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Risk Assessment in the Industry Chain of Industrialized Construction: A Chinese Case Study

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Abstract: The industry chain of industrialized construction is a key strategy for promoting the sustainable performance of China's construction industry. Its risk identification is the fundamental step to promote the development of the industry chain. The study was conducted in two phases. The first phase included an extensive literature review and case study analysis to document 32 key factors affecting the process of the industry chain of industrialized construction. In the second phase, 22 key factors influencing the development of the industry chain of industrialized construction in Shandong Province were screened through data collection and expert consultation. A complex network of industrialized construction risk associations (CNICRA) was developed to assess these risks by considering the interrelationship among risks, network nodes, and network edges, and the comprehensive degree indicators for improving the model's accuracy and resolution. The results show that enterprise collaboration level is the most important factor in the industry chain of industrialized construction. The industrialized system is the most transmittable factor of risk. This study investigated a list of risks in the industrialization of construction, optimized a complex network of risk association, and provided theoretical support for risk management of the industry chain of industrialized construction and understanding of risk response strategies for decision makers.

Keywords: industry chain of industrialized construction; complex networks; comprehensive degrees; risk identification

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1. Introduction

The rapid development of the global economy and the continuous improvement of the industrial chain has accelerated the pace of industrialization and urbanization in many countries, and the concept of innovation, coordination, low-carbon, openness and sharing has been developed [1,2]. The traditional energy-intensive construction industry's greenhouse gas emissions hasten global warming [3]. According to the latest data from Tsinghua University's Center for Building Energy Efficiency, China's total construction area in 2018 was 60.1 billion m^2, with urban residential construction accounting for 24.4 billion m^2, rural residential construction accounting for 22.9 billion m^2, and public construction accounting for 12.8 billion m^2. In this regard, public construction refers to buildings for people to carry out various public activities. It generally includes office buildings, commercial buildings, tourism buildings, communication buildings, transportation buildings, etc. The total carbon emissions were approximately 1.8 billion tonnes of CO_2, of which the carbon emissions from the production and transportation of building materials accounted for a relatively large proportion, approximately 65% and 30%, respectively. Consequently, in the context of global environmental protection and its development in 2019, the Chinese government has accelerated the rapid transformation of the traditional construction industry, considering assembled buildings as the main way to replace cast-in-place buildings [4,5]. In 2020, China's Ministry of Housing and Urban–Rural Development and other departments proposed to establish an intelligent construction system covering the life cycle of the industry chain, such as scientific research, design, components manufacture, construction with assembly, and operation. This means that an industrial community is formed by the same business enterprise groups in a certain region, and industry chains are formed by multiple industrial communities. The industry chain is mainly used to assess the completeness of the sustainable development of industrialized construction in the region.

The traditional construction industry is transitioning from high-energy and inefficient to green and low-carbon, innovative, and competitive. Developing an industry chain of industrialized construction is critical to its rapid transformation [6–8]. In several major issues of the national medium- and long-term economic and social development strategy, the Chinese government has stated that industry chains are an important feature of a large country's economy. The industry chain is divided into two modes: internal and external. The internal mode has four dimensions: the value chain, enterprise chain, spatial chain, and supply and demand chain; the external mode has three dimensions: enterprise regulation, market guidance, and government regulation [9,10]. The industry chain of industrialized construction effectively guides the articulation of key nodes, such as design, production, transportation, and construction, and lays a solid foundation for industrialized construction's rapid transformation and high-quality development. To make a breakthrough in the field of the industry chain of industrialized construction [11], Chinese scholars have studied it with different entry points and achieved certain results. However, a gap is currently seen in the research related to the risk identification of the industry chain of China's industrialized construction. This paper mainly studies its risk. After the analysis in Section 1, the rest of the paper is organized as follows: Section 2 is a brief overview of the relevant literature. Section 3 is the introduction of the method. Section 4 is a case study. Section 5 summarizes the results of the study, limitations and future research directions. By identifying risks, this study helps to promote the future development of the industry chain of China's industrialized construction.

2. Literature Review

In recent years, the number of studies on promoting the development of the industry chain of industrialized construction has increased. Researchers and practitioners accept the fact that industrialized construction offers significant improvements in environmental protection and efficiency over traditional buildings. Section 2.1 summarizes the current state of development of industrialized construction in China and internationally. Section 2.2 summarizes the state of application of complex network theory in current risk assessment.

2.1. Industrial Chain of Industrialized Construction

In-depth research is performed in China to better understand the industry chain, benefit distribution, evaluation mechanisms, sustainable development, and building information modeling (BIM). For example, Zhang and Yu proposed a multi-objective optimization model to solve the problem of delayed delivery of components and other parts, and they validated the model's accuracy using real-world examples [12]. Han, Skibniewski, and Wang built a corporate chain of prefabricated component manufacturers and contractors and used an integrated game model to analyze the profit levels of firms in the chain under different behavioral decisions [13]. Li and Mao discussed the interests of the main participants in the enterprise chain and developed a system dynamics model to simulate the interactions between the enterprises, mainly including the interests of the three main enterprises: contractors, design institutes, and suppliers [14]. Feng et al. analyzed the coordination and cooperation mechanisms between producers of components in the chain based on an evolutionary game model under the government's penalty and incentive conditions and the ways to achieve a win–win situation in production construction [15]. Zhao et al. established the performance evaluation mechanism of the industrial chain from the perspective of sustainable development [16]. Tan et al. used an explanatory structural model to analyze the barriers to BIM adoption in the assembly industry and developed a three-tier strategy [17]. Du, Sugumaran, and Gao proposed an industrial chain information tracking and supply mechanism to coordinate various links in the industrial chain and demonstrated the mechanism's feasibility through a case study [18].

In addition to Chinese scholars who study industry chain of industrialized construction, researchers in many countries around the world study construction supply chains. Iran, the Netherlands, Australia, Thailand, etc., place a greater emphasis on governance, decision optimization and technology management research in the supply chain, such as new materials and technology development, the application of lean production concepts, integrated cost–duration–quality decision making, supply chain modularization and supply, management information, resource and environmental efficiency, and industrialized building systems (IBS) [19]. For example, Wu et al. introduced transaction costs (TCs) to prefabricated housing for the first time, using TCs as an entry point to identify stakeholders via social network analysis. The study results had a positive impact on supply chain governance [20]. Arashpour et al. argued that robust supply decisions are critical and examine the effect of firm-related decisions on costs, a finding that aids decision makers [21]. Hsu, Aurisicchio, and Angeloudis determined the most favorable component of scheduling plan and inventory variation based on a two-stage stochastic planning model and a hybrid planning model to analyze the optimal production schedule and optimal outsourcing quantities for prefabricated components in a manufacturing environment with uncertain productivity [22]. Lachimpadi et al. discovered that IBS could achieve greater environmental benefits by studying aspects such as waste material utilization and recycling [11]. Bari et al. compared IBS to traditional waste management practices and discovered that IBS could improve waste utilization [23]. Qi, Chen, and Costin proposed an architectural framework for integrating Radio Frequency Identification System (RFID) and BIM technologies [24,25].

2.2. Application of Complex Network Models in Risk Assessment

The complex network model was applied to sociological research in the early stage, which was then gradually applied to research in natural science, biology, engineering science, etc. [26]. The complex network model discovers the common laws in complex systems through the method of network analysis, and its main analysis indexes are network density, average path length, degree and degree distribution, and clustering coefficient. As industrialization and urbanization accelerate, the relationships between risk factors are becoming more networked [27]. To solve the problem of risk identification, the characteristics of complex network models have attracted the attention of scholars in the field of engineering management. Previously, Ledwoch, A et al. applied the concept of systemic risk to demonstrate that centrality indicators can be used for complex supply network risk assessment [28]. Yang, Lou, and Zhao developed a complex network model for complex project risk management, analyzed changes in network density, and determined the optimal immunization strategy [29]. Fu et al. investigated ways to develop the green building industry by analyzing the complex relationships between green building stakeholder behaviors using complex networks [30]. Qazi, A and Dikmen applied complex networks to risk assessment of complex construction, a data-driven Bayesian belief network approach to capture the impact of each risk overall [31]. Wambeke, BW and Liu, M applied complex networks to risk assessment in the management domain and concluded that overcommitment is the most significant factor leading to project schedule disruptions and reduced productivity [32]. In the above application, the significance ranking of nodes in a complex network provides a basis for risk assessment of network nodes and prioritization of risk disposal of nodes in the network. However, the existing critical node identification methods have problems such as low resolution and complicated calculations. This study improves the current complex network model according to its shortcomings.

In summary, scholars from various countries have made significant contributions to the promotion of the industry chain of industrialized construction. China has great potential for development. Identifying the risk factors that affect its development are crucial to promoting its better development. The networked relationship among risks makes it a complex system, and risk factors do not exist in isolation from each other. In this case, risk factors are considered as nodes of a network, and their relationships are abstracted as connections between them; thus, it is reasonable that the theory of complex network models is used to solve such problems [33].

3. Materials and Methods

In this study, a research method is designed to study the risk response strategy of the industry chain of industrialized construction. Figure 1 explains the logical framework of the method, which consists of four steps. The first step is to complete the risk identification. The risks of the industrialized construction chain are presented in a tabular format by reviewing the literature review and past cases. The second step is to complete the risk evaluation. The relationship between risks was quantified by employing a questionnaire and formed into an adjacency matrix. The third step is to complete the risk analysis. This step is divided into two main parts. Firstly, the visualization software Pajek was used to build the complex network of industrialized construction risk associations (CNICRA) based on the adjacency matrix. A topological analysis of the network is performed to determine the hierarchy of risks. Second, based on the risk hierarchy, a comprehensive degree was added to improve the resolution of risk analysis and to determine the critical risks and significant abnormal risk transmissions. The fourth step was to complete the risk response. Based on the conclusions drawn in the first three steps, risk mitigation measures were proposed.

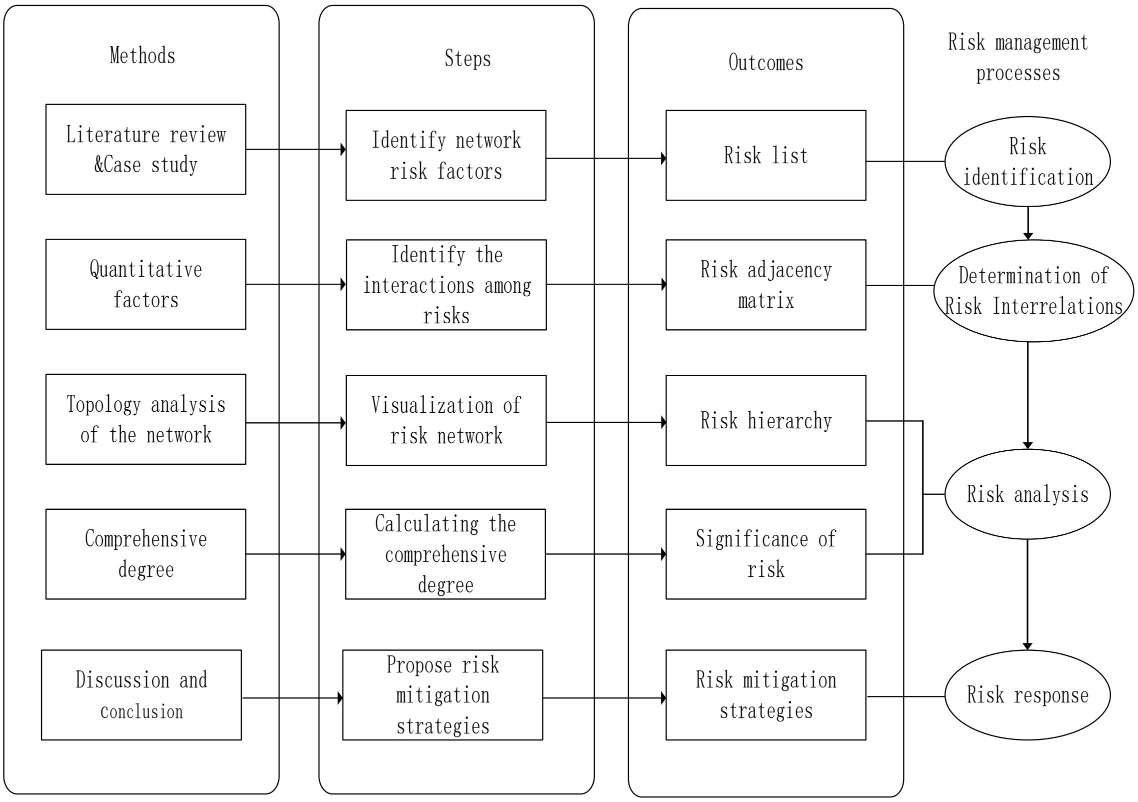


Figure 1. Research framework of risk management approach.

3.1. *Risk Identification*

Each network is composed of two components: nodes and links. This step is complemented by literature studies and case studies to identify risk nodes for a comprehensive investigation of the risks of industrialized construction [34]. To expand the search, we reviewed much of the existing research in the area of industrialized construction risk management, and a number of relevant cases with multiple specific risk triggers have been included in the analysis.

With the extension of the industry chain of industrialized construction, more participants, such as component dealers, designers, and constructors, are involved and considered. The structure of their interrelationships is also becoming increasingly complex and diverse, which will lead to system-related risks and which will affect the stability of the chain. For example, inconsistent design standards or design defects that originate from the design stage often lead to design changes by designers [35]. Changes tend to generate rework, and cost increases, making it difficult for contractors to achieve a tradeoff between supplier component price and project process. Information blockage between enterprises leads to construction schedule delays [36]. Such situations may be caused by poor industrialization systems or enterprise collaboration level. A list of chain-associated risks was identified in this study for further analysis.

Based on the literature approach, journal articles in the field of risk management in the industry chain of industrialized construction were selected and examined to identify 27 risks after unifying the different manifestations of similar risks (Table 1). The literature was mainly selected from the Web of Science, and the keywords searched were industrialized construction, suppliers; industrialized construction, design; industrialized construction, construction; industrialized construction, risk management; industrialized construction, China, risk assessment; industrialized construction, excluding the Chinese region when screening. Three principles should be followed in the selection of risk factors. First, the risks with a high degree of impact in each literature should be selected. Second, factors should be selected in both Chinese and international contexts to improve the applicability of the study results. Finally, factors with strong interactions among risks should be selected to facilitate model building.

Table 1. Risks of industrialized construction based on literature method.

Code	Risk	Organization	Reference
V1	Need of Skilled Labor	All	[37]
V2	More Knowledge Resources	All	[37]
V3	Uneven regional development	All	[38]
V4	Component production line capacity	Production Units	[36]
V5	Governmental Incentives	Government	[39]
V6	Stocks Control Ability	Production Units	[40]
V7	Enterprise collaboration level	All	[41]
V8	Fragmentation Issues	All	[42]
V9	Design Complication	Design Units	[43]
V10	Technology Adoption	All	[44]
V11	Innovation Capability	Design Units	[39]
V12	Fear of Investment	Investment Units	[37]
V13	Imperfect Supervision System	Construction Units	[45]
V14	Poor Construction Ability	Construction Units	[29]
V15	Diversity of Components	Production Units	[46]
V16	Advanced Equipment	Production Units	[46]
V17	Strategic Objectives of the Company	All	[43]
V18	Social Perception	All	[37]
V19	Flexible production capacity	Production Units	[47]
V20	Undetailed Construction Plan	Construction Units	[45]
V21	Credit Risks	All	[37]
V22	Ease in Procurement System	Construction Units	[45]
V23	Un-controlled Carbon Emissions	Construction Units	[45]
V24	Outflow of Talents	All	[48]
V25	Company Management	All	[49]
V26	Industrialization System	Production Units	[37]
V27	Scientific Research Investment Level	All	[37]

In addition, some risks were identified via the five typical levels of developing industry chain of industrialized construction in Table 2, consisting of Promoting the Industrial Residential Building (IRB) Policy in Shenzhen [50], Chinese Real Estate Developers Introduce Industrial Methods to Improve Construction Efficiency and Quality, Evaluation of the Development Level of Industrialized Buildings in Guangzhou [51], Hierarchical Study on the Influencing Factors of Construction Industrialization in Xiamen, and Assembly Building Industrialization Development in Gansu [52]. As a special economic zone in China, Shenzhen has always had the responsibility of testing and promoting new policies, and the Industrial Residential Building (IRB) is no exception, but how do construction contractors view the newly released IRB policy in Shenzhen and determine which characteristics of the enterprise have a significant impact on the IRB policy? China's leading residential real estate developers are introducing industrialized construction methods to improve construction efficiency and quality and to evaluate and control the risks involved in the application of new construction systems in industrialized buildings. Guangzhou was an early promoter of local industrial construction development policies, which led to the early and rapid development of industrialized buildings in southern China. The choice of Guangzhou as a case study is representative and can better verify the applicability of the evaluation index system. As one of the eight national pilot cities of residential industrialization, Xiamen has a certain scientific and universal character to study the many difficulties faced by the promotion of the industry chain of industrialized construction. Gansu Province is located in the critical area of the national "One Belt and One Road" initiative, and improving the whole industry chain of industrialized construction is an important measure for Gansu Province to respond to the rapid development of the country under the new historical opportunity.

Table 2. Risk investigation approach and risk triggers for five case projects.

Case Analysis Project	Survey Technique	Code	Risk
Promoting the IRB Policy in Shenzhen	Interviews and Questionnaire	V28	Effectiveness of the Policy
Chinese Real Estate Developers Introduce Industrial Methods to Improve Construction Efficiency and Quality	Interview	V29	Large Differences between Design and Site Conditions
Evaluation of the Development Level of Industrialized Buildings in Guangzhou	Official Data and Questionnaires	V30	Building Industrialization Research and Development Achievements
Hierarchical Study on the Influencing Factors of Construction Industrialization in Xiamen	Interview	V31	Inadequate Standards
Assembly Building Industrialization Development in Gansu	Investigation and Research	V32	Industry Market Demand

A total of five risks were summarized based on the above project profile analysis, including the effectiveness of the policy, large differences between design and site conditions, industrialized construction research and development achievements, inadequate standards, and industry market demand. Combining these 5 risks with 27 risks from the literature review, there are 32 risk factors linked to the industry chain of industrialized construction.

3.2. Determination of Risk Interrelations

This step involves defining the link in the risk network, which expresses the influence between two nodes [53]. Determining the edges of the network is inherently a process of analyzing whether there is an association between two risks and assigning a value to each association. In this paper, the risk association data are analyzed for binary directed values. Risk association is a directional and causal propagation process and therefore requires directional values. Then, weighted association data are obtained through questionnaires or directly from professionals. Given the subjective consciousness involved, the data processing methods described above only amplify these errors rather than making them accurate. While the use of binary values also relies on subjective judgments, they can reduce subjective influences by simplifying the data types.

Given a causal relationship between the effects of certain risk factors, a directed complex network is established, using 1 and 0 to describe the association between risks, as in Equation (1). An asymmetric adjacency matrix is constructed, for which the following specific definitions are provided.

$$m_{ij} = \begin{cases} 1, v_i \text{ impact } v_j \\ 0, v_i \text{ does not affect } v_j \end{cases} \tag{1}$$

Let $G = (V, E)$ be the network graph, where V represents the network nodes, $V = v_1, v_2, v_3, v_4, \ldots, v_n$, E represents the network edges, $E = e_1, e_2, e_3, e_4, \ldots e_n$, and m_{ij} represents the relationship between v_i and v_j. The resulting $M(G) = (m_{ij})_{n*\mathrm{n}}$ is referred to as the adjacency matrix of the network graph G, as shown in Table 3.

Table 3. Risk factor adjacency matrix.

Risk Factors	v_1	v_2	v_3	$\cdots$	v_n
v_1	0	m_{12}	m_{13}	$\cdots$	m_{1n}
v_2	m_{21}	0	m_{23}	$\cdots$	m_{2n}
v_3	m_{31}	m_{32}	0	$\cdots$	m_{3n}
$\vdots$	$\vdots$	$\vdots$	$\vdots$	0	$\vdots$
v_n	m_{n1}	m_{n2}	m_{n3}	$\cdots.$	0

The risk association data m_{ij} were determined through the questionnaire. The survey targets mainly include project managers, designers, professors, and supplier representatives who are engaged in this field. The first round of questionnaires was collected, organized, and summarized to identify risks with significant differences in assessment. Then, it is fed back to the experts anonymously, consulted again, focused again, and fed back again until a consensus is obtained. This indicates the end of the questionnaire. The final results of the questionnaire are collected in the form of an adjacency matrix. Since the adjacency matrix of each respondent is different, the final determination of risk association data should follow the principle of frequency maximization. That is, no less than five experts with the same binary data for the certain risk will be the final association data.

3.3. Risk Analysis

3.3.1. Overall Network Analysis

Density is the network measure that is more descriptive of the entire network rather than of the individual nodes/links [54]. Density is defined as the ratio of existing ties to the maximum number of possible ties in the network if everyone in the group is connected to everyone else. It can be calculated using Equation (2). The network density ranges from 0 to 1. The higher the density, the greater the risk interrelationship in the network. Path length generally refers to the shortest distance between two nodes, and the average of all node path lengths is the network's average path length; it can be calculated using Equation (3). We believe that the shorter the average path length, the more efficient it is to send messages between them.

$$D = \frac{E}{V(V-1)} = \frac{\left(\sum_{\mathrm{v}_i \in V} CNICRA_{v_i}\right)}{V(V-1)} \tag{2}$$

$$L = \frac{1}{E(E-1)} \sum_{v_i, v_j \in V} d_{ij} \tag{3}$$

Equation (2), where D represents density of the network, E represents the number of edges, V represents the number of nodes. $CNICRA_{v_i}$ represents node i on the complex network of industrialized construction risk associations

Equation (3), where L represents the average of all node path lengths, d_{ij} represents the distance between v_i and v_j.

3.3.2. Local Network Analysis

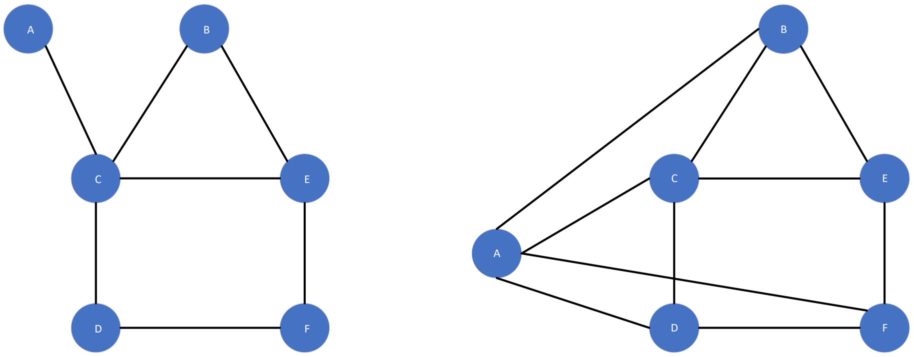
The clustering coefficient reflects the degree of aggregation of the nodes in the network [55]. It is the ratio of the number of edges connected by the nodes to the number of edges with a tendency to connect, as defined in Equation (4). The higher the clustering coefficient of a node, the greater the degree of clustering of its neighboring nodes.

$$C_i = \frac{2d_i}{E(E-1)} \tag{4}$$

where C_i represents the clustering coefficient of node i, d_i represents the degree of node i, and E represents the number of edges in the network.

When certain elements of a network are closely related enough that they form subgroups, such subgroups are referred to as cohesive subgroups in complex network analysis [56]. When investigating how many subgroups exist in the network, the analysis of the characteristics of the relationships between internal members and the relationships between subgroups is referred to as cohesive subgroup analysis. In local network analysis, weak component analysis is used, which is less demanding on the network. It only requires a one-way connection between two nodes. The strong component analysis is more demanding on the network. It requires a two-way connection between two nodes, which is less practical and difficult to meet in actual cases. The commonly used analysis methods are faction analysis [57] and K-cluster analysis. Factions are such a subset of actors, and the members of the faction are more closely related. From a graph-theoretic perspective, a faction is a maximal complete subgraph consisting of at least three points, i.e., there is a direct relationship between all nodes. The relationship between points in a subgraph can be significantly affected by the removal of one or more points in the subgraph, showing "fragility". K-cluster is defined as: each node is adjacent to all but but k points, where the degree of any adjacent node is not less than $n-k$. The relationship between points in the subgraph is not significantly affected by the removal of one or a few points in the subgraph, showing "robustness" [58].

A graph theory example is used to explain the structural features of faction analysis and K-cluster analysis, as shown in Figure 2. Let there exist 6 nodes A, B, C, D, E, F in the subgraph. The number of nodes in (a) is greater than 3 and there is a direct relationship between the nodes, which is a 3 faction. All the nodes in (b) have a distance greater than 3, and 6 of them have a degree of at least 3, i.e., (b) is a 3-cluster. By removing point C in (a), point A is isolated. The subgraph will be more affected by the removal of C. In (b), by removing point C, A can also be connected to B, D, and F. This has less impact on the whole network; thus, the K-cluster is more robust than the structure of the faction analysis.



(**a**) Three-faction.

(**b**) Three-cluster.

Figure 2. Structural features of faction analysis and K-cluster analysis.

3.3.3. Individual Network Analysis

Centrality is an important measure for individual network analysis [59]. The paper focuses on two perspectives of degree centrality and betweenness centrality. Degree centrality is the most intuitive brightness metric to express the centrality of a node, portraying its local centrality index and its ability to influence [60,61]. This study analyzes degree centrality in terms of two aspects of the network, out-degree and in-degree. In-degree is a common way of portraying the degree centrality of a directed graph. It measures the degree of influence on a node, indicating salience, and out-degree is a measure of a node's collinearity, as defined in Equation (5), where d_i^{in} represents the entry edge between v_i and other nodes, and d_i^{out} represents the edge between v_i and other nodes. Equation (6) shows the difference between the in-degree and out-degree values of a risk.

$$InDegree_{v_i} = \sum_{i=1, i \neq j}^{n} d_i^{in} OutDegree_{v_i} = \sum_{i=1, i \neq j}^{n} d_i^{out} \tag{5}$$

$$GapDegree_{v_i} = OutDegree_{v_i} - InDegree_{v_i} \tag{6}$$

Equation (5), where $InDegree$ represents in-degree, $OutDegree$ represents out-degree, d_i^{in} represents the entry edge between v_i and other nodes, d_i^{out} represents the edge between v_i and other nodes.

Equation (6), where $GapDegree$ represents the difference between in-degree and out-degree.

Betweenness centrality indicates the incidence of a given node/link falling between two other nodes/links [62]. The more times a node appears in the shortest path between any two nodes, the greater the betweenness centrality of that node. The first step of this algorithm is to find the shortest path between any two vertices, and then, count the number of times each intermediate node appears in all shortest paths. A node/link with a high intermediate centrality value has a high level of control over the influence passing through it, and the node somehow plays the role of a gatekeeper. The betweenness centrality of v_i is given by Equation (7), where ${}^{\sigma}v_z, v_j$ is the total number of shortest paths from node v_z to node v_j, and ${}^{\sigma}v_z, v_j(v_i)$ is the number of those paths that pass through v_i.

$$Betweenness_{v_i} = \sum_{l_i, l_j, l_z \in L} {}^{\sigma}l_z l_j(l_i) / {}^{\sigma}l_z, l_j \tag{7}$$

where $Betweenness_{v_i}$ represents betweenness of node i, ${}^{\sigma}l_z, l_j$ is the total number of shortest paths from node v_z to node v_j, ${}^{\sigma}l_z, l_j(l_i)$ is the number of shortest paths from node v_z to node v_j that pass through v_i.

3.4. Comprehensive Degree

The above-mentioned risk association model for complex networks has shortcomings in the key node identification method. For example, degree centrality is a method based on local characteristics, but degree centrality does not consider the influence of node location and surrounding nodes, and its classification effect is not ideal; betweenness centrality is a method based on global characteristics, and the calculation process is complicated. Many scholars have proposed more improved methods for this. Berahmand et al. proposed a local ranking method to identify critical nodes, which measures the propagation ability of nodes based on important location parameters [63] Namtirtha et al. proposed an improved calculation method that assigns weights to all edges in the network [64] However, there are some shortcomings: (1) the computational difficulty; (2) some methods only consider the local network structure in the analysis; (3) the low resolution of the method and the poor ability to identify key nodes in the network.

In response to the above issues, a comprehensive degree index was added to determine the importance of risk factors at the same level. The nodes in the risk network model interact with nodes that are directly connected to them and impact nodes that are far away. To reduce the complexity of the computational process, only the degree of impact on neighbors and sub-neighbors is considered to distinguish the importance of the nodes. The dynamically adjustable influence parameter u is set, which is used to measure the degree of influence of nodes on sub-neighbors. The comprehensive degree of the node is obtained. In the same level of risk factors, the node with a greater composite degree is more important. The specific process is designed as follows.

Step 1: The out-degree of risk factors at the same risk network level and the total number of nodes affected within a two-step distance are determined.
Step 2: The influence parameter for the same stratum of risk factors using the out-degree of the nodes and the total number of nodes affected within a two-step distance are determined, as in Equation (8).
Step 3: The number of sub-neighboring nodes is calculated using the node's out-degree and the total number of nodes affected within a two-step distance, as in Equation (9).
Step 4: The comprehensive degree of the node is calculated using the parameter values from the preceding steps, as in Equation (10).

$$\mu_{v_i} = \frac{d_i^{out}}{N(v_i)} \tag{8}$$

$$Q(v_i) = N(v_i) - d_i^{out} \tag{9}$$

$$P(v_i) = d_i^{out} + \mu_{v_i} Q(v_i) \tag{10}$$

where μ_{v_i} represents the influence parameter, d_i^{out} represents the out-degree, $N(v_i)$ represents the total number of nodes affected within a two-step distance, $Q(i)$ represents the number of sub-neighboring nodes, and $P(\mathrm{v}_i)$ represents the comprehensive degree.

3.5. Result

In summary, the first step identifies the research subjects using a literature review and case study analysis and presents them in the form of a list. The second step quantifies the relationship between risks through a questionnaire and generates a visual network. In the third step, the important hierarchy of risks is initially determined by overall, local, and individual analysis of the network. Then, the risk factors with the greatest significant impact in the critical factor hierarchy and the most significant abnormal risk transmission in the transmission hierarchy are identified by introducing the composite degree index. Finally, targeted mitigation measures are proposed based on the experimental findings.

4. Case Study

Case studies are the technique of choice when considering the "how" and "why" questions. This study addresses a "how to" type of question to understand how risks are linked in the industry chain of industrialized construction. This case project was chosen because of its high project complexity, which makes the risk analysis more meaningful.

4.1. Background

To promote the rapid transformation of industrialized construction, Shandong Province has initially built an industrialized construction project driven by industrialized pilot cities, industrialized base enterprises driven by construction projects, industrial chains built by base enterprises, industrial clusters built by industrial chains, industrial clusters formed by industrial parks, industrial parks radiating urban areas, urban areas to promote the synergy of the whole industrial chain, the whole industrial chain to support cross-provincial and overseas expansion of industrialized construction development model.

Shandong Province is accelerating the development of the industry chain of industrialized construction, but where the whole industrial chain is not complete and with bottleneck constraints. To demonstrate the identification of critical risks and the development of risk response strategies based on an improved complex network model, a parametric analysis of the risk network for the industry chain of industrialized construction in Shandong Province was performed.

4.2. Industry Chain Composition

An industry chain of industrialized construction system with power, support systems, and multi-level enterprises as the primary units was created, as shown in Figure 3. The power system is derived from inherent technology and innovation, including artificial intelligence and biotechnology, which drive the rapid extension and expansion of the industry chain, external policies and collaboration, including government subsidies, financial support and cooperation among enterprises to increase their eagerness to move up the chain. Policy support is the source of the support system. The government encourages and supports key enterprises to lead the development and establishes a negative list of policy bottlenecks [65]. Talent support is the key element to building the industry chain, increasing the introduction of key talent, including data development, management, manufacturing, and other areas of high-quality talents. Data support plays a vital role in acquiring and analyzing large amounts of data, matching and optimizing it for corporate procurement, etc. Multi-level enterprises primarily include raw material security layer enterprises, scientific research support layer enterprises, and product output layer enterprises. Each enterprise collaborates with the others, utilizing the industrial chain as a link to meet high coordination requirements between enterprises [66].

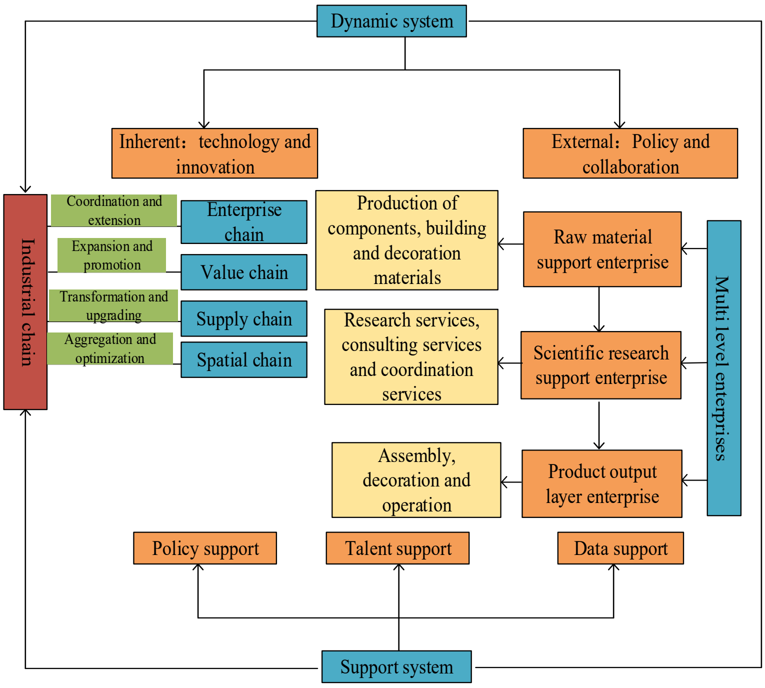


Figure 3. Composition of the industry chain of industrialized construction.

4.3. Data Collection

Some of the 32 risks that this study identified would not have occurred. Only risks that occurred notably in this case project were considered, which kept the complex network model from becoming overly complex and improved the accuracy of its practical application. Based on 32 risks, we collected data and questionnaires to quantitatively determine the risk that occurred in the case.

By consulting the statistical yearbook of Shandong Province in 2020, the total area of new construction of assembly buildings in 16 urban areas was understood, of which Jinan City has the largest area of 691.18 hectares and Binzhou City has only 10.73 hectares. This indicates an excessive regional development gap, corresponding to V3 of the 32 risks. Second, the province's industrial base was visited and was divided into three categories:

integrated applications, scientific and technological research and development, and parts production. Industrial bases refer to assembly building-related enterprises with clear development goals, better industrial base, advanced and mature technology, strong R&D and innovation capability, large industrial relevance, focus on training of assembly building-related talents, and can play a demonstration leading and driving role, mainly including design, components production, construction, equipment manufacturing, science, and technology R&D, etc. Currently, the main focus is on the production of components, and the number is unevenly distributed. Jinan has the most industrial bases, with 28, and Binzhou has the least, with only one. It can be seen that the province's industrialization system is not yet complete, corresponding to the 32 risks in V26. The specific distribution is shown in Figure 4.

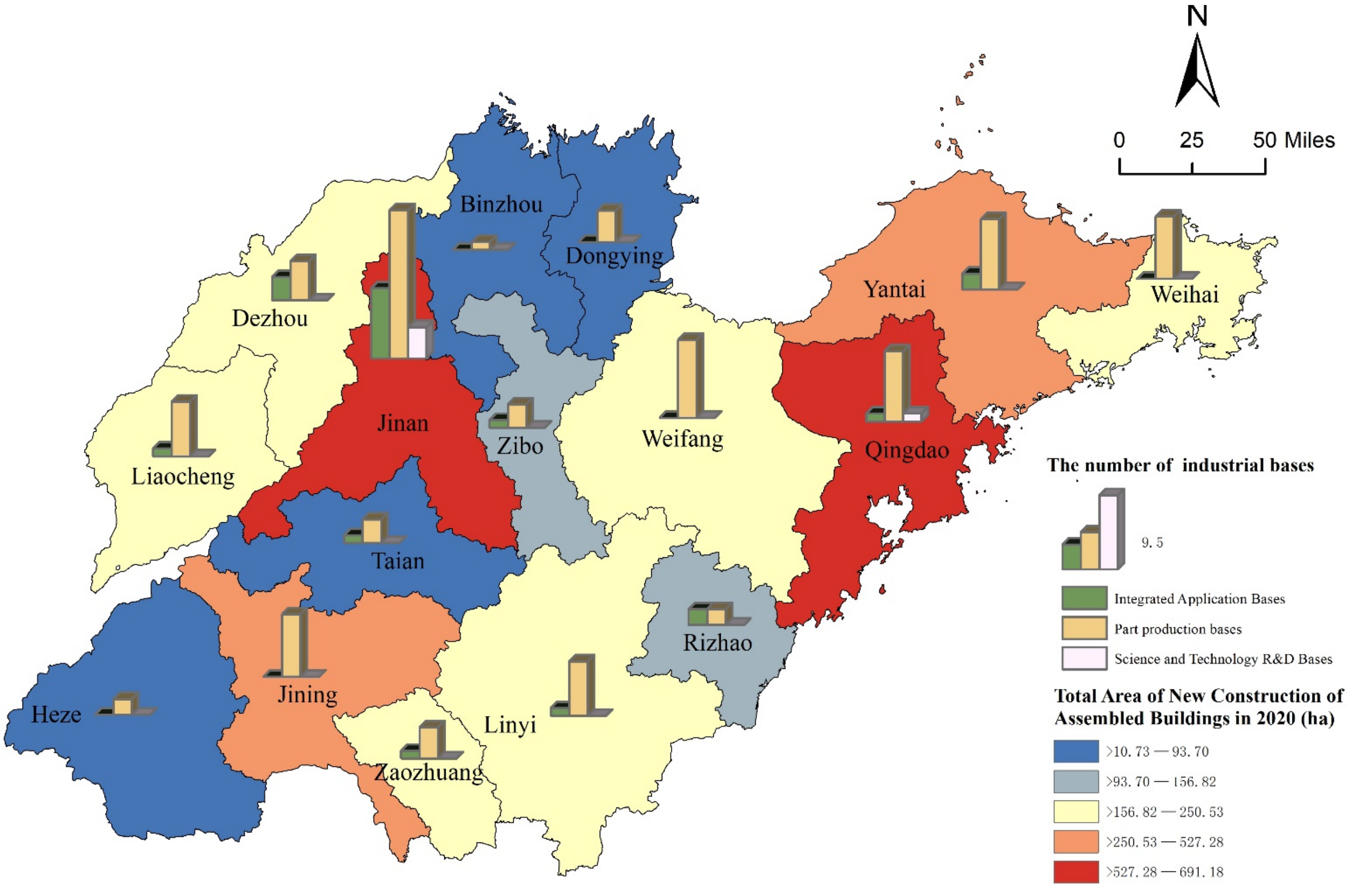


Figure 4. Distribution of new assembly floor space and bases in Shandong Province.

In terms of existing technical standards, Shandong Province has promulgated 13 national technical standards from 2014 to 2021, such as "evaluation standards for assembled buildings" and "technical regulations for the application of assembled steel building slabs", etc. It shows that Shandong Province has made great contributions to the construction of the technical standard system. Therefore, V31 of the 32 risks can be excluded.

Through the collection of relevant data, risk factors consistent with this case were selected and redundant factors were excluded. The importance of the remaining risks was assessed by questionnaire. Between April 2022 and May 2022, 131 online questionnaires were distributed to participants in all segments of industrialized construction chain. The surveys were accompanied by cover letters to explain the purpose of the study and to ensure participant confidentiality. Of the 131 participants contacted, 75 responded and 63 submitted complete responses, for a valid response rate of 84%. In the questionnaire, risk importance is rated on a 5-point Likert scale, from 1 to 5, indicating not occurring, not important, important, very important, and occurring risk. The descriptive statistics of the respondents, as shown in Table 4, indicate that they are in different job attributes and job titles. They have extensive work experience in their field of work. In general, the characteristics of the respondents confirm the validity of the findings.

Table 4. Basic information of survey respondents.

Item	Category	N	Proportion
Work attributes	Investment units	18	21.69
	Design units	13	15.66
	Production units	13	15.66
	Construction units	16	19.28
	Universities	23	27.71
Work experience	≤3	12	14.46
	3~5	16	19.28
	6~8	16	19.28
	8~10	16	19.28
	≥10	23	27.71
Number of projects involved	1	5	6.02
	2	24	28.92
	≥3	54	65.06
Title	Primary	9	10.84
	Intermediate	24	28.92
	Advanced	31	37.35
	Others	19	22.89

A weighted average of the remaining 29 risk factors was calculated from the questionnaire scores, and the values were normalized. Risks with normalized values higher than 2/3 will be considered significant. The 19th risk value is 0.67, and the 20th risk value is 0.664. Therefore, the first 19 risks with a normalized value of not less than 0.667 on a five-point Likert scale are shown in Table 5. A total of 21 risk nodes formed the complex network of risk associated in this case (Figure 5).

Table 5. Processing data.

Code	Proportion (%)					Mean Score	Normalization
	Score 1	Score 2	Score 3	Score 4	Score 5		
V27	0	3.61	12.05	46.99	37.35	4.18	1.00
V7	1.2	1.2	14.46	50.6	32.53	4.12	0.95
V28	0	3.61	12.05	56.63	27.71	4.08	0.92
V5	2.41	4.82	12.05	45.78	34.94	4.06	0.90
V32	0	1.2	10.84	68.67	19.28	4.06	0.90
V11	0	1.2	21.69	60.24	18.87	4.02	0.87
V18	0	2.41	15.66	66.27	15.66	3.95	0.81
V10	0	1.2	21.69	60.24	16.87	3.93	0.80
V16	0	3.61	15.66	65.06	15.66	3.93	0.80
V22	0	6.02	14.46	61.45	18.07	3.92	0.79
V19	0	6.02	16.87	57.83	19.28	3.9	0.77
V24	2.41	4.82	24.1	38.55	30.12	3.89	0.76
V13	1.2	3.61	14.46	66.27	14.46	3.89	0.76
V4	2.41	4.82	18.07	54.22	20.48	3.86	0.74
V17	2.41	3.61	14.46	66.27	13.25	3.84	0.72
V15	1.2	6.02	21.69	50.6	20.48	3.83	0.71
V9	1.2	4.82	21.69	57.83	14.46	3.8	0.69
V21	4.82	4.82	13.25	61.45	15.66	3.78	0.67
V25	0	3.61	24.1	62.65	9.64	3.78	0.67

Normalization = (mean-minimum mean)/(maximum mean-minimum mean).

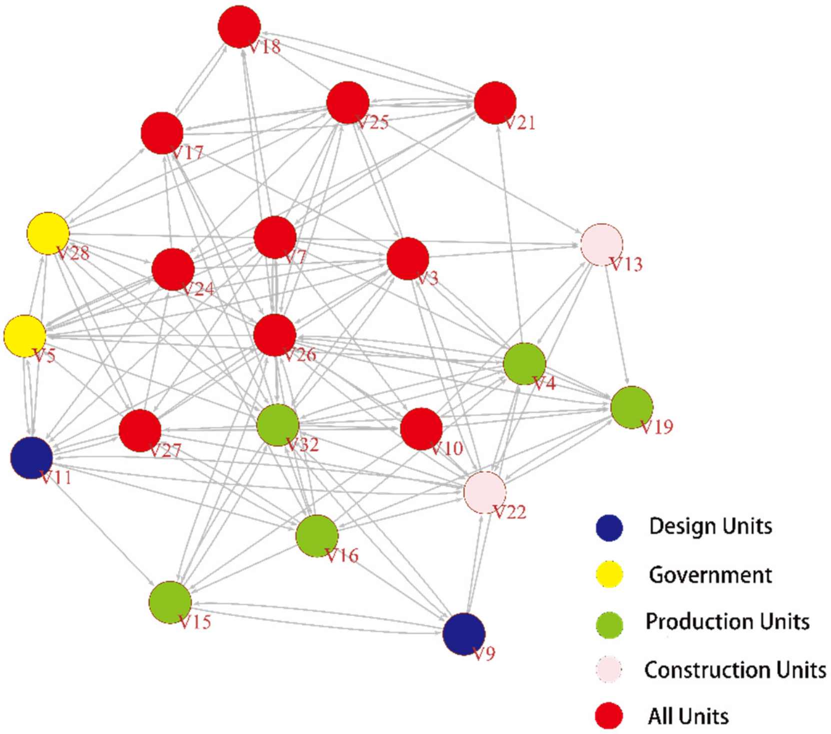


Figure 5. Complex network of risk association in Shandong Province.

4.4. Result of Network Analysis

4.4.1. Overall Network Analysis

The network density of the complex network of risk association of the industry chain of industrialized construction in Shandong Province is 0.31, which indicates that the nodes are more closely connected. Therefore, the risk network of the industry chain of industrialized construction is more complex, the influence between them is transmitted through the network, and the risk interaction has a greater impact on the stability of the industry chain. The network has 131 paths with an average path length of 1.82. Therefore, different risk factors only need to be connected 1.82 times to influence each other, and some isolated risk factors are connected through some core factors. In addition, the maximum path in this network is three, indicating that a risk factor can trigger another risk factor by up to three steps.

4.4.2. Local Network Analysis

The clustering coefficient of the network is 0.39, indicating a high degree of clustering in the local risk network. The visualization of the clustering coefficients of the risk network (Figure 6) shows that the clustering coefficients for credit risk are low, while the clustering coefficients for social cognition are high. This indicates that the neighboring nodes of V18 are more likely to be neighbors.

This study uses weak component analysis to study the complex network of risk association of the industry chain of industrialized construction in Shandong province. Firstly, the adjacency matrix is symmetrized, and then, the risk factors are analyzed by faction, as shown in Table 6. Table 6 shows 19 sub-groups in this network, with V32 appearing 11 times and V27 appearing 10 times, implying that industry market demand and scientific research investment level are critical factors in the network. Figure 7 depicts the specific tree distribution of the subgroups, and the analysis shows that the network has three distinct branches, the longer the branch, the higher its faction score. v26 and v32 have the highest faction scores, indicating that more groups are involved in these two factors.

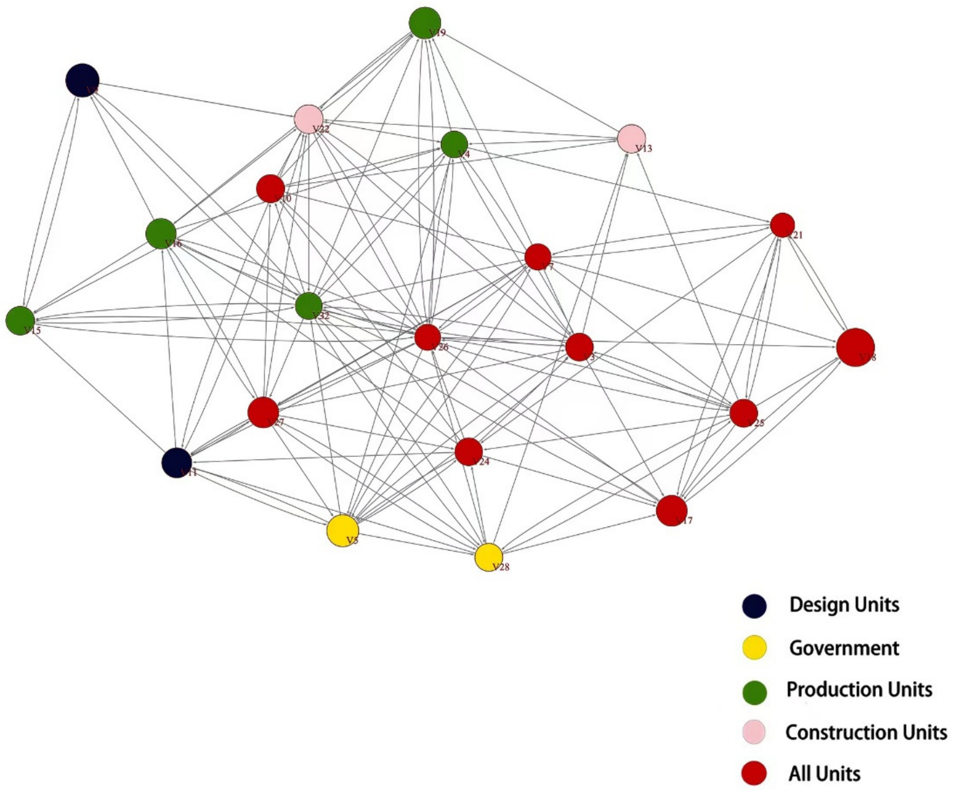


Figure 6. Visualization of clustering coefficients.

Table 6. Factional analysis of the network.

Code	Sub Group	Code	SUB GROUP
1	V32 V7 V27 V3 V26 V5	11	V4 V32 V3 V26 V5
2	V32 V7 V27 V10 V26	12	V28 V24 V27 V26 V11 V5
3	V32 V28 V27 V26 V5	13	V16 V24 V27 V26 V11
4	V16 V32 V22 V27 V26	14	V24 V27 V3 V26 V5
5	V32 V22 V27 V3 V26	15	V17 V24 V3 V26 V25
6	V32 V22 V27 V10 V26	16	V28 V17 V24 V26 V25
7	V4 V16 V19 V32 V22 V26	17	V16 V22 V27 V26 V11
8	V4 V19 V32 V22 V10 V26	18	V7 V27 V26 V11 V5
9	V19 V32 V7 V10 V26	19	V4 V19 V13 V22 V10
10	V4 V32 V22 V3 V26		

Since this network is more complex, its factional analysis is usually not steady. Therefore, this study further performs a K-clustering analysis on the risk network. When K is taken as 2 and the size is 7, it can accurately reflect the state of cohesive subgroups in the risk network of the industry chain of industrialized construction, and the specific analysis is shown in Table 7, with 13 distinct cohesive subgroups. From the Figure 8, it is obtained that V32, V26, and V27 bifurcate earlier, indicating that their K-cluster scores are the highest. The higher the score, the more groups that are involved in this factor.

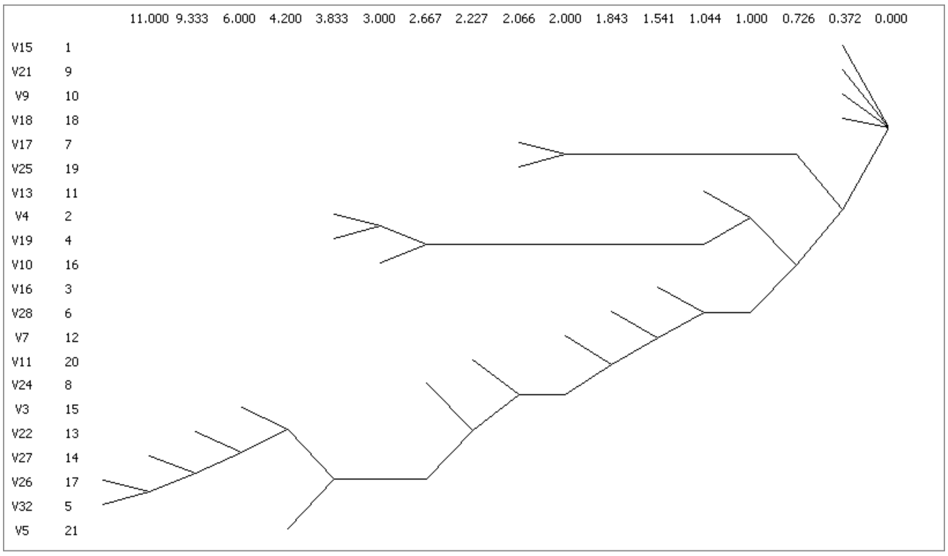


Figure 7. Factional analysis tree of the network.

Table 7. K-cluster analysis of the network.

Code	K-Bundle Coefficient	Code	K-Bundle Coefficient
V4 V16 V19 V32 V22 V10 V26	0.80	V32 V28 V17 V24 V27 V3 V26	1.07
V4 V16 V32 V22 V27 V3 V26	4.29	V32 V28 V17 V24 V3 V26 V5	1.07
V4 V16 V32 V22 V27 V10 V26	4.29	V32 V28 V24 V27 V3 V26 V5	3.00
V4 V32 V22 V27 V3 V10 V26	4.29	V32 V28 V7 V27 V26 V11 V5	2.00
V4 V32 V22 V27 V3 V26 V5	3.00	V32 V7 V22 V27 V3 V10 V26	2.00
V16 V19 V32 V22 V27 V10 V26	0.80	V24 V7 V27 V3 V26 V11 V5	2.00
V19 V32 V7 V22 V27 V10 V26	0.80		

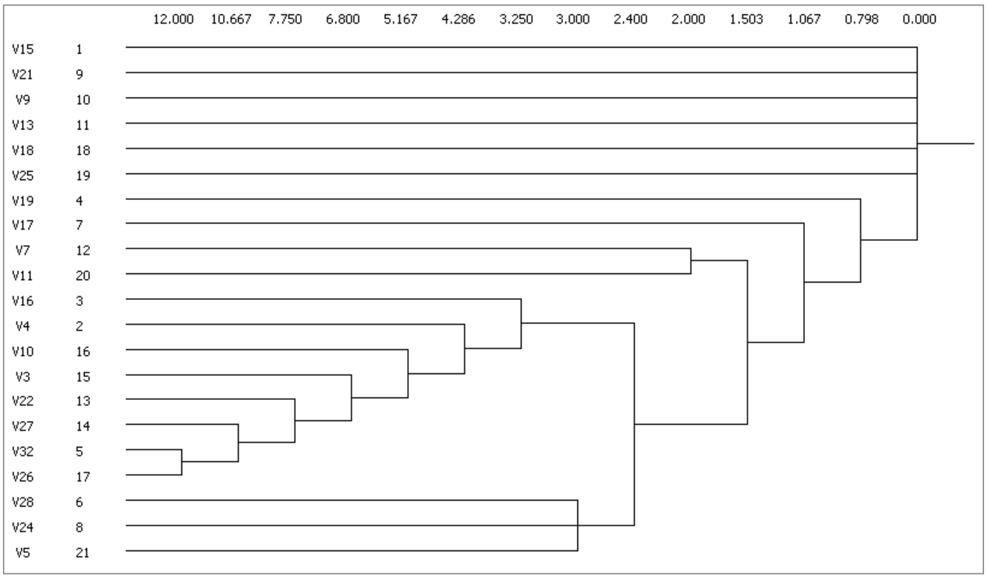


Figure 8. K-cluster analysis tree of the network.

4.4.3. Individual Network Analysis

According to the degree centrality, the underlying factors of the industry chain of industrialized construction in Shandong Province were identified and analyzed specifically, as shown in Table 8. The following conclusions were obtained.

Table 8. Centrality analysis of the network.

Number	Outdegree	Indegree	Degree Difference	Number	Outdegree	Indegree	Degree Difference
V26	12.00	12.00	0.00	V5	6.00	7.00	−1.00
V7	11.00	3.00	8.00	V22	5.00	10.00	−5.00
V32	9.00	11.00	−2.00	V21	5.00	5.00	0.00
V27	9.00	5.00	4.00	V11	5.00	7.00	−2.00
V25	8.00	5.00	3.00	V9	4.00	2.00	2.00
V3	8.00	8.00	0.00	V17	4.00	7.00	−3.00
V28	7.00	5.00	2.00	V15	3.00	6.00	−3.00
V24	7.00	5.00	2.00	V19	3.00	8.00	−5.00
V16	7.00	5.00	2.00	V13	3.00	4.00	−1.00
V4	7.00	7.00	0.00	V18	2.00	5.00	−3.00
V10	6.00	4.00	2.00				

According to degree centrality analysis of the complex network of the industry chain of industrialized construction of risk association in Shandong province in Table 8, the five types of risk factors, namely industrialization system (V26), enterprise collaboration level (V7), industry market demand (V32), scientific research investment level (V27), and company management (V25), have a significant impact. Moreover, some of the risks of the network have a greater degree of entry and exit, including enterprise collaboration level (V7), scientific research investment level (V27), where the degree of entry is greater than the degree of exit, indicating that these factors have a greater influence on and are less influenced by other risk factors.

Betweenness centrality portrays how a node resides between other nodes and acts as an intermediate transfer. Therefore, the network is analyzed for intermediate centrality. From the betweenness centrality analysis of the network (Table 9), the visualization of the betweenness centrality of risk network nodes (Figure 9) shows that the top five risk nodes are the industrialization system (V26), industry market demand (V32), uneven regional development (V3), component production line capacity (V4), and strategic objectives of the company (V17). These five risk factors have a high central centrality and play a critical role in risk transmission during the operation of the chain.

Table 9. Betweenness centrality analysis of the network.

Number	Betweenness Centrality	Number	Betweenness Centrality
V26	73.71	V24	11.74
V32	58.48	V28	11.73
V4	22.94	V16	10.79
V3	19.51	V11	8.39
V17	18.24	V15	7.00
V22	17.82	V10	6.03
V21	16.31	V19	5.84
V7	14.81	V13	2.84
V5	13.55	V18	1.47
V27	13.45	V9	1.14
V25	13.19		

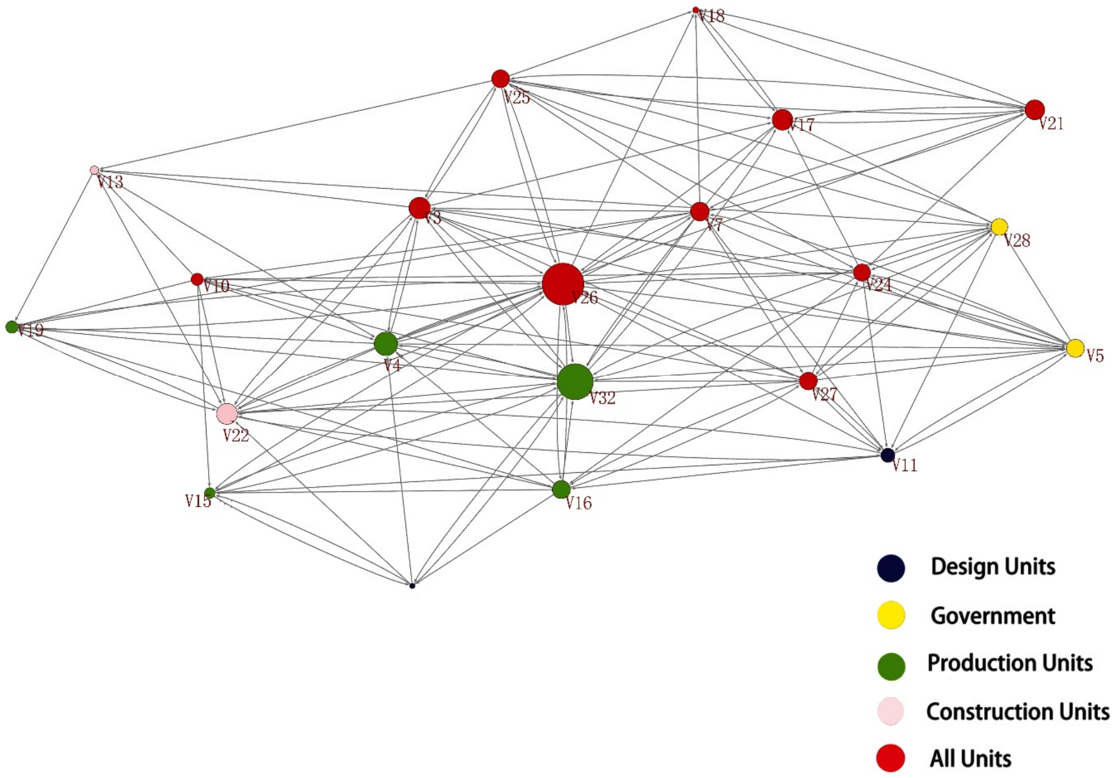


Figure 9. Betweenness centrality visualization of the network.

4.4.4. Hierarchical Analysis of Risk Factors

The critical risk factors of the industry chain of industrialized construction in Shandong province are derived from the overall analysis, local analysis, and individual analysis of the risk network model. Through the overall analysis of the risk network, a high degree of closeness between the nodes is obtained. The local analysis of the risk network is used to obtain the aggregation between nodes and the distribution of cohesive subgroups. Through the individual analysis of the risk network, the degree of influence of the nodes on the whole network and their risk transmission capacity are more focused on. The results of the above analysis are shown in Table 10. The critical risk factors of the industry chain of industrialized construction are enterprise collaboration level (V7) and scientific research investment level (V27). The intermediate transmission factors are the industrialization system (V26), industry market demand (V32), uneven regional development (V3), component production line capacity (V4), and strategic objectives of the company (V17).

Table 10. Hierarchical analysis of risk factors.

Code	Risk Factors	Hierarchical Results
V7	Enterprise Collaboration Level	Critical factors
V27	Scientific Research Investment Level	Critical factors
V26	Industrialization System	Intermediate conduction factor
V32	Industry Market Demand	Intermediate conduction factor
V4	Component Production Line Capacity	Intermediate conduction factor
V3	Uneven Regional Development	Intermediate conduction factor
V17	Strategic Objectives of the Company	Intermediate conduction factor

4.4.5. Comprehensive Degree Analysis

The preliminary hierarchy of risk factors is obtained from the above complex network analysis. The importance of risk factors is further determined by a comprehensive degree for the same risk level factors. The more significant the risk node, the higher the comprehensive degree. The calculation process of the comprehensive degree is parameterless, which eliminates the need to test parameter values in advance and reduces the calculation process's complexity. According to Equations (8)–(10) of Section 3.3, the intermediate transmission factors are, in order of importance, industrialization system (V26) > industry market demand (V32) > uneven regional development (V3) > component production line capacity (V7) > strategic objectives of the company (V17). The critical factors are, in order of importance, scientific research investment level (V27) < enterprise collaboration level (V7), as shown in Figure 10.

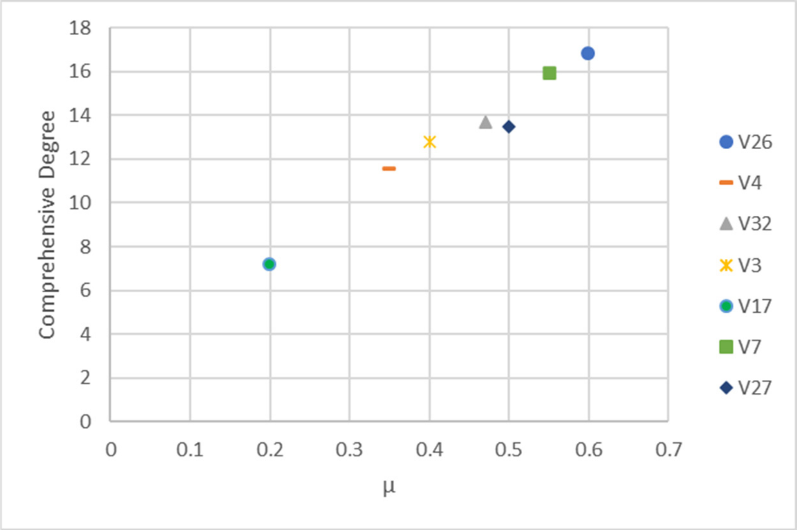


Figure 10. Comprehensive degree distribution.

5. Discussion

The Ministry of Housing and Urban–Rural Development of the People's Republic of China has released the 14th Five-Year Plan for the Development of industrialized construction, which aims to clarify the basic establishment of intelligent buildings and industry chain [67]. The plan is clear that industrialized construction still has the problem of poor development quality and efficiency, focusing on the market order is not standardized, the overall quality of construction is not high, project quality and safety accidents occur from time to time, digital collaboration barriers, and there is still a gap compared to the growing needs of the people for a better life. Previously, Gan, Y et al. identified some key quality factors that hinder the diffusion of industrialized buildings in the context of the Chinese construction industry. These factors include the inaccurate design of connection points between core components, lack of design specifications and standards for components, lack of quality management systems in the production process, etc. [68]. Wu, P et al. discussed the barriers to digital collaboration in industrialized buildings and concluded that financial-related factors and lack of support are the most critical factors causing the barriers to collaboration [69]. Thus, identifying and controlling the risks of the industry chain of industrialized construction is a prerequisite for solving the above problems and is in line with the strategic requirements of the plan. Internationally, Tabatabaee, S et al. discussed the risks of industrialized construction in terms of information, cost, etc., and prioritized risk factors to promote the sound development of industrialized construction enterprises [70]. Mohsen, A et al. identified factors that may contribute to higher skilled worker requirements to improve the implementation of industrialized building construction projects in Malaysia [71]. Consequently, the content of this study is of research value in both Chinese and international contexts. The main conclusions are as follows.

Firstly, a case study analyzes the risks associated with the industry chain of industrialized construction. Several key conclusions are valuable, including: (1) The density of the complex network of the industrial chain of industrialized construction is 0.31 and the average path length is 1.82, indicating that the network is highly compact and interactive. (2) Faction and two-cluster analyses of this network generated 19 and 13 significant small groups, respectively. The network appears to have a high degree of aggregation and multiple small group formations. (3) The level of scientific research investment and the level of enterprise collaboration belongs to the critical factor hierarchy of the industry chain of industrialized construction. The comprehensive degree analysis of the critical factor hierarchy shows that the comprehensive indexes of the level of scientific research input and the level of enterprise collaboration are 13.5 and 15.95, respectively. It is thus clear that the level of enterprise collaboration is the most critical factor. (4) The industrialization system, industry market demand, regional development imbalance, component production line capacity, and corporate strategic objectives belong to the intermediate transmission factor hierarchy of the industry chain of industrialized construction. After a comprehensive degree index analysis, the industrialization system has the highest comprehensive index of 16.8. Therefore, the industrialization system is the most significant abnormal risk transmission.

Secondly, since the industry chain of industrialized construction has many participating subjects, large capital investment, and complex risk factors, the risk of the industry chain is difficult to grasp, and the risk of any one link may affect the stability. This paper explores the interaction between risks from the perspective of a network and proposes a theoretically innovative and practically applicable risk analysis model. The model has several advantages and would contribute to earlier risk response decision making. A future-proofing framework is regarded as critical and helpful to risk assessment and response to the industry chain of industrialized construction. To improve the applicability of the risk network model in each stage of the industry chain, complete literature and case studies were carried out to ensure the sufficient capacity of the risk list, and the data were counted, organized, and summarized through several questionnaires. Finally, the relationship between risks were clarified. While Luo, LZ et al. are in the process of identifying risks in industrialized construction, the process of collecting data was too simple. Even though the data were tested for consistency, it lacked flexibility [72].

In addition, the model and strategy development process facilitate upfront decision making for each enterprise. When faced with feasibility analysis, project participants at all levels need to minimize the scope of risk prevention, including the number and importance of risk factors and personnel, departments, or organizations. Therefore, it is necessary to reduce and screen complex project risks to avoid multiple risk governance or waste of project resources. The article uses this engineering principle for modeling to determine the final risk network adapted to a specific case project. Xia, MM et al. developed an evaluation model based on gray fuzzy theory to assess and calculate the risks to obtain the core risks [65]. This model is suitable for risk evaluation of simple projects. However, fuzzy mathematical algorithms are difficult to apply to risk prevention and response in complex industrial construction chains. Therefore, the model is more comprehensive in both the preliminary data collection and post-processing.

6. Conclusions

This study examined the risk response strategy of the industry chain of the industrialized construction in Shandong Province and identified 21 risk factors through questionnaires and the current development of Shandong Province. They were also classified according to organization. Then, binary directed data were obtained by collecting data, organizing and summarizing, opinion feedback, collecting again, organizing, and summarizing again. Then, a risk network visualization model was built with risks as nodes and risk relationships as edges. Finally, the index analysis of the network leads to the conclusion that the critical factor currently affecting the industrial chain of industrialization construction in Shandong Province is the level of collaboration of enterprises, and the industrialization system is the most significant abnormal risk transmission. The feasibility and superiority of the method in developing risk response strategies are verified. The improved complex network model proposed in this study is suitable for assessing risk interaction and response in the industrialized construction industry chain to generate better risk management solutions and enrich the research theory of the industrialized construction industry chain. Furthermore, the interaction of risk factors is fully considered in this study. On this basis, the comprehensive degree index is introduced to improve the resolution of the network model.

Two limitations of this study create opportunities for future research. First, the majority of the subjects in this study were negative risks. In future studies, interactions with positive risks (i.e., opportunities) should be considered in an integrated manner. Second, although the classical empirical-based risk identification approach is more subjective, it is more practical. Ideally, the snowball method should be considered to achieve data collection and improve the accuracy of risk interaction assessment.

The directions for further research in this area of study are as follows. First, in the future, an analytical framework for the effective response to the industry chain of industrialized construction risks should be developed to optimize decision making within resource constraints. Second, in the future, we should set thresholds in the risk network in conjunction with indicators such as the risk management capability of the project management team, resource availability, etc., to provide early warning of high-risk factors. Finally, the approach in this paper is theoretical and lacks examples of application and validation. More case applications of this model should be conducted in the future to evaluate its effectiveness, and it would be useful to understand how the obtained results can be applied to the industry chain of the industrialized construction industry chain optimization models.

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Conflicts of Interest: The authors declare no conflict of interest.

Abbreviations

CNICRA	Complex Network of Industrialized Construction Risk Associations
BIM	Building Information Modeling
IBS	Industrialized Building Systems
TCs	Transaction Costs
RFID	Radio Frequency Identification System

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