypothesis was not supported. The rejected hypothesis was H9, which had a negative regression coefficient, with a *p*-value of 0.264. The positive effects of 'external environmental risks' on 'information risks' are shown to be statistically significant ($p < 0.001$); the standardized path coefficient is 0.677, exceeding 0.6; the CR value is 6.430, exceeding 1.960; and the same is true for H2–H5. The positive effects of 'component production risks', 'construction risks', and 'management risks' on 'supply chain resilience' are shown to be significant (H6–H8, $p < 0.01$).

Our analysis provides vital empirical insights into the risk factors influencing PBSCs' resilience. Specifically, the quantification of interrelationships confirms that component production and construction phase uncertainties are most detrimental to project continuity. Additionally, the propagation of these operational risks can be traced back to broader information infrastructure vulnerabilities that enable disruption to reverberate across interconnected activities. However, the adaptive capacity of organizational partnerships minimizes fallouts from relational disruptions.

Table 7. Influence path results (* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$).

Relationship	Standardized Factor Loadings	CR	*p*-Value	Support
EER → IR	0.677	6.430	***	Yes
TR → CR	0.923	12.820	***	Yes
DR → CCR	0.931	11.315	***	Yes
IR → MR	0.817	9.987	***	Yes
IR → ORR	0.835	10.217	***	Yes
CCR → SCR	0.240	1.345	0.039 *	Yes
CR → SCR	0.422	2.369	0.018 *	Yes
MR → SCR	0.247	1.802	0.041 *	Yes
ORR → SCR	−0.125	−1.117	0.264	No

5. Discussion

The above findings guide our targeted recommendations to strengthen adaptive capacities at critical leverage points. Enhancing transparency through digital integration, coordination protocols, and data analytics offers an essential starting point. Inventory buffering, modular design, and contingency planning will further bolster frontline resilience. Interestingly, partnership networks exhibit inherent flexibility to reconfigure around external contingencies due to mutual incentives, directing attention to technical and institutional issues first. By discussing these strategic priorities herein, this research transitions from a diagnostic assessment to outlining informed adaptation pathways for achieving resilience amidst complexity.

5.1. Enhancing Resilience through Information Sharing

5.1.1. Enhancing Information Transmission Efficiency

In the construction of an information-sharing system, ensuring smooth communication is crucial [55]. Effective information exchange not only involves communication among employees but also extends to information interchange with supply chain partners. Therefore, enterprises need to strengthen their information communication infrastructure, increase communication frequency, and establish a green channel for emergency information reporting, ensuring that decision-makers in the supply chain receive comprehensive data on risk situations in the shortest possible time [56].

5.1.2. Establishing Stable Cooperative Relationships

Long-term and stable cooperative relationships are essential factors in enhancing SCR. Enterprises can build a partner database and, based on resilience capacity assessments for disruption risks, determine reasonable selection methods and systems. Factors such as project performance, scale, business scope, credit levels, and emergency resilience capabilities should be considered for partner selection. Establishing long-term collaborative relationships and continually innovating those, as well as consciously expanding the resource capacity of the repository, are recommended.

5.1.3. Enhancing Risk Management Capability

Enhancing risk management capability encompasses aspects such as risk growth, enterprise operational capacity, strategic alliances, and subject coordination incentives [57]. To effectively implement a responsive resilience strategy, enterprises need to enhance their comprehensive operational capabilities, including organizational risk management professional training, establishment of a scientific performance system, and pre-planning engineering risk response measures, among other measures [58]. Additionally, it is essential to establish reasonable constraint and incentive mechanisms, including strategic alliances and subject coordination incentives. Through corresponding incentive measures, enterprises collaborate along the supply chain, creating a situation where prosperity and adversity are shared collectively.

5.1.4. Developing Detailed Policy Standards

The detailed formulation of policy standards according to the current situation of the promotion of the prefabricated construction industry is essential. It is crucial to establish a prefabricated building management framework system, clarify the target tasks at each stage of the process, and define the management and supervisory responsibilities of various departments to ensure the completeness of the regulatory process [59]. The government should also strengthen its leading and demonstrative role, encourage technological innovation and risk control, support prefabricated demonstration projects and demonstration parks through special funds, and expand channels for patent invention applications to promote deep cooperation between production enterprises and local universities and research institutions [60].

5.2. Enhancing Resilience in Each Phase

5.2.1. Design Phase

The design phase is the early stage of prefabricated building projects, which differs from traditional construction. In this phase, there is an increased emphasis on the detailed design of components. Technological innovations in the design of prefabricated components can further enhance the efficiency of production and utilization, adapting to diverse structural systems and functional requirements in different buildings. By incorporating modern technologies such as computer-aided design and 3D printing, the design process is digitized and integrated into an intelligent trajectory [61]. Modular design is employed, encompassing on-demand manufacturing of prefabricated components that can be assembled, as well as customizable prefabricated components.

5.2.2. Component Production Phase

The construction component production phase can be effectively controlled in prefabrication factories. Precise order management and production planning can be implemented to control the inventory of components, ensure timely delivery of orders, and reduce storage costs [62]. Strengthening monitoring and control during the production process is essential to promptly identify and address quality issues. It is also necessary to formulate reasonable production quantity plans. Prefabricated component production involves multi-party collaboration, making supplier management crucial. By establishing supplier performance evaluation criteria, enhancing communication with suppliers, and adopting other measures, the quality and service levels of suppliers can be improved, ensuring the stability and smoothness of the supply chain [63].

5.2.3. Transportation Phase

The transportation phase is often overlooked in modular construction projects. Currently, contractors mitigate risks by collaborating with reliable transportation companies. Transportation companies reduce transportation risks by ensuring that transportation personnel have qualified skills and high qualifications. Additionally, introducing multiple suppliers and transportation channels in the supply chain allows for timely adjustments to transportation plans in the event of supply chain disruptions [64]. In terms of predictive supply chain management, establishing a centralized supplier network and logistics sales management process facilitates capacity monitoring and timely handling of preventive safety stock, thereby reducing the chances of disruptive events.

5.2.4. Construction Phase

In the construction phase, it is essential to deploy efficient and advanced construction machinery and equipment. This includes automated construction equipment with the capability of automatic routing, as well as automation facilities that can meet the demands of large-scale construction. Additionally, precision control is achieved through measurement and detection equipment with high accuracy. New construction technologies and methods, such as BIM, can be employed to continuously manage and control the quality during the construction process. Proper planning of the construction site, enhanced site layout management efficiency, and strict control through construction planning and on-site coordination help reduce inefficiencies and conflicts in construction [65]. Specialization within the construction team and rational division of labor contribute to increased construction efficiency and quality.

6. Conclusions

This research employed a mixed-methods approach pairing expert surveys with SEM to quantify resilience factors for prefabrication supply chains. Findings revealed component manufacturing and construction site risks as the most detrimental to project continuity during disruptions, which could be traced to intricacies of modular staging. However, information flow vulnerabilities enable propagation, thus demanding priority intervention.

This paper offers an initial data-driven modeling foundation for assessing prefabrication supply chain resilience factors. However, limitations exist in encapsulating richer risk interdependencies and dynamics. The assumed model compartments may deviate from actual multifaceted interactions between uncertainties. Incorporating computational simulations and complex systems theories in further work could enhance model accuracy. Data limitations also constrained resilience metric response variability. As the Chinese prefab industry matures, expanded sampling over time would strengthen generalizability.

Nonetheless, the strategies prioritized offer direct pathways for construction firms to stabilize project flows. Precision resilience analytics can inform policy and institutional coordination as the industry scales. Methodological replication also carries tremendous potential for resilience modeling of other specialized supply chains wrestling with innovations under uncertainty. This underscores the versatility of contextualized assessments in guiding complex transitions toward favorable trajectories. Follow-up efforts should concentrate on validation across building techniques while addressing statistical and theoretical constraints.

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Appendix A

Table A1. Questionnaire.

Part I Basic Information							
Work	1. Research institute 2. Owner 3. Contractor 4. Design institute 5. Component production factory 6. Others						
Education background	1. Ph.D. 2. Master 3. Bachelor 4. Junior college and below						
Working experience (years)	1. 0–3 2. 3–5 3. ≥5						
Part II To what extent does the factor affect the resilience of the prefabricated building supply chain? 1—very low; 2—low; 3—general; 4—high; 5—very high							
External environmental risks	Natural environment	1	2	3	4	5
	Policies	1	2	3	4	5
	Standard specification	1	2	3	4	5

Table A1. *Cont.*

Categories	Factors	Scores				
Organizational relationship risks	Communication and coordination	1	2	3	4	5
	Cooperation satisfaction	1	2	3	4	5
	Benefit distribution	1	2	3	4	5
	Target consistency	1	2	3	4	5
	Organizational mutual trust	1	2	3	4	5
	Cooperation mechanism	1	2	3	4	5
Information risks	Information construction	1	2	3	4	5
	Information platform	1	2	3	4	5
	Information sharing	1	2	3	4	5
	Information transmission	1	2	3	4	5
Management risks	Crisis consciousness	1	2	3	4	5
	Risk response	1	2	3	4	5
	Experience summary	1	2	3	4	5
	Resource integration and reconstruction	1	2	3	4	5
	Risk tolerance	1	2	3	4	5
Design risks	Component design	1	2	3	4	5
	Change control	1	2	3	4	5
	Number of personnel	1	2	3	4	5
Component production risks	Component redundancy	1	2	3	4	5
	Component manufacturing	1	2	3	4	5
	Manufacturer management	1	2	3	4	5
Transportation risks	Logistics company reliability	1	2	3	4	5
	Transportation distance and cost	1	2	3	4	5
	Transport flexibility	1	2	3	4	5
	Level of transportation redundancy	1	2	3	4	5
Construction risks	Construction capacity	1	2	3	4	5
	Professional talents	1	2	3	4	5
	Construction technology	1	2	3	4	5
	Regulatory mechanisms	1	2	3	4	5
Part III How important is the resilience measurement index of the prefabricated building supply chain? 1—very unimportant; 2—unimportant; 3—generally important; 4—relatively important; 5—very important						
I1 Predictive capability The ability of each participant in the supply chain to actively defend and avoid risks through early warning, planning, and evaluation before the occurrence of risk events.		1	2	3	4	5
I2 Redundancy Supply chain participants reserve additional resources to cope with supply chain disruptions.		1	2	3	4	5
I3 Robustness When the supply chain is impacted, it can resist external interference and maintain its original state.		1	2	3	4	5
I4 Agility The response speed of the supply chain to emergencies.		1	2	3	4	5
I5 Adaptability The ability of the supply chain to adapt and respond to environmental changes by adjusting.		1	2	3	4	5
I6 Recovery capability The ability of the supply chain to quickly and effectively return to a normal state through recovery measures, that is, resource reorganization ability and crisis mitigation ability.		1	2	3	4	5
I7 Learning ability After the supply chain returns to a normal state, the ability to optimize the supply chain structure through learning.		1	2	3	4	5

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