Hindawi
Advances in Civil Engineering
Volume 2023, Article ID 8870224, 14 pages
https://doi.org/10.1155/2023/8870224

Research Article

Study on Mechanism of Factors Affecting Resilience of Prefabricated Building Supply Chain

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Received 7 June 2023; Revised 30 July 2023; Accepted 16 August 2023; Published 31 August 2023

Academic Editor: Raizal Saifulnaz Muhammad Rashid

Identifying key factors affecting the resilience of a prefabricated building supply chain and exploring the effect mechanism of these factors can help to improve the resilience of the prefabricated building supply chain. The main factors affecting the resilience of the prefabricated building supply chain are sorted out first on the basis of Hall's 3D theory and related research results. Then, the relationships between these factors and the dynamic change of influence of these factors on the resilience of the supply chain are studied through simulation by combining the fuzzy set theory, decision-making experimental analysis, and the system dynamics method. The results show that 10 s-level factors, such as disruption risk prediction and supply chain information sharing level, are active causal factors, while 9 s-level factors, such as disruption response time and disruption contingency plan, are passive result factors. Among the second-level factors, the disruption response time has the highest influence on the resilience of the prefabricated building supply chain, and component design versatility has the lowest influence on the resilience of the prefabricated building supply chain. The influence of the first-level factors, i.e., evolutionary ability, efficiency, and adaptability, descends in sequence. At last, specific suggestions for improving the resilience of the prefabricated building supply chain are put forward.

1. Introduction

Prefabricated buildings are built based on standardized design, factory production, and mechanized construction and have outstanding advantages of shortening the construction period, improving quality, and reducing pollution [1, 2] due to construction characteristics of the prefabricated buildings: industrialization, informatization, and environmental-friendliness [3]. The prefabricated building is an important means to realize the transformation and upgrading of the construction industry and achieve sustainable development [4]. With the continuous increase in the scale and complexity of construction projects, supply chain management for prefabricated buildings is becoming increasingly necessary [5]. The prefabricated building supply chain is not a simple industrial chain or process but a complex relationship network consisting of multiple stages and multiple subjects [6]. In addition, under the influence of epidemics and international situations in recent years, the upstream and downstream disturbances in the supply chain have increased significantly [7], and the risk of disturbance or even disruption in the supply chain has also greatly increased.

Supply chain resilience refers to the capability of the supply chain to quickly recover to an ideal state after being disturbed or disrupted [8]. The resilience of a supply chain is the focus of supply chain management [9]. Maintaining a high supply chain resilience is an effective way to lower supply chain disruption risk and ensure the stable operation of the prefabricated building supply chain, and it is also important for the increase of company competitiveness [10]. Therefore, to promote the sustainable development and application of prefabricated building, it is necessary to sort out factors affecting the resilience of the prefabricated building supply chain and explore key factors, as well as to investigate the influence characteristics and degree of each factor on supply chain resilience and relationships between these factors.

2. Literature Review

Research on factors affecting supply chain resilience has become a hotspot in academic research. Many scholars have studied the factors affecting supply chain resilience from the perspectives of vulnerability, abilities, and external factors that affect supply chain resilience. Ekanayake et al. [11–13] specified 58 factors related to industrialized buildings and classified them into 12 components such as flexibility, ability, and efficiency. They identified 37 factors related to the resilience of the prefabricated building supply chain from the perspective of vulnerability, explored the construction of a more resilient construction supply chain, and further identified 41 factors that constitute key abilities such as flexibility, adaptability, efficiency, and visibility from the perspective of abilities required by a resilient supply chain. Wedawatta et al. [14] considered extreme weather as one of the factors affecting the resilience of the construction supply chain and proposed to lower the vulnerability level of companies and enhance their ability to cope with extreme weather. Abidin and Ingirige [15] studied five key vulnerability factors through questionnaires: political change, market pressure, management, and financial and strategic vulnerability. Osunsanmi et al. [16] proposed construction 4.0 technologies and proved that the technologies can ensure the resilience of a construction supply chain in the face of risk by collecting data and performing structural equation modeling analysis on the data using SmartPLS. Zhang [17] established a construction supply chain resilience evaluation index system from five dimensions, including predictive ability, absorption ability, adaptability, and recovery ability, and verified the same through real cases.

Some scholars verify and further analyze the mechanism of each factor affecting supply chain resilience based on different research methods. Zhang et al. [18] constructed a conceptual model of factors affecting the resilience of the prefabricated building supply chain from the perspective of resilience management and found through an empirical study that production and construction have a significant impact on supply chain resilience, while information and partnerships can significantly regulate production and construction. Zhu et al. [19] studied the factors affecting the resilience of the prefabricated building supply chain through literature analysis and interpretative structural modeling (ISM) method and found that improving the level of information sharing between a design firm and a supply chain as well as the logistics and transportation capabilities have a positive effect on improving supply chain resilience. Lu et al. [20] used DEMATEL and ISM methods to construct a prefabricated building supply chain resilience evaluation model to analyze key factors affecting supply chain resilience and the effect mechanism thereof. Ekanayake et al. [21] found, by using SNA and SDM methods, that on-site assembly is the least resilient portion of a supply chain, while prevention is the most effective measure. Zhang and Yu [22] considered the relationship between prefabricated component transportation cost and resilience under the condition of low transportation efficiency and transportation disruption in prefabricated buildings and proposed a solution method of a resilience-cost tradeoff optimization model to contribute to knowledge and methodologies for prefabricated component supply chain management. Wang et al. [23] constructed, from six aspects, including flexible resources, production, and R&D, risk management, supply flexibility, etc., an index system of factors affecting the resilience of a prefabricated building supply chain, and discovered key influencing factors such as abilities to response to and deal with risks and information visualization.

To sum up, researches in the past on supply chain resilience mainly focused on two aspects: exploring factors affecting the resilience of a prefabricated building supply chain through actual investigation and theoretical study to recognize a fact that factors affecting the resilience of the prefabricated building supply chain can be divided into multiple levels and multiple types and constitute a complex system; and verifying the influence of the factors on the resilience of the prefabricated building supply chain through methods such as structural equations. However, these researches ignore the interaction between factors and the dynamic change of influence of the factors on prefabricated building supply chain resilience. Therefore, on the basis of the existing research results, this paper aims to further explore key factors affecting the resilience of the prefabricated building supply chain, analyze the relationships and characteristics of these factors, and study the dynamic impact of each factor on supply chain resilience.

3. Identification of Factors Affecting the Resilience of Prefabricated Building Supply Chain

The prefabricated building supply chain is a network system composed of prefabricated component manufacturers, raw material suppliers, and owners, with prefabricated building design and construction firms being the core and includes component production, storage, transportation, and on-site assembly [24]. Based on the characteristics of prefabricated buildings, this paper explores the factors affecting the resilience of the prefabricated building supply chain in three key stages of prefabricated building design, production and transportation, and construction.

At present, there is no uniform regulation in academia on the division of supply chain resilience stages. For example, Sheffi [25] divided supply chain resilience into three stages: before supply chain disruption, during disruption, and after disruption. Ponomarov and Holcomb [26] divided supply chain resilience into three stages: preparation, response, and recovery. Hohenstein et al. [27] divided supply chain resilience into four stages: preparation, response, recovery, and increase.

Most scholars focus on the response and recovery of a supply chain, that is, the ability of the supply chain to recover to its original state after being damaged [28, 29]. Few scholars pay attention to the avoidance of potential risks [30, 31] and the increased potential after being disturbed [32, 33], which reflects the improvement process after the supply

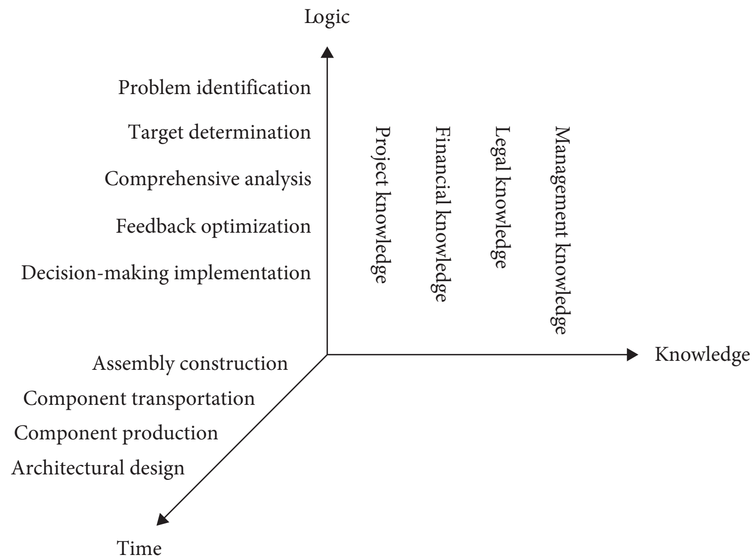

Figure 1: 3D analysis model for resilience of prefabricated building supply chain.

chain is damaged and restored to its original state. According to Hall's 3D theory, a system process is generally divided into a plurality of stages and steps based on time, logic, and knowledge dimensions, and the knowledge and skills required to complete these stages and steps are considered to form a hierarchical 3D structure system. In this way, the influence of subjective decision-making on factor selection can be lowered [34]. Therefore, in this paper, factors affecting the resilience of a prefabricated building supply chain are selected in consideration of the four aspects, i.e., preparation, response, recovery, and increase, and a 3D analysis model for prefabricated building supply chain resilience is constructed based on Hall's 3D theory as shown in Figure 1.

In the time dimension, a prefabricated building supply chain mainly includes four stages: design, production, transportation, and construction. In the logic dimension, the prefabricated building supply chain mainly includes target determination, target analysis, feedback optimization, and decision-making implementation. From the knowledge dimension, the prefabricated building supply chain mainly includes professional knowledge in fields such as management, law, and information technologies. Factors affecting the resilience of a prefabricated building supply chain in preparation, response, recovery, and increase aspects are analyzed in time, logic, and knowledge dimensions. The factors affecting resilience of the prefabricated building supply chain can be divided into three parts: efficiency, adaptability, and evolutionary ability. Efficiency emphasizes the time and speed of supply chain recovery [35]. Adaptivity emphasizes steady changes in supply chain recovery and supply chain reorganization [36]. The evolutionary ability emphasizes updates and improvements after supply chain recovery [37]. Finally, the factors affecting the resilience of the prefabricated building supply chain are obtained, as shown in Table 1.

4. Factors Affecting the Resilience of Prefabricated Building Supply Chain

4.1. Method Selection. In this article, relationships between and characteristics of factors affecting the resilience of prefabricated building supply chains are analyzed mainly through the Decision-Making Experiment and Evaluation Laboratory (DEMATEL) method. The DEMATEL method was proposed by scholars Gabus and Fontela in 1972 and had the advantage that the interaction between various factors can be comprehensively considered based on the experience and knowledge of experts so as to reveal the core driving factors of a complex problem and figure out the causality of the driving factors. The DEMATEL method requires experts to make judgments on the interaction between various factors. To reduce the subjectivity of expert scoring and ensure the high reliability of the obtained data, calculation is performed based on the DEMATEL method in combination with triangular fuzzy numbers. Five experts on prefabricated building supply chains (including three professors in the field of prefabricated buildings from universities and two senior engineers in the prefabricated building industry) were selected for scoring. A 5-level Likert scale (very high influence, high influence, low influence, very low influence, no influence) was used during scoring. Scores were converted into corresponding values [38], as shown in Table 2.

4.2. Standardized Calculation of Triangular Fuzzy Numbers. According to Table 2, the evaluation results of each expert are listed as $(l_{ij}^k, m_{ij}^k, r_{ij}^k)$ (where l, m, r, respectively, represent the first score, the second score, and the third score in triangular fuzzy numbers corresponding to an influence level; i or j represents the factor; and k represents the expert), which shows an assessment by expert k for the influence of factor i on factor j. The assessment is recorded in a 19×19 table.

Table 1: Factors affecting the resilience of prefabricated building supply chain.

First-level factor	Symbol	Second-level factor	Symbol	Interpretation
Efficiency	A_1	Disruption contingency plan	A_{11}	Disruption recovery plan
		Demand-based construction ability	A_{12}	Construction ability meeting owner demands
		Disruption risk prediction	A_{13}	Supply chain disturbance forecasting
		Risk pooling	A_{14}	Disruption loss allocation
		Disruption response time	A_{15}	Market change response time
		Design information sharing level	A_{16}	Reduce errors and improve quality
		Component deployment ability	A_{17}	Component deployment flexibility
Adaptability	B_1	Multi-component manufacturer supply	B_{11}	Number of component manufacturers
		Prefabricated component storage capacity	B_{12}	Component redundancy
		Component transportation redundancy	B_{13}	Transportation includes excess capacity
		Supply chain contract flexibility	B_{14}	Component deployment flexibility
		Component design versatility	B_{15}	Component design for multiple purposes
		Supply chain information sharing level	B_{16}	Information sharing level
		Supply chain coordination ability	B_{17}	Coordination among design, production, and construction
		Information technology application level	B_{18}	Information technology application ability
Evolutionary ability	C_1	Risk response experience accumulation	C_{11}	Risk experience accumulation
		Social relationship accumulation	C_{12}	Valuable resources and valuable knowledge
		Risk response learning ability	C_{13}	Ability to learn, explore, and summarize
		Risk experience application ability	C_{14}	Ability to absorb and utilize experience

Triangular fuzzy numbers are converted into precise numerical values [39] using Converting Fuzzy Data into Crisp Scores method through the following formula:

$$xl_{ij}^k = \frac{l_{ij}^k - \min_{1\le k\le K} l_{ij}^k}{\Delta_{\min}^{\max}}, \tag{1}$$

$$xm_{ij}^k = \frac{m_{ij}^k - \min_{1\le k\le K} l_{ij}^k}{\Delta_{\min}^{\max}}, \tag{2}$$

$$xr_{ij}^k = \frac{r_{ij}^k - \min_{1\le k\le K} l_{ij}^k}{\Delta_{\min}^{\max}}. \tag{3}$$

In these equations, $\Delta_{\min}^{\max} = \max_{1\le k\le K} r_{ij}^k - \min_{1\le k\le K} l_{ij}^k$.

$$xls_{ij}^k = \frac{xm_{ij}^k}{1 + xm_{ij}^k - xl_{ij}^k}, \tag{4}$$

$$xrs_{ij}^k = \frac{xm_{ij}^k}{1 + xr_{ij}^k - xm_{ij}^k}, \tag{5}$$

$$x_{ij}^k = \frac{xl_{ij}^k\left(1 - xls_{ij}^k\right) + xrs_{ij}^k xrs_{ij}^k}{1 - xl_{ij}^k + xr_{ij}^k}, \tag{6}$$

$$a_{ij}^k = \min_{1\le k\le K} l_{ij}^k + x_{ij\,k}\,\Delta_{\min}^{\max}, \tag{7}$$

$$a_{ij} = \frac{1}{k}\sum_{k=1}^{k} a_{ij}^k. \tag{8}$$

According to the formula mentioned above, the required 19×19 matrix $A = [a_{ij}]_{19}$ for DEMATEL can be obtained, as shown in Table 3.

4.3. Calculation Based on DEMATEL Method. The influence, affectedness degree, centrality, and causality of the factors are calculated, and the relationships between the influencing factors are identified through the following formulas in combination with the calculated direct influence matrix A.

$$D = \frac{1}{\max_{1\le i\le 19}\sum_{j=1}^{19} a_{ij}} A, \tag{9}$$

$$T = D(1 - D)^{-1}, \tag{10}$$

$$r_i = \sum_{j=1}^{19} t_{ij}, \tag{11}$$

$$c_j = \sum_{i=1}^{19} t_{ij}, \tag{12}$$

Table 2: Influence levels of factors.

Influence level	Score in triangular fuzzy numbers
No influence	(0, 0.1, 0.3)
Very low influence	(0.1, 0.3, 0.5)
Low influence	(0.3, 0.5, 0.7)
High influence	(0.5, 0.7, 0.9)
Very high influence	(0.7, 0.9, 1.0)

$$W_i = \frac{r_i + c_i}{\sum_{i=1}^{n}(r_i + c_i)}, \tag{13}$$

where r_i is the sum of each row in matrix T and indicates influence (D). c_j is the sum of each column in matrix T and indicates affectedness degree (R). When $i = j$, factors with a positive causality value are causal factors, while factors with a negative causality value are result factors [40], where $r_i + c_j$ indicates centrality ($D + R$), and $r_i - c_j$ indicates causality ($D - R$). The influence, affectedness degree, centrality, and causality of each factor affecting the resilience of prefabricated building supply chain are shown in Table 4.

4.4. Result Analysis. Table 4 shows that the casual factors include A_{13}, A_{16}, A_{17}, B_{11}, B_{12}, B_{16}, B_{17}, B_{18}, C_{11}, and C_{12}. The disruption risk prediction (A_{13}) has the highest influence and the 5th highest affectedness degree, indicating a high activity and a certain degree of passivity. Similar factors include component deployment ability (A_{17}), supply chain information sharing level (B_{16}), supply chain coordination ability (B_{17}), information technology application level (B_{18}), risk response experience accumulation (C_{11}), and social relationship accumulation (C_{12}). The influence and affectedness degree of the design information sharing level (A_{16}), multicomponent manufacturer supply (B_{11}), and prefabricated component storage capacity (B_{12}) are low.

The result factors include A_{11}, A_{12}, A_{14}, A_{15}, B_{13}, B_{14}, B_{15}, C_{13}, and C_{14}. The disruption response time (A_{15}) has the highest affectedness degree and the 7th highest influence, indicating a high passivity and a certain degree of activity. Similar factors include disruption contingency plan (A_{11}), demand-based construction ability (A_{12}), and risk experience application ability (C_{14}). The component transportation redundancy (B_{13}) has a higher affectedness degree ranking (10th) and a lower influence ranking (16th), indicating a high passivity. The risk pooling (A_{14}), disruption response time (A_{15}), supply chain contract flexibility (B_{14}), component design versatility (B_{15}), and risk response learning ability (C_{13}) have low influence and affectedness degrees and are less related to other factors.

5. Dynamic Simulation Analysis of Factors Affecting the Resilience of Prefabricated Building Supply Chain

Based on the analysis of the influence, affectedness degree, centrality, and causality of each factor of the resilience of the prefabricated building supply chain, the causal relationship and system dynamics (SD) model of the factors affecting the resilience of the prefabricated building supply chain are constructed by using the SD method. Under a preset time condition, the interaction mechanism between the factors, the influence on the supply chain, and the dynamic change pattern are simulated.

5.1. Causality between Factors Affecting the Resilience of Prefabricated Building Supply Chain. The factors affecting the resilience of the prefabricated building supply chain are interrelated. These factors have different influences on the efficiency, adaptability, and evolutionary ability of the supply chain. SD based on feedback control theory is a method for computer simulation to study complex systems [41] and can clearly reflect the relationships between factors affecting the resilience of a supply chain system and their dynamic changes to further reveal the causality between the resilience influencing factors. Therefore, in this article, the causality between the factors affecting the resilience of the prefabricated building supply chain is found using Vensim software in combination with the previous analysis, as shown in Figure 2.

Figure 2 shows that there are multiple feedback loops in the diagram showing the causality between factors affecting the resilience of the prefabricated building supply chain. Taking "efficiency" as an example, there are 14 cycles related to efficiency, and the longest cycle is selected to reflect the correlation between factors. Similarly, there are three main paths in the diagram of causality between factors affecting the resilience of the prefabricated building supply chain:

(1) efficiency ⟶ prefabricated building supply chain resilience ⟶ supply chain operating pressure ⟶ information technology application level ⟶ risk response learning ability ⟶ social relationship accumulation ⟶ risk response experience accumulation ⟶ disruption risk prediction ⟶ disruption contingency plan ⟶ disruption response time ⟶ efficiency;

(2) adaptability ⟶ prefabricated building supply chain resilience ⟶ supply chain operation pressure ⟶ information technology application level ⟶ supply chain coordination ability ⟶ adaptability;

(3) evolutionary ability ⟶ prefabricated building supply chain resilience ⟶ supply chain operation pressure ⟶ information technology application level ⟶ risk response learning ability ⟶ risk experience application ability⟶social relationship accumulation ⟶ risk response experience accumulation ⟶ evolutionary ability.

5.2. System Dynamics Flow of Factors Affecting the Resilience of Prefabricated Building Supply Chain. The relationships between the factors are shown in Table 5, where the influence coefficient indicates the effect power of a factor affecting another factor [42]. In order to further clarify the feedback form and pattern of the system, an SD flowchart of the factors affecting the resilience of the prefabricated building

Table 3: Direct influence matrix of factors affecting the resilience of prefabricated building supply chain.

	A_{11}	A_{12}	A_{13}	A_{14}	A_{15}	A_{16}	A_{17}	B_{11}	B_{12}	B_{13}	B_{15}	B_{16}	B_{17}	B_{18}	C_{11}	C_{12}	C_{13}	C_{14}
A_{11}	0.7152	0.8783	0.2107	0.2107	0.5970	0.6622	0.6759	0.4000	0.3981	0.3981	0.3000	0.7690	0.7690	0.6000	0.5000	0.4061	0.4104	0.4104
A_{12}	0.7690	0.5000	0.8783	0.6922	0.6943	0.1217	0.3078	0.4000	0.3981	0.3981	0.2010	0.4000	0.3000	0.5000	0.7690	0.6000	0.5981	0.6922
A_{13}	0.4000	0.2107	0.5000	0.8783	0.5000	0.1217	0.1217	0.3078	0.2107	0.2107	0.2477	0.1217	0.1217	0.1217	0.5000	0.3078	0.2107	0.4061
A_{14}	0.7690	0.7690	0.5939	0.2107	0.8783	0.4000	0.5000	0.4000	0.4000	0.4000	0.3000	0.7000	0.6000	0.4000	0.6805	0.4000	0.6000	0.6922
A_{15}	0.5000	0.6000	0.3998	0.3000	0.5000	0.8783	0.6143	0.1217	0.2107	0.1217	0.7690	0.5000	0.4000	0.3000	0.4061	0.3078	0.3078	0.2107
A_{16}	0.5000	0.7000	0.2107	0.3078	0.7000	0.4000	0.8783	0.7378	0.5939	0.6922	0.1217	0.7690	0.7690	0.5000	0.4000	0.2107	0.2107	0.3000
A_{17}	0.3000	0.5000	0.2107	0.2107	0.6000	0.3000	0.6922	0.8783	0.7690	0.6000	0.3000	0.3000	0.4000	0.3000	0.3078	0.3078	0.2107	0.2107
B_{11}	0.4000	0.4000	0.3078	0.1217	0.5998	0.1217	0.7690	0.5939	0.8783	0.7378	0.2107	0.3078	0.6000	0.4000	0.2107	0.5000	0.1217	0.1217
B_{12}	0.5000	0.6000	0.4000	0.1022	0.6167	0.1056	0.6622	0.4061	0.4061	0.8783	0.2107	0.3000	0.6000	0.2107	0.2107	0.4000	0.1217	0.2107
B_{13}	0.5939	0.1217	0.3000	0.7690	0.4000	0.1217	0.1217	0.3078	0.1217	0.2107	0.1217	0.2107	0.2107	0.1217	0.3000	0.2107	0.2107	0.2107
B_{14}	0.4000	0.4000	0.3000	0.2107	0.3998	0.3000	0.2089	0.2089	0.1217	0.2107	0.8783	0.2107	0.3000	0.1217	0.1217	0.1217	0.1217	0.1217
B_{15}	0.4000	0.7690	0.6000	0.2107	0.7690	0.6922	0.6000	0.1217	0.2107	0.5000	0.2168	0.8783	0.7690	0.7000	0.4000	0.3078	0.4000	0.3078
B_{16}	0.5000	0.7690	0.2107	0.2107	0.8500	0.7152	0.7690	0.2107	0.4061	0.4061	0.1217	0.6922	0.8783	0.6000	0.5000	0.4000	0.5000	0.6000
B_{17}	0.5000	0.7000	0.3000	0.1217	0.6000	0.7690	0.5000	0.1217	0.2107	0.5000	0.3078	0.8264	0.6000	0.8783	0.6000	0.4061	0.6000	0.5000
B_{18}	0.7690	0.6000	0.7690	0.6759	0.7690	0.3078	0.3078	0.4000	0.4000	0.4000	0.4000	0.2107	0.5000	0.2107	0.8783	0.6922	0.4000	0.6000
C_{11}	0.5939	0.5939	0.5939	0.3078	0.5939	0.2107	0.5000	0.4000	0.5000	0.5000	0.3000	0.4000	0.5939	0.5000	0.6922	0.8783	0.5000	0.6000
C_{12}	0.4000	0.4061	0.4772	0.3078	0.5000	0.2107	0.2107	0.2107	0.3000	0.3078	0.1217	0.3078	0.3000	0.3078	0.6922	0.5000	0.8783	0.7690
C_{13}	0.7690	0.5000	0.7690	0.4000	0.5000	0.2107	0.2107	0.1217	0.2107	0.2107	0.1217	0.1264	0.2107	0.2107	0.7690	0.5000	0.7690	0.8783
C_{14}	0.7152	0.8783	0.2107	0.2107	0.5970	0.6622	0.6759	0.4000	0.3981	0.3981	0.3000	0.7690	0.7690	0.6000	0.5000	0.4061	0.4104	0.4104

Table 4: D, R, $D+R$, $D-R$ values of factors affecting resilience of prefabricated building supply chain.

Factors	Influence (D)		Affectedness (R)		Centrality ($D+R$)		Causality (DR)	
	D value	Rank	R value	Rank	$D+R$ value	Rank (weight)	$D-R$ value	Rank
A_{11}	1.1377	8	1.3073	3	2.4450	3 (0.0648)	−0.1696	18
A_{12}	1.1621	3	1.3086	2	2.4707	2 (0.0655)	−0.1465	17
A_{13}	1.1933	1	1.0911	5	2.2844	5 (0.0605)	0.1022	4
A_{14}	0.7011	17	0.8183	16	1.5194	17 (0.0403)	−0.1172	16
A_{15}	1.1414	7	1.3581	1	2.4995	1 (0.0662)	−0.2166	19
A_{16}	0.9385	12	0.8488	15	1.7873	14 (0.0474)	0.0897	7
A_{17}	1.1178	10	1.0776	6	2.1954	7 (0.0582)	0.0402	9
B_{11}	0.9099	13	0.8168	17	1.7267	16 (0.0458)	0.0931	6
B_{12}	0.9001	15	0.8669	14	1.7670	15 (0.0468)	0.3320	1
B_{13}	0.8477	16	0.9626	10	1.8103	13 (0.0480)	−0.1149	15
B_{14}	0.6491	18	0.6585	18	1.3076	18 (0.0346)	−0.0094	11
B_{15}	0.5703	19	0.6407	19	1.2110	19 (0.0321)	−0.0704	13
B_{16}	1.1257	9	1.0552	8	2.1809	8 (0.0578)	0.0705	8
B_{17}	1.1574	4	1.0597	7	2.2171	6 (0.0587)	0.0977	5
B_{18}	1.1493	5	0.9208	12	2.0701	10 (0.0549)	0.2285	2
C_{11}	1.1776	2	1.1725	4	2.3501	4 (0.0623)	0.0051	10
C_{12}	1.1477	6	0.9580	11	2.1057	9 (0.0558)	0.1897	3
C_{13}	0.9035	14	0.9179	13	1.8214	12 (0.0483)	−0.0144	12
C_{14}	0.9397	11	1.0306	9	1.9703	11 (0.0522)	−0.0909	14

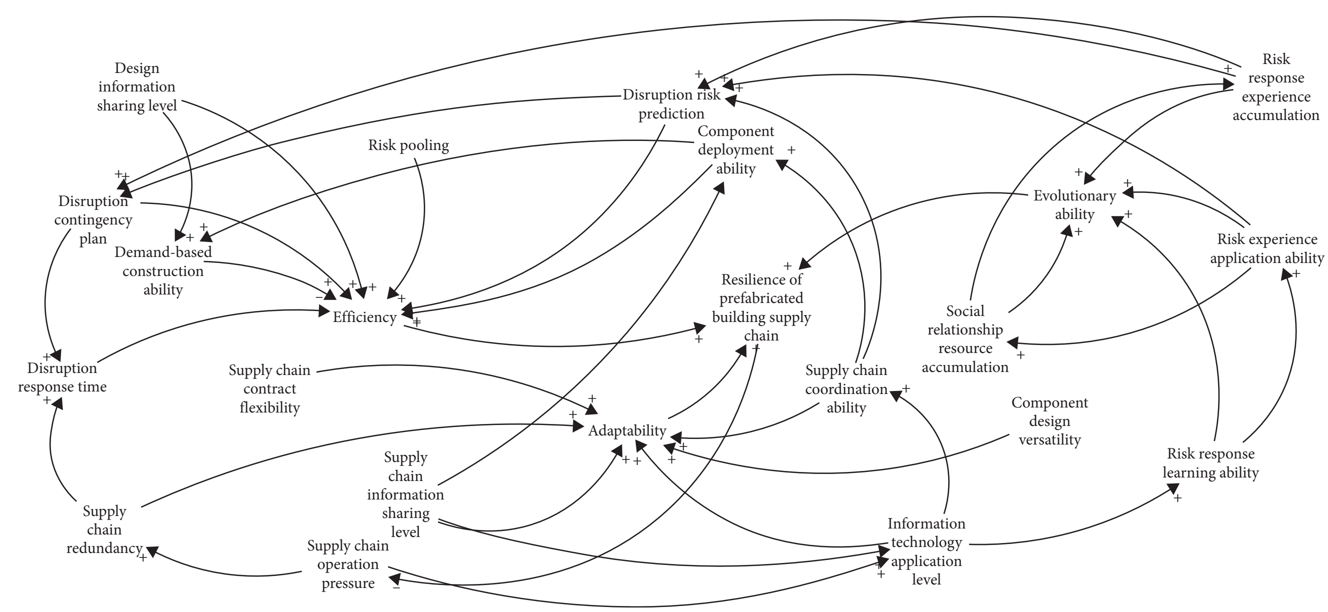

Figure 2: Causality between factors affecting the resilience of prefabricated building supply chain.

supply chain is created on the basis of Table 5 to reflect the impact of changes in various influencing factors on the system and reveal the feedback mechanism between these influencing factors. Refer to Figure 3 for details.

5.3. Determination of System Dynamics Model Equation and Simulation Parameters for Prefabricated Building. Model variables are defined based on the principle of SD in combination with the diagram of causality among factors. Refer to Table 6 for details.

Model equations are as follows:

$$\mathrm{RSC} = A_1 \times \mathrm{QA}_1 + B_1 \times \mathrm{QB}_1 + C_1 \times \mathrm{QC}_1, \tag{14}$$

$$\begin{aligned} R_1 = {} & (A_{14} \times \mathrm{QA}_{14} + A_{11} \times S_1 + A_{15} \times \mathrm{QA}_{15} \\ & \times S_2 \times S_3 \times S_4 \times S_5 + A_{12} \times \mathrm{QA}_{12} \times S_6 \times S_7 + A_{16} \\ & \times \mathrm{QA}_{16} + A_{17} \times \mathrm{QA}_{17} \times S_8 \times S_9 + A_{13} \times \mathrm{QA}_{13} \\ & \times S_{10} \times S_{11}) \times \mathrm{EXP}(\mathrm{RSC} \times 0.07), \end{aligned} \tag{15}$$

TABLE 5: Variable symbols of the resilience of prefabricated building supply chain and relationships between factors.

Relationship between factors	Symbol	Relationship between factors	Symbol
Supply chain resilience	RSC	Coefficient of influence of supply chain coordination ability on component deployment ability	S_8
A_1 increment	R_1	Coefficient of influence of information sharing level on component deployment ability	S_9
B_1 increment	R_2	Coefficient of influence of risk experience application ability on disruption risk prediction	S_{10}
C_1 increment	R_3	Coefficient of influence of supply chain coordination ability on disruption risk prediction	S_{11}
Coefficient of influence of disruption risk prediction on the disruption contingency plan	S_1	Coefficient of influence of information sharing level on information technology application level	S_{12}
Coefficient of influence of component transportation redundancy on disruption response time	S_2	Coefficient of influence of information technology application level on supply chain coordination ability	S_{13}
Coefficient of influence of disruption contingency plan on disruption response time	S_3	Coefficient of influence of information technology application level on risk response learning ability	S_{14}
Coefficient of influence of multi-component manufacturer supply on disruption response time	S_4	Coefficient of influence of risk response learning ability on risk experience application ability	S_{15}
Coefficient of influence of prefabricated component storage capacity on disruption response time	S_5	Coefficient of influence of risk response experience accumulation on risk experience application ability	S_{16}
Coefficient of influence of design information sharing level on demand-based construction ability	S_6	Coefficient of influence of the degree of social relationship accumulation on risk response experience accumulation	S_{17}
Coefficient of influence of component deployment ability on demand-based construction ability	S_7	Coefficient of influence of supply chain contract flexibility on risk pooling	S_{18}

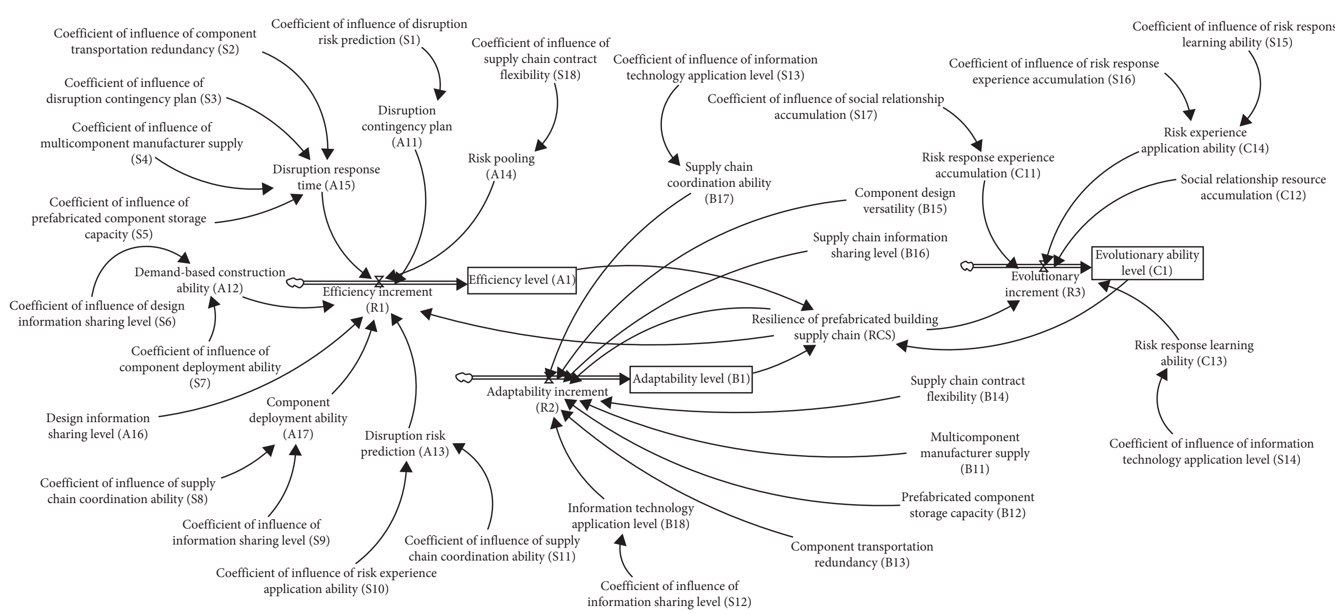

FIGURE 3: System dynamics flowchart of factors affecting the resilience of prefabricated building supply chain.

$$R_2 = (B_{18} \times \mathrm{QB}_{18} \times S_{12} + B_{13} \times \mathrm{QB}_{13} + B_{12} \times \mathrm{QB}_{12} + B_{11} \times \mathrm{QB}_{11} + B_{14} \times \mathrm{QB}_{14} + B_{17} \times \mathrm{QB}_{17} \times S_{13} + B_{15} \times \mathrm{QB}_{15} + B_{16} \times \mathrm{QB}_{16}) \times \mathrm{EXP}(\mathrm{RSC} \times 0.07), \tag{16}$$

$$R_3 = (C_{13} \times \mathrm{QC}_{13} \times S_{14} + C_{12} \times \mathrm{QC}_{12} + C_{14} \times \mathrm{QC}_{14} \times S_{15} + C_{11} \times \mathrm{QC}_{11}) \times \mathrm{EXP}(\mathrm{RSC} \times 0.07). \tag{17}$$

In these equations, $\mathrm{QA}_1 + \mathrm{QB}_1 + \mathrm{QC}_1 = 1$

Table 6: Set of resilience level variables of prefabricated building supply chain.

Variable	Symbol	Description
Level variable	A_1, B_1, C_1	First-level factor
Rate variable	R_1, R_2, R_3	Increment of first-level factor
Auxiliary variable	RCS	Supply chain resilience
	A_{11}, A_{12}, A_{13}, A_{14}, A_{15}, A_{16}, A_{17}, B_{11}, B_{12}, B_{13}, B_{14}, B_{15}, B_{16}, B_{17}, B_{18}, C_{11}, C_{12}, C_{13}, C_{14}	Second-level factor
	S_1, S_2, S_3, S_4, S_5, S_6, S_7, S_8, S_9, S_{10}, S_{11}, S_{12}, S_{13}, S_{14}, S_{15}, S_{16}, S_{17}, S_{18}	Influence coefficient
Constant	QA_1, QB_1, QC_1	Weight of first-level factor
	QA_{11}, QA_{12}, QA_{13}, QA_{14}, QA_{15}, QA_{16}, QA_{17}, QB_{11}, QB_{12}, QB_{13}, QB_{14}, QB_{15}, QB_{16}, QB_{17}, QB_{18}, QC_{11}, QC_{12}, QC_{13}, QC_{14}	Weight of second-level factor

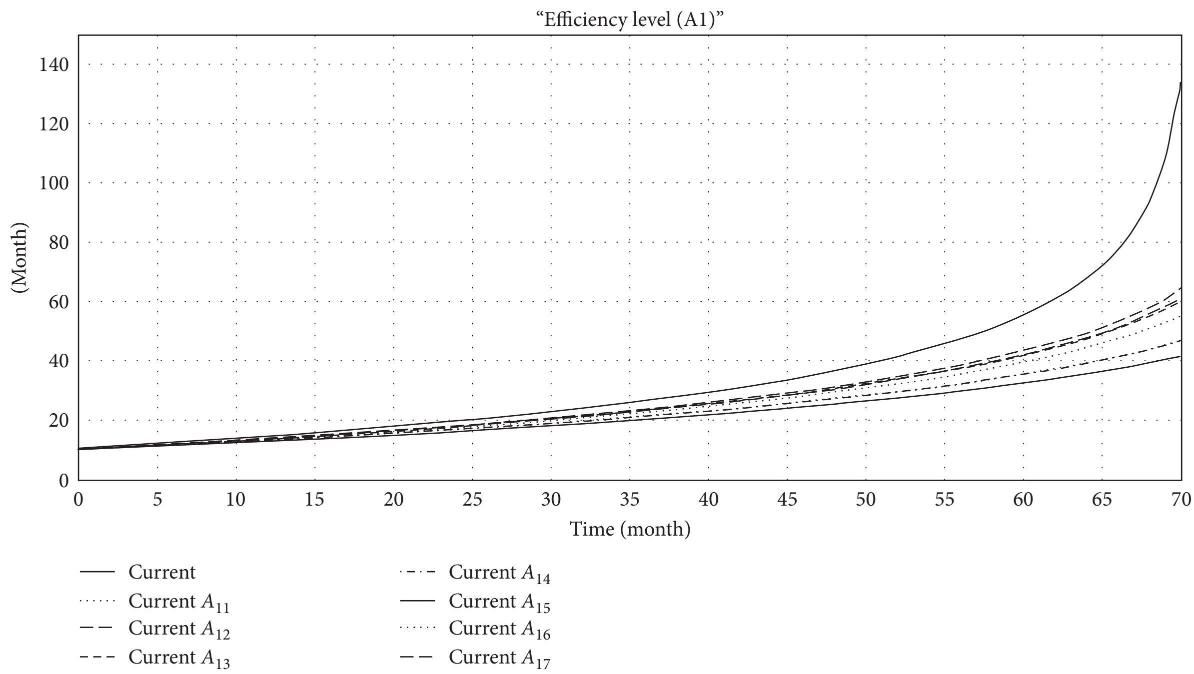

Figure 4: Influence of factors in efficiency.

For an SD model, the constant values and the initial values of variables in each equation need to be determined. Based on data in Table 4, the weights of the first-level factors are (QA_1, QB_1, QC_1) = (0.40, 0.38, 0.22). The weights of the second-level factors in efficiency are (QA_{11}, QA_{12}, QA_{13}, QA_{14}, QA_{15}, QA_{16}, QA_{17}) = (0.16, 0.16, 0.15, 0.10, 0.16, 0.12, 0.15). The weights of second-level factors in adaptability are (QB_{11}, QB_{12}, QB_{13}, QB_{14}, QB_{15}, QB_{16}, QB_{17}, QB_{18}) = (0.12, 0.12, 0.13, 0.09, 0.08, 0.15, 0.16, 0.15). The weights of second-level factors in the evolutionary ability are (QC_{11}, QC_{12}, QC_{13}, QC_{14}) = (0.28, 0.26, 0.22, 0.24). The influence coefficients are (S_1, S_2, S_3, S_4, S_5, S_6, S_7, S_8, S_9, S_{10}, S_{11}, S_{12}, S_{13}, S_{14}, S_{15}, S_{16}, S_{17}, S_{18}) = (1.62, 1.28, 1.81, 1.34, 1.33, 1.37, 1.55, 1.59, 1.56, 1.37, 1.59, 1.56, 1.58, 1.58, 1.33, 1.61, 1.58, 1.08). For the model, the simulation time is 70 months, the simulation step length DT is 1 month, and the initial value of the three first-level factors is set to 10 (dimensionless value). Parameter values are input into the SD model for system simulation analysis.

5.4. Simulation and Result Analysis. In this simulation, 19 s-level factors are simulated, and the initial value of each influencing factor is set to 0.05. According to the control variable method, under a condition that the change value of one of the influencing factors is kept at 0.13 and the other factors are kept constant, 19 simulations are performed to obtain the change data and change trend diagram of the resilience level of the prefabricated building supply chain when the change of each factor is the same (as shown in Figures 4–6), so as to obtain the influence of different factors on the resilience of the prefabricated building supply chain. The disruption response time is the decrement.

The data obtained by adjusting each factor is compared with the original data (current). The change data of the second-level factors of the efficiency level is shown in Figure 4. The following factors in the efficiency are listed in an descending order of influence: disruption response time (A_{15}), component deployment ability (A_{17}), demand-based construction ability ($A_{12)}$, disruption risk prediction (A_{13}), disruption

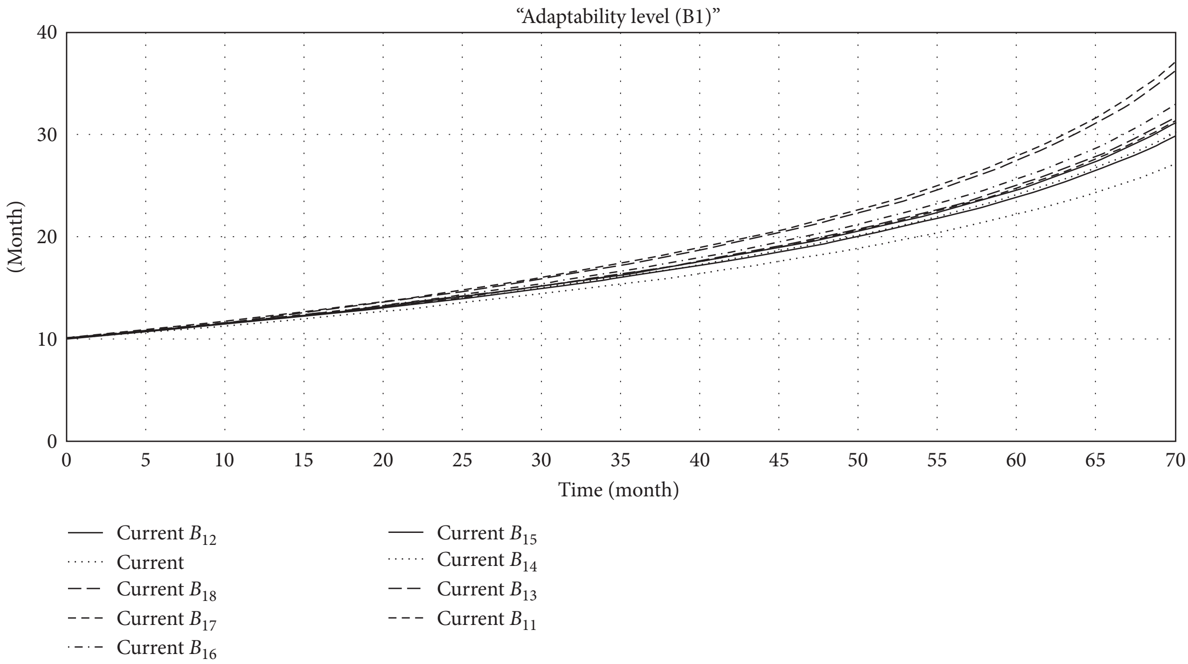

Figure 5: Influence of factors in adaptivity.

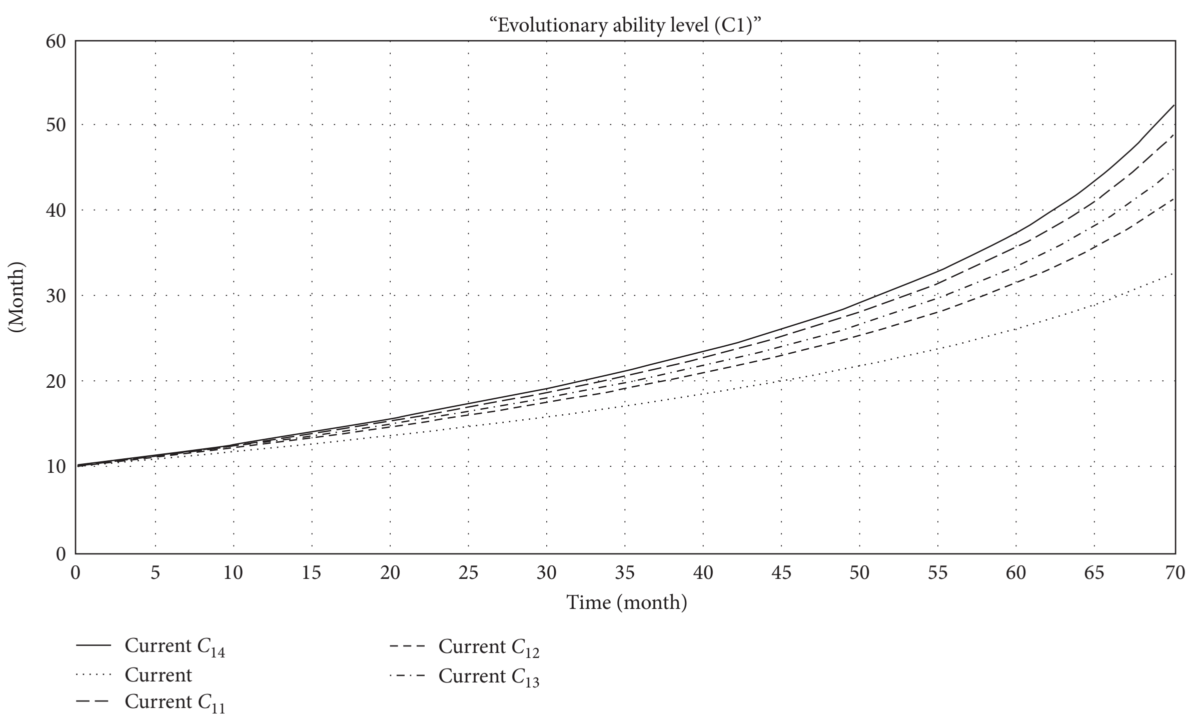

Figure 6: Influence of factors in evolutionary ability.

contingency plan (A_{11}), design information sharing level (A_{16}), and risk pooling (A_{14}). As the simulation time increases, the influence of disruption response time (A_{15}) on the resilience of the prefabricated building supply chain is most significant. Component deployment ability (A_{17}), demand-based construction capabilities (A_{12}), and disruption risk predictions (A_{13}) also have a high influence on supply chain resilience. A disruption contingency plan (A_{11}), design information sharing level (A_{16}), and risk pooling (A_{14}) have a relatively low influence on prefabricated construction supply chain resilience.

The change data of the second-level factors of adaptability are shown in Figure 5. The following factors in adaptability are listed in a descending order of influence: supply chain coordination ability (B_{17}), information technology application level (B_{18}),

Table 7: Influence data of factors in efficiency.

Time (month)	Current	Current A_{11}	Current A_{12}	Current A_{13}	Current A_{14}	Current A_{15}	Current A_{16}	Current A_{17}
0	10	10	10	10	10	10	10	10
1	10.2201	10.2619	10.2749	10.2728	10.2375	10.3266	10.2395	10.2801
2	10.4429	10.5272	10.5534	10.5492	10.478	10.6580	10.4819	10.5640
3	10.6683	10.796	10.8358	10.8294	10.7215	10.9944	10.7274	10.8517
				…………				
67	38.2927	49.0173	53.3704	52.6207	42.29	83.8335	42.7702	55.3208
68	39.2916	50.8168	55.6118	54.7801	43.5467	92.9961	44.0608	57.7879
69	40.3453	52.7835	58.1099	57.1781	44.8874	106.8550	45.4398	60.5652
70	41.46	54.951	60.9289	59.8722	46.3243	132.767	46.9202	63.7378

Table 8: Influence rate of factors affecting the resilience of prefabricated building supply chain.

First-level factor	Second-level factor	Influence
Efficiency	Disruption contingency plan	0.1494
	Demand-based construction ability	0.2129
	Disruption risk prediction	0.2033
	Risk pooling	0.0609
	Disruption response time	0.5489
	Design information sharing level	0.0680
	Component deployment ability	0.2373
Adaptability	Multi-component manufacturer supply	0.0777
	Prefabricated component storage capacity	0.0747
	Component transportation redundancy	0.0845
	Supply chain contract flexibility	0.0577
	Component design versatility	0.0511
	Supply chain information sharing level	0.1051
	Supply chain coordination ability	0.1719
	Information technology application level	0.1579
Evolutionary ability	Risk response experience accumulation	0.2571
	Social relationship accumulation	0.1455
	Risk response learning ability	0.1980
	Risk experience application ability	0.3469

supply chain information sharing level (B_{16}), transportation redundancy (B_{13}), multicomponent manufacturer supply (B_{11}), prefabricated component storage capacity (B_{12}), supply chain contract flexibility (B_{14}), and design versatility (B_{15}). The supply chain coordination ability (B_{17}) and information technology application level (B_{18}) have the highest influence on the resilience of the prefabricated building supply chain. The supply chain information sharing level (B_{16}), transportation redundancy (B_{13}), multicomponent manufacturer supply (B_{11}), and prefabricated component storage capacity (B_{12}) have a high influence on the resilience of the supply chain. The supply chain contract flexibility (B_{14}) and design versatility (B_{15}) have a low influence on the resilience of the prefabricated building supply chain.

The change data of the second-level factors of the evolutionary ability are shown in Figure 6. The following factors in evolutionary ability are listed in a descending order of influence: risk experience application ability (C_{14}), risk response experience accumulation (C_{11}), social relationship accumulation (C_{12}), and risk response learning ability (C_{13}). The risk experience application ability (C_{14}) has the highest influence on the resilience of the prefabricated building supply chain. The risk response experience accumulation (C_{11}), social relationship accumulation (C_{12}), and risk response learning ability (C_{13}) have a high influence on supply chain resilience.

According to the simulation data, a relatively accurate influence rate of each factor can be calculated. The influence rate mainly reflects the influence level on the resilience of the prefabricated building supply chain when the change rate of each factor is the largest. Take efficiency data as an example, see Table 7 for details. The average supply chain resilience level of an initial plan (current) in 70 months is 21.7914. The level value of the initial plan is subtracted from the monthly level value of the disruption contingency plan, and then an average value, 3.4207, is calculated. The ratio of the average value to the level value of the initial plan is 0.1569. In other words, the influence rate is 0.1569. In the same way, influence values of other factors can be obtained, see Table 8 for details. It can be seen that these factors having significantly different influences on the resilience of the prefabricated building supply chain. The disruption response time has the highest influence on the resilience of the prefabricated building supply chain, while the component design versatility has the lowest influence. The influence rate of the first-level factors can be obtained by weighting the influence rate of the second-level factors. The influence rate of the efficiency is 0.2261, the influence rate of the adaptability is 0.1055, and the influence rate of the evolutionary ability is 0.2366. In view of the above, the evolutionary ability has the highest influence on the resilience of the prefabricated building supply chain, and the adaptability has the lowest influence.

6. Research Conclusions and Suggestions

A prefabricated building supply chain is a complex system affected by various factors [43]. In this paper, relationships between factors affecting the resilience of the prefabricated building supply chain are studied through fuzzy set theory and decision-making experimental analysis method, and the interaction mechanism, effect level, and dynamic change pattern of these factors are analyzed through the SD method. The following conclusions are drawn:

(1) Factors affecting the resilience of a prefabricated building supply chain are correlated, and the characteristics and influence modes of these factors are different. Disruption risk prediction, design information sharing level, component deployment ability, multicomponent manufacturer supply, prefabricated component storage capacity, supply chain information sharing level, supply chain coordination ability, information technology application level, risk response experience accumulation, and social relationship accumulation are casual factors. Disruption contingency plans, demand-based construction ability, risk pooling, disruption response time, component transportation redundancy, supply chain contract flexibility, component design versatility, risk response learning ability, and risk experience application ability are result factors.

(2) Through simulation analysis of the influence trend and effect level of the factors affecting the prefabricated building supply chain resilience, it can be known that the influence of the following second-level factors descends in sequence: disruption response time, risk experience application ability, risk response experience accumulation, component deployment ability, demand-based construction ability, disruption risk prediction, risk response learning ability, supply chain coordination ability, information technology application level, disruption contingency plan, social relationship accumulation, supply chain information sharing level, component transportation redundancy, multicomponent manufacturer supply, prefabricated component storage capacity, design information sharing level, risk pooling, supply chain contract flexibility, and component design versatility.

By weighting the influence rate of the second-level factors, it can be known that the influence of the following first-level factors descends in sequence: evolutionary ability, efficiency, and adaptability.

Based on the above conclusions, suggestions for increasing the resilience of the prefabricated building supply chain are as follows:

(1) First, strengthen the evolutionary ability. In terms of evolutionary ability, focusing on the influence of risk experience application ability and paying attention to collection of risk experience data and analysis of risk cases can better prevent disruption risks or improve disruption risk response efficiency. The risk response experience accumulation, social relationship accumulation, and risk response learning ability are also important. The supply chain evolution ability can be improved by actively accumulating and learning risk response experience in the industry, expanding and accumulating social relationships, etc.

Therefore, building a comprehensive risk management mechanism, improving the preidentification, in-process control, and post-processing in risk management, strengthening cooperation among participants, and promoting resource sharing among all parties are primary measures to improve the resilience of the prefabricated building supply chain.

(2) Second, improve efficiency. In terms of efficiency, the influence of disruption response time is the most significant. Therefore, we should first focus on improving the response speed of all participants, optimizing the response process, and enhancing information exchange and resource exchange. For the factors of component deployment ability, demand-based construction ability, and disruption risk prediction, by improving the component coordination, ability matching, and risk prediction awareness of participates, the supply chain risk response-ability and response efficiency can be improved, and the visibility of risks can be increased. In addition, for the factors of disruption contingency plan, design information sharing level, and risk pooling, supply chain resilience can be improved by developing better contingency plans, using information technologies to achieve more efficient collaborative design, and more reasonable risk pooling or transfer schemes.

Therefore, shortening the disruption response time, optimizing response measures, and enhancing the full-process and all-round coordination and collaboration capabilities of all parties are important to improve the resilience of the prefabricated building supply chain.

(3) Finally, improve adaptability. In terms of adaptability, we should focus on strengthening the supply chain coordination ability and information technology application level. The coordination and informatization level of parties can be improved by unifying

standards, formulating general rules, and promoting the application of information technologies. The flexibility to deal with risks and the timeliness of response should be improved by establishing trust relationships and increasing information-sharing efficiency among participants. In addition, by formulating reasonable contract terms about rewards and punishments and division of responsibilities, building a standardized design system, improving component versatility, increasing alternative transportation options, alternative suppliers, and remaining inventory are also conducive to improving the adaptability of the supply chain. Attention should also be paid to balancing the economics of the supply chain.

Therefore, establishing general standards and coordination mechanisms, improving information technology application mechanisms, access mechanisms, and security mechanisms, and balancing resource reserve and economic benefits are effective measures to improve the resilience of the prefabricated building supply chain.

Data Availability

All data, models, and code generated or used during the study appear in the submitted article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

This paper is supported by the National Natural Science Foundation of China, no. 72171028, the Project of Sichuan Circular Economy Research Center, no. XHJJ-2106, and the Innovation Fund for Postgraduates of Xihua University in 2022, no. YCJJ2021077.

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