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Understanding Safety Performance of Prefabricated Construction Based on Complex Network Theory

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Abstract: With the rapid expansion of prefabricated construction in China, significant changes in safety performance are still unapparent for numerous prefabricated constructions, and safety accidents are constantly exposed in public. The ignorance of interactions among safety risks impedes efficacious improvement, which instructs the need for a thorough analysis of these interactions based on complex network theory. This paper starts with the identification of 37 safety risks refined through literature review and expert interviews, and 90 interrelationships among them verified by virtue of the questionnaire survey, laying a foundation for the establishment of a prefabricated construction safety risk network (PCSRN). The topological analysis results prove that PCSRN is a scale-free as well as a small-world network, which indicates the high-efficiency propagation and diffusion among safety risks in prefabricated constructions. Moreover, eight critical nodes are identified with four different ranking criteria, and corresponding safety strategies are proposed to address them. The developed method not only provides a novel insight to interpret the safety risks of prefabricated construction but also has the potential to advance safety performance of this sector.

Keywords: safety risks; prefabricated construction; complex network theory; interactions

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1. Introduction

As one of the worst global pandemics in human history, the coronavirus disease 2019 (COVID-19) has infected at least 465 million people and caused more than 6.06 million deaths, which continues to exact a heavy toll across the world and ravages the world economy in the context of new virus variants. With the elevated COVID-19 caseloads overwhelming the admission capacity of designated infectious diseases hospitals, the construction of emergency hospitals is supposed to be a practical and essential move to control the pandemic, which was verified in Wuhan, the epicenter of the COVID-19 outbreak and main battlefield in China. The two specialty field hospitals of Huoshenshan and Leishenshan were built from the ground up within 9 and 12 days, respectively [1]. Such remarkable construction speed of the two hospitals was profited by employing prefabrication technology which avoids time-consuming in situ construction work. The United States and other western countries also adopted this technology to quickly install ICUs and build various temporary building shells as isolation spaces for epidemic prevention and control, injecting flexibility into the traditional medical environment [2].

Prefabrication is an industrialized built process that involves a certain amount of building components manufactured in specialized facilities, transported to construction sites, and assembled at designated locations [3]. More than shortening construction duration [4], prefabricated construction is highly praised and increasingly advocated for its inherent benefits of reducing lifecycle cost [5], increasing production efficiency [6], and enhancing environmental performance [7]. Under the promotion of national policies, the scale of China's prefabricated construction market has gradually expanded, and a total of

630 million square meters of prefabricated buildings were built in 2020 in China, accounting for 20.5% of the newly constructed building area. However, along with the increasing proportion of prefabricated buildings in China, the improvement in safety performance is limited. There is an unapparent indication supporting a decline in accident incidence rate, which is illustrated in Figure 1. Meanwhile, similar evidence could also be found in the USA, where the Bureau of Labor Statistics reported that workers in prefabricated building projects are exposed to higher rates of injuries and accidents (10.2 per 100 workers) than the rates (5.2 per 100 workers) in the traditional cast-in-place construction projects [8]. Not only are these results contrary to the conception that prefabricated construction is comparatively safe to some extent, but they also raise doubts about the general perception of safety concerning prefabricated building projects.

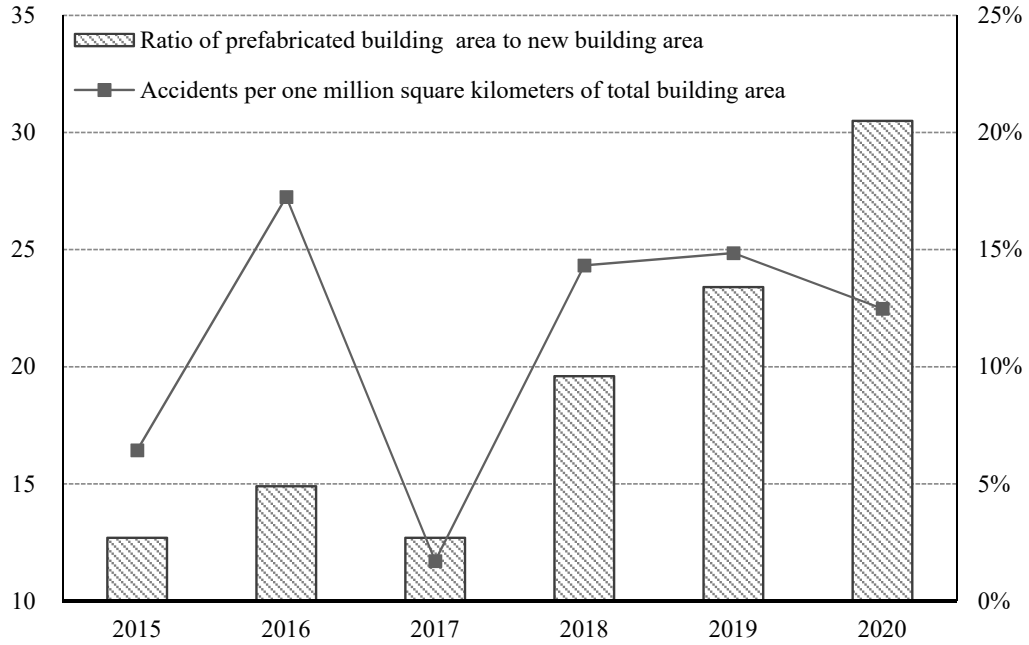

Figure 1. Prefabricated construction safety performance chart.

Compared with the conventional construction method, prefabricated building projects would be up against manifold safety risks and considerable uncertainties on account of their unique and innovative processes [9]. Not only this, the safety risks in prefabricated building projects are superficially fragmented, but substantially interdependent [10]. One safety risk could be the incentive for another safety risk, resulting in several safety risks concurrently emerging in one accident [11]. These interactions among safety risks form the prefabricated construction safety risk network (PCSRN) which impedes conspicuous improvement in the safety performance of prefabricated building projects. In the content of the accelerative promoting prefabricated construction [3], capturing the intrinsic characteristics of PCSRN and understanding the interdependencies among the safety risks are of paramount importance.

Against these backgrounds, this paper accomplishes a comprehensive analysis in order to acquire adverse risks compromising the safety of prefabricated constructions and investigate underlying interactions among them for suggesting preventive strategies to improve their safety performance. This work is set about after systematically identifying safety risks of the prefabricated construction and scientifically extracting interactions among them. Afterward, all safety risks and their interactions are aggregated together in a network, and then PCSRN comes into being. Ultimately, complex network theory (CNT) is exploited to give an insight into the patterns of interactions by examining the topological characteristics of PCSRN. The remainder of this paper is organized as follows: Section 2 briefly reviews the study on risks of prefabricated construction, the analysis approach for safety risks of prefabricated construction, and complex network theory and application.

Section 3 presents the methodology framework, which introduces the formation process of PCSRN and the content of network analysis. Section 4 utilizes complex network theory to capture the characteristics and vital nodes of PCSRN. Section 5 carries out a detailed discussion of the result from Section 4. Section 6 summarizes the conclusions.

2. Literature Review

2.1. Risks of Prefabricated Construction

The industrial production mode of the prefabricated building has exerted a profound influence over the deep-rooted traditional building industry. As an emerging architectural paradigm, there is a growing consensus that prefabrication would hatch manifold detrimental uncertainties and risks for its unique characteristic [12]. With the purpose of improving the performance of prefabricated building projects, plenty of research into risk analysis about prefabricated construction has been carried out during the last decades. In virtue of expert interviews, Luo et al. [11] obtained 24 types of risks that hinder the promotion process of prefabricated buildings in China and examined the level of the importance of these risks. Similarly, Jiang et al. [13] conducted a study on the constraints of prefabricated development, in which 23 influencing factors that reduced stakeholders' enthusiasm for prefabricated construction were accessed based on semi-structured interviews. Zhang et al. [14] deciphered risks that hinder the adoption of prefabrication and propounded suggestions for prefabrication implementation in Hong Kong. More than the general risks, multiples studies shed lights on the specific risks by virtue of manifold methods. As an effective method for analyzing the cause and effect relationships among components of a system [15], the decision-making trial and evaluation laboratory (DEMATEL) model was employed by Ji et al. to evaluate the impact of different delay risk factors with a combination of the analytic network process (ANP) method [16]. Concerning the dynamic changes of risks, Li et al. [17] established a simulation model of assembly construction schedule based on system dynamics to explore the sensitive factors leading to schedule delay. Furthermore, Li et al. [18] developed a hybrid model which integrated system dynamics with discrete event simulation to analyze the interrelationships of schedule risks, enabling managers to gain a deeper insight into schedule management of prefabricated construction. In terms of investment risks, Aminbakhsh et al. [19] utilized the analytic hierarchy process (AHP), a comprehensive multi-criteria analysis method [20], to assess the prioritization of investment risks in prefabricated constructions. Lee and Kim [21] introduced a failure mode and effects analysis (FMEA) method approach to deduce the key factors that increase construction costs at each stage of a modular project in Korea. Xue et al. [10] believed that collaborative management of stakeholders had a positive impact on controlling the investment risk of prefabricated buildings and explored the evolution process of collaboration among stakeholders to improve the cost performance. Additionally, other risk studies are concerned with the issues related to the supply chain. Wang et al. [22] conceived a disturbance evaluation model using simulation-based methods to access the risk of precast supply chain. Introducing the social network analysis (SNA) derived from structural approaches in sociology to the socio-technical system [23], Luo et al. [24] constructed the supply chain risk network to understand the supply chain risks and risk interactions embedded across the prefabricated building projects in Hong Kong. Hsu et al. [25] put forth a mathematical model for the design and optimization of modular construction supply chains to achieve a risk-averse logistics system.

2.2. Analysis Approach for Safety Risks of Prefabricated Construction

Relatively speaking, there is no extensive literature that addresses safety risks related to the prefabricated construction. Fard et al. [26] analyzed the types of safety risks involved in the construction of modular prefabricated buildings by screening 125 construction-related accidents from the database; the statistical result indicated that the majority of accidents occurred during installation processes. Jeong et al. [27] extracted the safety risk factors of modular construction from the collected accident cases, and intuitively presented

the causal logic of the accident through the formulation of the causal map. Liu et al. [28] put forward a cloud model-based approach to study the key factors and evaluate the safety of prefabricated construction. Goh et al. [29] assessed the safety challenges endured during on-site assembly and established a simulation tool suitable for discerning hazards beforehand for crane lift planning. By means of comparing the worker safety risk lists confirmed by site supervisors for both on-site and off-site construction scenes, Ahn [30] offered an evidence-based verification for such belief that off-site construction has lower safety risks than on-site construction. Chang [31] screened 23 safety risk factors involved in six categories of personnel, machine, material, environment, technology and management, and constructed a dual-objective optimization model aimed at minimizing system safety loss and controlling cost.

In numerous previous studies, emphasis was primarily placed on the identification and estimation of safety risks in prefabricated building projects. However, such studies remained narrow in their focus on mulling over the interactions among the safety risks and exploring the influencing mechanisms in prefabricated constructions.

2.3. Complex Network Theory and Application

Complex network can be applied to effectively dissect the coupled relationship that exists among safety risks from the topological feature perspective. By abstracting the highly interconnected elements in reality into the nodes and the interactions between the elements into the edges, a network graph which can offer a novel and visual anatomization for the structural characteristics of complex system is formed [32]. Zhou et al. [33] studied the topological characteristics of the directed weighted causation network to reveal the critical factors and key event chains in rail accidents. Li et al. [32] presented a network-based analysis of the inherent characteristics derived from risk transmission in the subway operation system. Eteifa et al. [34] introduced a network-based method in which the fatal accident root causes of construction fatalities and the interactions among them are exposed. Xu et al. [35] constructed a complex network to analyze the contagion relationship among different financial risk factors. Qiu et al. [36] creatively combined data mining and complex network model to build a coal mine accident causation network based on association rules among accident-causing factors, clarifying the coal mine accident-causing mechanism. Zhou et al. [37] proposed a power system analysis framework to explore the structure and robustness of power systems from the perspective of complex networks.

With the assistance of network theory, the inherent features of complex system come to the surface. Applying complex network theory to explore the topological features of PCSRN, it would be far easier to capture the critical safety risks that deserve more attention and reveal the patterns of risk interactions, thus the safety performance of prefabricated constructions can be significantly elevated by taking precautionary measures and formulating corresponding strategies.

3. Methodology

A research framework including three phases is proposed for understanding the safety performance of prefabricated construction, as displayed in Figure 2. The research framework starts with the first phase in which safety risks of prefabricated construction and risk interactions are collected by literature review, expert interview, and questionnaire survey. Integrating the safety risks and risk interactions into the adjacency matrix, and importing it into the visualization software, the next phase would be shaping prefabricated construction safety risk network. In the final phase, the overall characteristics of prefabricated construction safety risk network are explored and the critical risks are discovered.

3.1. Data Collection

3.1.1. Identification of Safety Risks of Prefabricated Construction

Due to the distinction in construction technology, the safety risks of prefabricated constructions are unlike those of general constructions. Hence, the whole life cycle of the

prefabricated building project is divided into four stages: design, off-site manufacture, transportation, and on-site assembly. On this basis, a comprehensive literature review was carried out to screen special safety risks of prefabricated construction. The literature search was not limited to the field of safety risks of prefabricated construction. Still, it was screened in the context of schedule risks, cost risks of prefabricated construction, and even general construction and engineering risks. Following sorting of the previous eligible research results, the risk factors were categorized into different stages, and meanwhile, a preliminary safety risk list was formed.

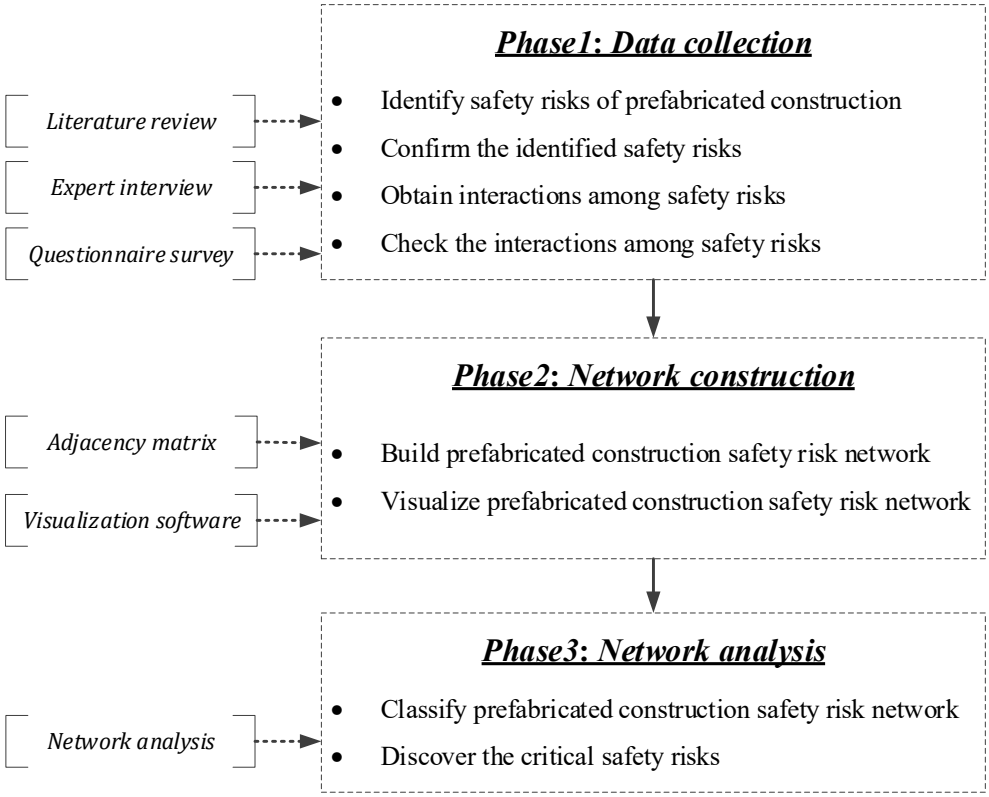

Figure 2. Research framework.

In addition, to be in accord with the actual situation of the prefabricated building industry in China, ten professionals in this field were invited to conduct semi-structural interviews to modify and adjust the initial safety risk list. The interviewed team members included one civil supervision engineer, two assistant designers, two project managers, and five project safety consultants. Each interviewee had a minimum of five years of working experience in prefabricated construction and three years in safety management. Prior to the discussion, respondents were informed of the detailed definition of each safety risk. The interview mainly focused on two aspects: (1) retain/eliminate the safety risk identified in the literature review and justify them; (2) supplement other prefabricated construction safety risks not included in the preliminary risk list, if necessary. The safety risk list was further verified and expanded leveraging expert knowledge, the risks identified from the literature were deleted or modified, two new risks were added (R16, R24), and the original 36 risks were revised as 37 risks with new risk ID. Ultimately, a comprehensive list of safety risks for a typical prefabricated building project was obtained, as provided in Table 1. The list ascertains 4 safety risks in the design stage, accounting for 10.81%; 19 safety risks in the stage of the off-site manufacture, accounting for 51.35%; 7 safety risks in the transportation phase, accounting for 18.92%; and 33 safety risks of on-site assembly, accounting for 89.16%, some of which participate in multiple stages.

Table 1. The list of prefabricated construction safety risks.

Risk ID	Risk Name	Subordinate Stage				Source
		Design	Manufacturing	Transportation	Assembly	
R1	Lack of safety considerations in design	•				[38–41]
R2	Error in design	•				[34,42–44]
R3	Design variations	•				[9,34,42,45]
R4	Shortage of skilled on-site/off-site workers		•		•	[27,42,45,46]
R5	Weak safety awareness of workers		•		•	[27,46,47]
R6	Human mistake		•	•	•	[26,47,48]
R7	Absence of safety instructions on site assembly				•	[27,49,50]
R8	Inappropriate use of personal protective equipment (PPE)		•		•	[28,51,52]
R9	Illegal operation		•		•	[31,34]
R10	Misjudgment of dangerous situations		•	•	•	[34,53]
R11	Workers' physical and mental state		•	•	•	[34,54]
R12	Damaged/defective equipment		•		•	[26,27]
R13	No personal protective equipment (PPE)		•		•	[27,34]
R14	Unqualified safety protection system				•	[27,28,34]
R15	Damaged prefabricated components				•	[9,27,55,56]
R16	Quality defects of prefabricated components		•			[28,56]
R17	Unstable structure				•	[27,34]
R18	Insufficient connection strength of prefabricated components				•	[44,48,57–61]
R19	No/unscheduled equipment maintenance		•		•	[28,31,47]
R20	Unsecured equipment/tool/object			•	•	[27,47,62]
R21	Poor organizational communication		•		•	[11,44,59,60]
R22	Inadequate safety education and training		•		•	[59,61,62]
R23	Adoption of safety practices similar to traditional construction		•		•	[63–65]
R24	Deficiency of integration among stakeholders	•	•	•	•	[11,45,61,66,67]
R25	Incomplete safety codes and standards		•		•	[11,26,61,68]
R26	Poor housekeeping		•		•	[27,40]
R27	Insufficient safety investment				•	[46,51,69]
R28	Scarcity of coordination of site activities				•	[31,34]
R29	Inadequate supervision		•		•	[28,31,70]
R30	Improper selection of lifting equipment				•	[21,29,31,71]
R31	Arbitrary storage/stacking of prefabricated components				•	[66,72]
R32	Working in an unfriendly environment				•	[27,73]

Table 1. *Cont.*

Risk ID	Risk Name	Subordinate Stage				Source
		Design	Manufacturing	Transportation	Assembly	
R33	Adverse weather condition			•	•	[26,47,74,75]
R34	Utilization of heavier and large prefabricated components			•	•	[27,76,77]
R35	High exposure to hazardous material		•		•	[31,78,79]
R36	Poor performance of the motion planning				•	[34,52,71]
R37	Thoughtless site construction scheme				•	[39,80]

3.1.2. Obtain the Relationships between Safety Risks

Upon confirming the safety risks affecting prefabricated building projects, a self-completion postal and online questionnaire-based survey was developed to quantitatively assess the interactions among the acquired risks, including the number of ties, for the network theory-based analysis of the next step. The questionnaire consists of four parts. The first part is the introduction; the second part aims to investigate the basic information of participants, including institution/company, working position, and related working experience; the third part seeks to judge the interaction among safety risks of prefabricated building projects, and acknowledgment is in the last part.

As the core of the questionnaire, the third part was designed in the form of risk structure matrix (RSM), which was expanded from design structure matrix (DSM) introduced by Steward [81]. DSM enables the relations and dependencies among workflow activities in the system to be represented and analyzed, while RSM facilitates identifying interactions among the risks associated with these activities [82]. RSM is a binary and square matrix, where the row position is regarded as the initiator of the relationship, and the column position as the receiver of the relationship. If R_i is believed to exert an influence on R_j, that is, the occurrence of R_i may lead to the occurrence of R_j (regardless of the probability), the number 1 is filled in the corresponding space; otherwise, 0 is filled. Figure 3 shows an example of the RSM representation of a risk network. With the exclusion of the strength of links, the questionnaire only requires respondents to judge and score possible relationships of risks in the matrix questionnaire box. Therefore, the measure applied in the research can alleviate the confusion and divergence in link establishment and evaluation, and effectively reduce the recognition work in the questionnaire, which contributes to improving the quality of the questionnaire recovery.

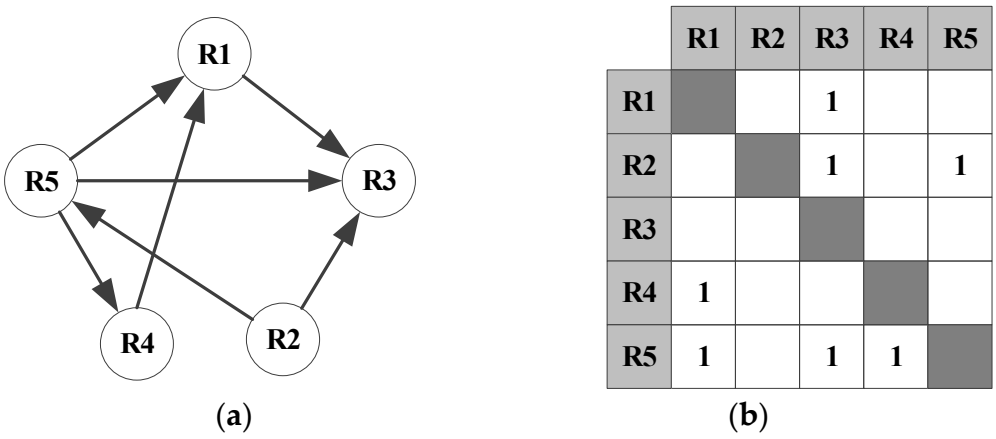

Figure 3. (**a**) Example of relationships among risks, (**b**) Example of RSM.

To cover as many different stakeholders to take part in the questionnaire survey as possible, this study adopted two sampling strategies comprising simple random sampling strategy and snowball sampling strategy. The snowball sampling strategy involves designating a specific participant among stakeholders, who then recommends and invites other stakeholder groups and representatives to participate in the questionnaire. Then the referral process is repeated until the survey covers all important and representative stakeholder groups. Easy-to-contact and cooperative representatives from China's leading prefabricated construction companies were selected to start the recommendation process. The invited representatives were then requested to investigate their colleagues in the company and appoint other stakeholder groups and representatives directly involved in the construction of the prefabricated building projects. Furthermore, simple random sampling was used as a supplement to the snowball sampling strategy to attract more professionals to participate in the survey.

A total of 154 online questionnaires were distributed, and 92 responses were received, with a recovery rate of 59.7%, of which 20 questionnaires were affirmed invalid due to incomplete filling or regular selection of influencing relationships, and 70 questionnaires were valid, with an effective rate of 76.1%. A response rate of 20% is generally considered satisfactory and 30% is good enough for the construction industry according to Black [83]. In this regard, the response rate of this study is deemed reasonable and satisfactory. The background information of the interviewees is shown in Table 2. Among them, the interviewees from the owner and the construction unit account for the largest proportion of 31.43% and 30%, respectively, those from the prefabrication plant account for 17.14%, design units account for 11.43%, and consultants account for a relatively small proportion of 1.43%. The interviewees are distributed among the main stakeholders of the prefabricated construction. Most of them have participated in the delivery of at least one prefabricated building project and have rich working experience, hence, lending further credence to questionnaire data.

Table 2. Background information of interviewees.

Basic Information		Account
Your workplace	Owner	31.43%
	Design unit	11.43%
	Material and equipment supplier	4.29%
	Prefabrication plant	17.14%
	Construction unit	30.00%
	Consulting unit	1.43%
	Other	4.29%
Years have you worked in prefabricated construction	Less than 5 years.	28.57%
	6–10 years.	51.43%
	11–15 years.	14.29%
	More than 15 years	5.71%
The number of prefabricated building projects you have involved	0	2.86%
	1	18.57%
	2	32.86%
	3	35.71%
	4 or more	10.00%

The answer results of the questionnaire were statistically analyzed through the frequency statistics method in Table 3. The corresponding figures in the boxes represent the frequency distribution of the questionnaire survey that the two safety risks are deemed to exert an influence on each other. At last, a total of 90 non-zero results were extracted, that is, 90 risk relationships were determined through the questionnaire survey.

Table 3. Statistics results of recovered questionnaire.

	R_1	R_2	R_3	R_4	R_5	R_6	R_7	R_8	R_9	R_{10}	R_{11}	R_{12}	R_{13}	R_{14}	R_{15}	R_{16}	R_{17}	R_{18}	R_{19}	R_{20}	R_{21}	R_{22}	R_{23}	R_{24}	R_{25}	R_{26}	R_{27}	R_{28}	R_{29}	R_{30}	R_{31}	R_{32}	R_{33}	R_{34}	R_{35}	R_{36}	R_{37}
R_1	0	0	18	0	0	0	0	0	0	0	0	0	0	0	0	13	0	16	0	17	0	0	0	0	0	0	0	0	27	0	0	0	0	0	13	0
R_2	0	0	14	0	0	0	0	0	0	0	0	0	0	0	0	9	0	11	0	12	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
R_3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	9	0	0	0	12	0	0	0	0	0	0	0	0	0	18	0	0	0	0	0	13	0
R_4	0	0	0	0	0	10	16	0	17	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	11	0	0	0	0	0	11	0
R_5	0	0	0	0	0	8	0	18	10	17	0	0	0	0	0	0	0	0	0	11	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
R_6	0	0	0	0	0	0	0	0	0	0	0	9	0	0	11	24	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
R_7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	19	0	5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
R_8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	10	0	0
R_9	0	0	0	0	0	0	0	0	0	0	0	14	0	0	10	8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	12	0	0	0	0	0	0
R_{10}	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	7	0	0	18	0	0	0
R_{11}	0	0	0	0	0	17	0	0	13	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
R_{12}	0	0	0	0	0	0	0	0	0	0	0	0	0	10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
R_{13}	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
R_{14}	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
R_{15}	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	13	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
R_{16}	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
R_{17}	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
R_{18}	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	25	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
R_{19}	0	0	0	0	0	0	0	0	0	0	0	12	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
R_{20}	0	0	0	0	0	0	0	0	0	0	0	0	0	0	15	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
R_{21}	0	0	30	0	0	0	18	0	0	0	0	0	0	0	0	0	0	0	11	0	0	0	0	0	0	23	0	11	0	0	9	0	0	0	0	0	20
R_{22}	9	0	0	12	10	26	0	0	13	9	0	0	0	0	0	0	0	0	0	14	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
R_{23}	0	0	0	0	0	0	0	0	0	0	0	0	8	13	0	0	0	0	0	0	26	10	0	0	0	0	0	0	9	0	0	0	0	0	0	0	0
R_{24}	0	13	24	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	8	0	16	0	0	0	0	0	0	0	0	0	0	0	0	0	0
R_{25}	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	21	0	10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
R_{26}	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	6	9	0	0	15	0	0
R_{27}	0	0	0	0	0	0	0	0	0	0	0	0	23	14	0	0	0	0	0	0	0	19	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
R_{28}	0	0	0	0	0	0	12	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	10	0	0	0	0	0	0	0	0	0	0	0
R_{29}	0	0	0	0	0	0	0	11	0	0	0	0	0	9	0	0	0	0	17	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
R_{30}	0	0	0	0	0	0	0	0	0	0	0	0	0	0	12	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
R_{31}	0	0	0	0	0	0	0	0	0	0	0	0	0	0	22	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
R_{32}	0	0	0	0	0	0	0	0	0	11	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	21	0	0
R_{33}	0	0	0	0	0	0	0	0	0	12	0	0	0	0	0	26	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
R_{34}	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	18	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
R_{35}	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
R_{36}	0	0	0	0	0	0	0	0	0	0	0	0	0	0	14	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
R_{37}	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	23	0	0	0	0	0	17	0

3.1.3. Consensus Analysis

Consensus analysis ensures the accuracy of survey identification results by detecting the consistency of multiple individuals in answering questions and providing correct answers to a series of questions. This paper applies the social network analysis software Ucinet for consistency analysis. The answer results of 90 risk relationships obtained from 70 questionnaires are sorted into a 70 × 90 question-by-answer response matrix. The eigenvectors of the response matrix are proved to represent the extent to which respondents' opinions are interpreted by a single pattern, corresponding to the existence of a single answer key [84]. The consensus analysis result obtained from Ucinet is presented in Table 4. The ratio of the first feature root to the second feature root is 8.821, greater than the threshold 3 [84], indicating that the answers of questionnaires achieve a consensus, which lays the solid and reliable foundation for the further analysis.

Table 4. Eigenvalues for question-by-answer response matrix.

Largest eigenvalue:	61.724
2nd largest eigenvalue:	6.997
Ratio of largest to next:	8.821

3.2. Network Construction

3.2.1. Build Prefabricated Construction Safety Risk Network

According to the interaction results of risks obtained from the questionnaire stage, the adjacency matrix (A) necessary for constructing the network is formed, as shown in Table 5. On the base of the adjacency matrix, prefabricated construction safety risks and interactions among them can be abstracted into a directed network model, including information of node set (V) and edge set (E), which is defined as G (V, E). In consequence, PCSRN will be an un-weighted directed network composing V node set of 37 nodes and E edge set of 90 edges.

3.2.2. Visualize Prefabricated Construction Safety Risk Network

A network visualized through the software can be distinctly displayed and dynamically tracked. Netminer version 4.0 is widely utilized due to its splendid competence in processing and exploring complicated nonlinear networks. Thus, Netminer is applied to visualize PCSRN and uncover the patterns of risk interactions in subsequent work. The network graph is mapped in Figure 4.

3.3. Network Analysis

Network analysis is the process of interrogating PCSRN algorithmically using tools derived from graph theory to entail understanding its inherent structural features and revealing its functional characteristic, which would be performed at different topological scales ranging from the overall global structural organization to individual nodes.

3.3.1. Network Classification

Different types of networks present disparate topological fingerprints which facilitate and constrain their dynamical behaviors. Detecting specific types of networks allows the discovery of the unifying principles and interpretation of different phenomena related to the system functionality. One extreme of the network is a network with a completely random graph and at the opposite end of the spectrum is a random ER graph. Different from these two kinds of networks, most networks in the real world are between completely regular and irregular, completely random and non-random. Small-world effect and scale-free effect are two ubiquitous phenomena observed in a variety of real networks. For the purpose of exploring these two kinds of networks, some basic metrics including the average path length L, the clustering coefficient C, and the degree distribution $p(k)$ are introduced in Table 6.

Table 5. Adjacency matrix of prefabricated construction safety risks.

	R_1	R_2	R_3	R_4	R_5	R_6	R_7	R_8	R_9	R_{10}	R_{11}	R_{12}	R_{13}	R_{14}	R_{15}	R_{16}	R_{17}	R_{18}	R_{19}	R_{20}	R_{21}	R_{22}	R_{23}	R_{24}	R_{25}	R_{26}	R_{27}	R_{28}	R_{29}	R_{30}	R_{31}	R_{32}	R_{33}	R_{34}	R_{35}	R_{36}	R_{37}
R_1	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	0	1	0	0	0	0	0	0	0	0	1	0	0	0	0	0	1	0
R_2	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
R_3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1	0	0	0	0	0	0	0	0	1	0	0	0	0	0	1	0
R_4	0	0	0	0	0	1	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	1	0
R_5	0	0	0	0	0	1	0	1	1	1	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
R_6	0	0	0	0	0	0	0	0	0	0	0	1	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
R_7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
R_8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0
R_9	0	0	0	0	0	0	0	0	0	0	0	1	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0
R_{10}	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	1	0	0
R_{11}	0	0	0	0	0	1	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
R_{12}	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
R_{13}	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
R_{14}	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
R_{15}	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
R_{16}	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
R_{17}	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
R_{18}	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
R_{19}	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
R_{20}	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
R_{21}	0	0	1	0	0	0	1	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	1	0	1	0	0	1	0	0	0	0	0	1
R_{22}	1	0	0	1	1	1	0	0	1	1	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
R_{23}	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	1	1	0	0	0	0	0	0	1	0	0	0	0	0	0	0
R_{24}	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
R_{25}	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
R_{26}	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	1	0	0
R_{27}	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
R_{28}	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0
R_{29}	0	0	0	0	0	0	0	1	0	0	0	0	0	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
R_{30}	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
R_{31}	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
R_{32}	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0
R_{33}	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
R_{34}	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
R_{35}	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
R_{36}	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
R_{37}	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	1	0

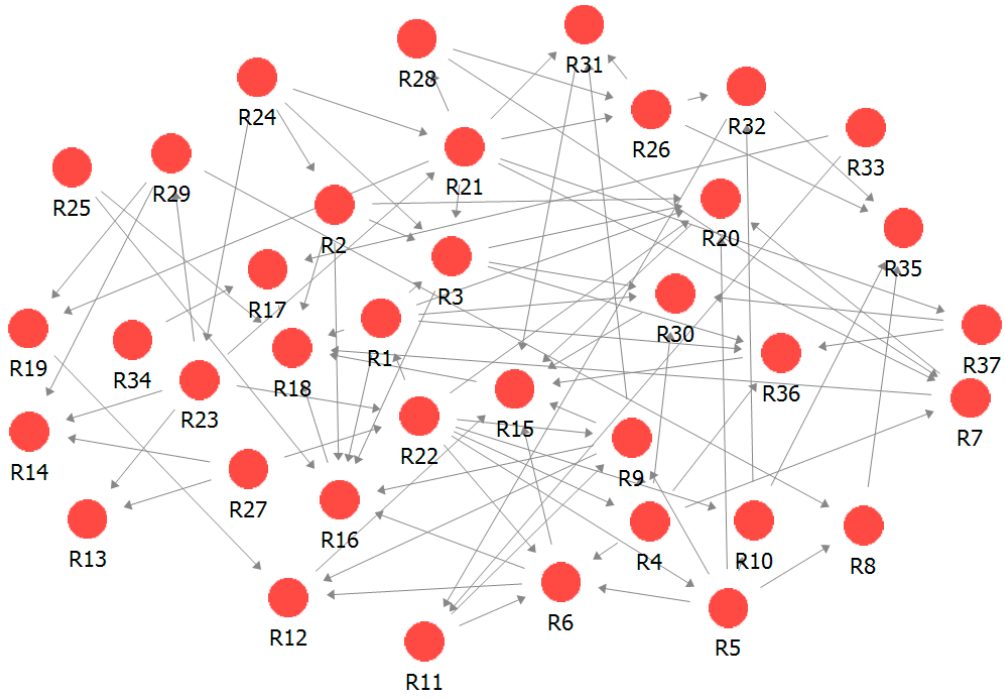

Figure 4. Prefabricated construction safety risk network (PCSRN).

Table 6. Basic metrics related to small-world or scale-free effect.

Basic Metrics	Equation	Definitions of Basic Metrics
Average path length	$L = \frac{1}{N(N-1)} \sum_{i,j \in V(i \neq j)} d_{ij}$	Average path length is defined as the average number of steps along the shortest paths for all possible pairs of network nodes.
Clustering coefficient	$C_i = \frac{M_i}{k_i(k_i-1)}$	The clustering coefficient of a node is the ratio of the number of actual edges there are among neighbors to the number of potential edges there are among neighbors.
Degree distribution	$p(k) = \frac{n_k}{n}$	The property of degree distribution $p(k)$ is the proportion of nodes with degree k in the network

(1) Small-world network

Comparatively speaking, small-world networks exhibit shorter average path lengths and higher clustering coefficients [85]. The small-world feature is closely related to network clustering, or rather, most nodes in the network are not directly connected, but can be reached from every other node by a small number of steps. An indirect measure of the small-world feature is the comparison between the observed network and random networks with equivalent scale.

(2) Scale-free network

A scale-free network is a network whose degree distribution follows or at least asymptotically follows power-law decay, with exponents γ falling between 2 and 3 [86]. Scale-free property indicates that the roles of different nodes in the structure and function of a network may be largely different [87]. More specifically, a scale-free network is inhomogeneous in nature where most nodes have limited link connections, while a few nodes have many connections.

3.3.2. Nodes Ranking

Intuition clearly indicates that not all nodes are equally important for their different roles in structure and function. For the purpose of quantifying the importance of nodes and identifying vital influential nodes, diverse ranking criteria have been coined from different perspectives including global information [88] (such as closeness centrality, betweenness centrality, and eigenvector centrality), local information [89] (such as degree, semi-local, and H-index), random walk [90] (such as PageRank, LeaderRank, and HITS), and position [91] (such as K-shell decomposition, MDD, and INK). Different ranking criteria provide insights into different dimensions of importance. Therefore, taking these four kinds of criteria into consideration, eigenvector centrality, degree difference, HITS, and K-shell decomposition are employed to rank nodes' importance and discover vital nodes in PCSRN.

(1) Eigenvector Centrality

Eigenvector centrality is a more sophisticated view of centrality which evaluates centrality or popularity score of a node while giving consideration to the importance of its neighbors. Nodes with a small number of influential contacts may have higher eigenvector centrality than nodes with a large quantity of mediocre contacts [92]. Mathematically, the eigenvector centrality of a node is the sum of the neighbors' eigenvector centralities divided by λ—the largest eigenvalue of the adjacency matrix of the network [93]. From the perspective of propagation, high eigenvector centrality is helpful for discerning critical nodes with long-term influence.

(2) Degree difference

The node degree refers to the number of direct connections of a node. Due to the different connection directions of nodes, the degree of nodes in a directed network can be divided into out-degree and in-degree. In some cases, special attention needs to be paid to the distinction between out-degree and in-degree. The concept of degree difference is proposed, which is calculated by subtracting the in-degree from the out-degree of a particular node, to express the net influence level of the node. A high degree difference implies that a node is more likely to influence other nodes in the network than to be affected.

(3) HITS

HITS algorithm is a classic web sorting algorithm. As nodes may play different roles in directed networks, it evaluates the influence of each node through mutual correction iteration of two aspects: authority and hub [94]. Hubs and authorities exhibit a reciprocally reinforcing relationship: a high-quality hub points to many authorities, and a high-quality authority is pointed at by many hubs [95]. In a directed network, the authority score of a node is calculated by adding the hub scores of all nodes pointing to the node, and the hub score of a node is summed by the authority scores of all nodes pointing to the node. A high authority score means that the node contains more useful information, and a higher hub score signifies that the node has a more prominent status in information transmission.

(4) K-shell decomposition

K-shell (also known as K-core) decomposition is a method of coarsely granulating the nodes' spreading influence according to their positions in the network [96]. The location of a node is defined by k-shell decomposition analysis. This process recursively strips the nodes in the network with degrees less than or equal to k and assigns each node an integer index or coreness, k_s, standing for its position according to successive layers (k shells) in the network. Apparently, a node with a larger coreness indicates that the node is located in a more central position and is possibly more influential in the network.

4. Result

4.1. Topology Analysis of PCSRN

By means of investigating whether PCSRN is a scale-free and a small-world network, inherent properties of PCSRN are demonstrated, which brings a novel insight into the nature of safety performance in prefabricated construction.

4.1.1. Scale-free Characteristic

Given the small scale of the established PCSRN, the degree of nodes takes on heavy tail distribution and the statistical characteristics are not obvious, so it is reasonable to measure the cumulative degree distribution function. Similar to degree distribution of scale-free network, the cumulative degree distribution satisfies the power-law distribution with exponent γ_{cum}, which can be written as $p(k) \propto k^{-\gamma_{cum}}$. The curve fitting of the cumulative distribution of node degree in PCSRN is depicted in Figure 5. From this double logarithmic chart, it is apparent that the curve decays according to a power-law distribution which has the approximate fit $p(k) \sim 1.969 * k^{-1.137}$ with γ_{cum} = 1.137 (R^2 = 0.67), and consequently the exponent of degree distribution $\gamma = \gamma_{cum} + 1$ would be 2.137, which takes a value between 2 and 3. Unquestionably, PCSRN is a scale-free network rather than a random one. Owing to the property of scale-free, PCSRN only contains a few safety risk nodes as hubs that bridge many connections with their neighbors, while simultaneously the majority of nodes have a small chance of linking to others. The coexistence of these two phenomena results in PCSRN presenting more robustness to random attacks and vulnerability to deliberate attacks. Therefore, targeted actions for hub nodes can generate disturbances in PCSRN and systematically cut down its connectivity which will eventually result in the mitigation of safety risks.

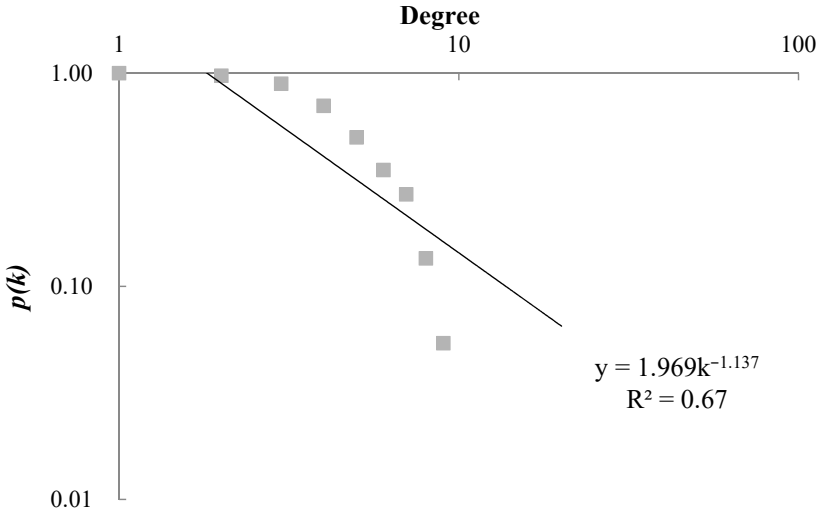

Figure 5. Cumulative degree distribution of PCSRN.

4.1.2. Small-world Characteristic

Small-world networks are often associated with the possession of lower average path length yet higher clustering coefficient. An indirect measure of small-world feature is the comparison between the observed network and random networks with equivalent scale. The average path length and clustering coefficient of 10 random networks with the same scale as PCSRN are generated and recorded. In the light of concrete comparison result in Table 7, it can be found that the average path length (2.142) of PCSRN is significantly lower than the average short length of random networks (2.256) and the clustering coefficient (0.105) is distinctly higher than the clustering coefficient of random networks (0.061). The result denotes that PCSRN is a small-world network. The exhibition of small-world effect of PCSRN means that the correlation among risks is quite close and the average shortest

path length between risks increases rather slowly as a function of the number of risks, which exhibits more accelerating propagation of safety risks in PCSRN.

Table 7. The average path length and clustering coefficient of 10 random networks.

The Random Network	No.									
	1	2	3	4	5	6	7	8	9	10
Clustering coefficient	2.033	2.127	2.266	2.349	2.233	2.212	2.195	2.321	2.349	2.478
Average path length	0.065	0.041	0.071	0.053	0.07	0.069	0.076	0.072	0.053	0.046

4.2. Vital Node Identification

Based on the conclusion elicited from topological analysis, PCSRN manifests the small-world and scale-free characteristics inherently, and only the key nodes can be controlled to disrupt the transmission cascade of safety risks in the network. With the four indicators introduced above, a node influence-based analysis was performed to distinguish the vital nodes worthy of special attention. Table 8 exhibits the top fifteen ranking in the eigenvector centrality, degree difference, HITS, and k-shell decomposition. Nodes ranked in the top three in each of these four indicator results are highlighted in bold. R22 (Inadequate safety education and training), R3 (Design variations), and R1 (Lack of safety considerations in design) score high on eigenvector centrality since they have positive ties with most central (popular) actors in the network. In terms of the metric of the degree difference, R21 (Poor organizational communication), R22 (Inadequate safety education and training), and R1 (Lack of safety considerations in design) are regarded as factors with a prominent net influence level. Three safety risks ranked in accordance with authority scores of HITS are confirmed to be R20 (Unsecured equipment/ tool/ object), R16 (Quality defects of prefabricated components), and R18 (Insufficient connection strength of prefabricated components). According to hub scores of HITS, R1 (Lack of safety considerations in design), R3 (Design variations), and R2 (Error in design) are the most efficient propagators controlling over the connectivity of network structures. With regard to k-shell decomposition indicator, there are 14 triangular nodes with a k-shell score of 4 as presented in Figure 6. The result is relatively coarse since the nodes with the same k-shell score cannot be compared horizontally. Therefore, k-shell decomposition method is applied as an auxiliary method to identify key nodes in this paper.

Table 8. Results of importance evaluation and ranking of safety risks.

Rank	Risk ID	Eigenvector Centrality	Risk ID	Degree Difference	Risk ID	HITS (Authority)	Risk ID	HITS (Hub)	Risk ID	k-Shell Decomposition
1	R22	0.288456	R21	5	R20	0.489881	R1	0.509800	R1	4
2	R3	0.276495	R22	5	R16	0.409649	R3	0.367013	R2	4
3	R1	0.276237	R1	5	R18	0.336063	R2	0.358002	R3	4
4	R20	0.273462	R4	4	R30	0.317234	R22	0.326439	R4	4
5	R15	0.269162	R5	4	R36	0.317234	R4	0.297322	R5	4
6	R9	0.263363	R23	4	R3	0.260739	R5	0.288680	R6	4
7	R16	0.252491	R24	4	R6	0.246528	R7	0.197609	R9	4
8	R6	0.241608	R2	3	R9	0.246528	R25	0.178414	R15	4
9	R4	0.218869	R27	3	R10	0.147169	R9	0.158832	R16	4
10	R18	0.207733	R29	2	R7	0.115187	R37	0.151798	R18	4
11	R5	0.200196	R25	2	R15	0.100211	R21	0.146025	R20	4
12	R2	0.187688	R33	2	R31	0.078133	R6	0.140138	R22	4
13	R30	0.187094	R26	1	R1	0.078102	R11	0.117965	R30	4
14	R36	0.187094	R28	1	R4	0.078102	R16	0.080404	R36	4
15	R21	0.183673	R37	1	R5	0.078102	R15	0.080404	R21	3

What is obvious from the outcomes is that the top three safety risks in each of the indicator analysis results are partially overlapped and consistent. In fact, almost all the top three nodes of eigenvector centrality, degree difference and HITS also own the maximum

K-shell value of 4, which characterizes them as the most influential nodes in PCSRN. Eight risks on aggregate are identified as the critical construction safety risks of prefabricated building projects, including R22 (Inadequate safety education and training), R21 (Poor organizational communication), R1 (Lack of safety considerations in design), R3 (Design variations), R2 (Error in design), R20 (Unsecured equipment/tool/object), R16 (Quality defects of prefabricated components), and R18 (Insufficient connection strength of prefabricated component). These vital nodes are highlighted as star nodes and moved to the upper level of the network diagram, as illustrated in Figure 7. Intuitively, critical safety risks originate from all stages of prefabricated construction. There are four safety risks in the assembly stage, followed by the design stage and manufacturing stage with three safety risks, respectively, and only one critical safety risk belongs to the transportation stage. These critical risks are worth high attention from the project team in view of their striking direct and/or propagating effects on many successors and/or predecessors.

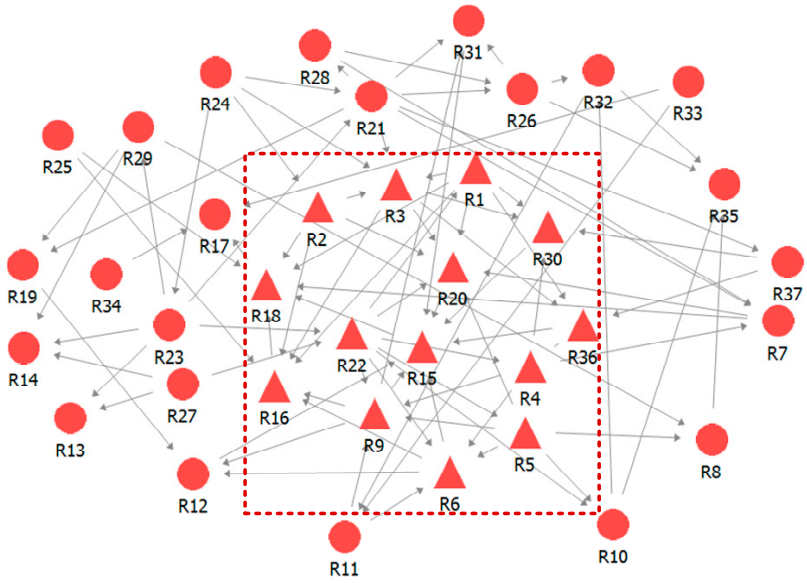

Figure 6. k-shell decomposition of nodes.

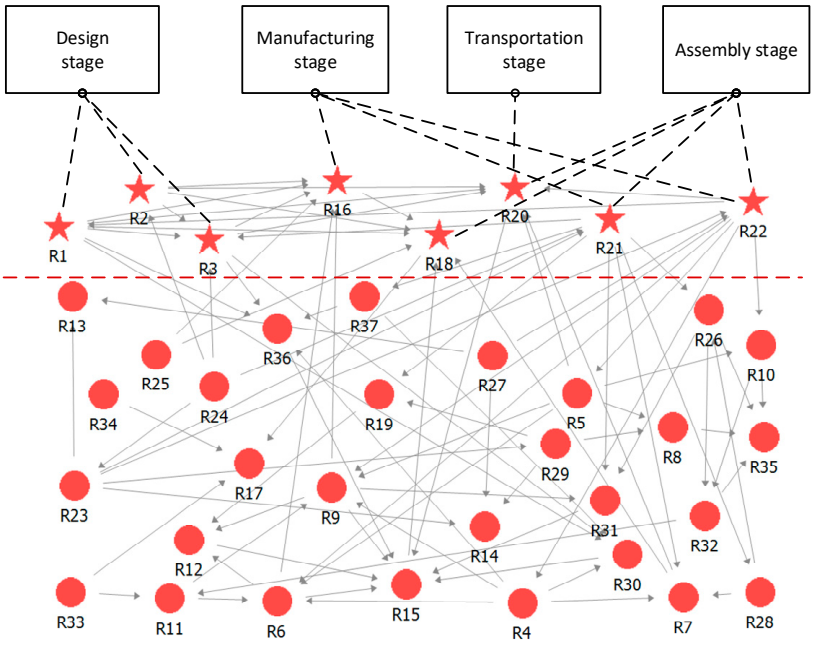

Figure 7. The identification of key nodes in PCSRN.

5. Discussion

5.1. Comparison of Safety Risks

Motivated by the observation that there is a restricted improvement of safety performance in prefabricated construction, this study applied complex network theory to unveil the underlying reason for the unsatisfactory condition and formulate corresponding strategies. Overall network topology analysis revealed the fact that PCSRN processes small-world and scale-free characteristics, which was also discovered in Subway construction safety risk network (SCSRN) [37] and Behavioral risk chain network of accidents (BRCNA) [54] in building construction. The presence of these two phenomena indicates that although safety risks of prefabricated construction are diverse from general construction safety risks, the nature of effortless transmission and efficient diffusion in safety risks are constant. Precisely because of the complex interactions among safety risks, the prediction and uplift of safety performance in prefabricated construction become arduous work.

In terms of key nodes identification, four criteria provide diverse ranking of nodes subject to their importance. In light of the hub of HITS and k-shell decomposition, safety risks at the design stage are more influential. While in the context of degree difference, the essentiality of critical management risks in the manufacturing and assembly phases is manifested. Considering the authority of HITS, the most significant material and equipment risks during manufacturing, transportation, and assembly are detected. Obviously, compared with the method of a single dimension indicator, the way adopted in this study covering different criteria results in a more comprehensive identification of critical safety risks.

Management safety risks involving R21 (Poor organizational communication) and R22 (Inadequate safety education and training) play prominent roles in PCSRN on account of their strong capacity for triggering and transmitting other risks. Such a result is consistent with the finding in BRCNA, where improper communication and coordination, as well as lack of safety education and training are regarded as two significant accident causes [54]. Poor organization communication, which is affected by a lack of interactive platforms for safety communication and lower involvement of different project stakeholders (e.g., architects, manufacturers, engineers, transports, and contractors) in cooperation, remains the foremost impediment to the safety practice within prefabricated construction. More often than not, the absence of organization communication leads to improper component size design, sketchy technical clarification, and construction process conflicts. Given that the implementation of prefabricated construction regularly necessitates bulky and heavy modular components fabricated in manufacturing plants, hoisting, moving, and installation of these oversized heavy loads would be constrained by space and technical restrictions. Nevertheless, the principal workforce for prefabricated construction is aging workers from rural areas who do not complete training for safety-related skills and knowledge [97]. It could be asserted that without proper safety education and training in safety management, workers would be exposed to numerous hazards unconsciously owing to incomprehensive understanding or misunderstanding of these restrictions.

As for R20 (Unsecured equipment/tool/object), R16 (Quality defects of prefabricated components), and R18 (Insufficient connection strength of prefabricated component), they all pertain to the material and equipment factors of the prefabricated construction process. Compared with the traditional cast-in-place concrete construction method, struck-by injuries caused by falling objects abound in prefabricated building projects owing to the unfixed prefabricated components, materials, and tools used or produced during the construction. Moreover, conditions in which the modular component itself was defective occurred oftentimes. This may be ascribed to inept welding or bonding during the component's manufacturing process, damage due to impact during transport to the on-site, or destruction to the component on account of distortions during crane lifting. It is well-accepted that the strength of component interfaces is vital to the security and durability of an entire prefabricated building project since the deterioration of component connection engenders defects in projects and poses accidental collapses of the structure.

What is more, the residual critical safety risks, R1 (lack of safety considerations in design), R2 (error in design), and R3 (design variations) are concerned with design issues, indicating attention on safety performance of prefabricated construction has been paid to the upfront design stage in the project whole life cycle. Generally speaking, prefabrication is deemed as an ideal scenario for application of the design for manufacture and assembly (DfMA) philosophy [9], which indubitably highlights the significance of design works in prefabricated building projects. Without sufficiently considering safety restraints and understanding safety requirements at the initial design phase, safety risks would transfer to downstream processes, resulting in safety accidents arising at off-site manufacturing and on-site assembly [98]. More specifically, lacking safety considerations in design, design errors, and design variations would extremely affect the quality and safety of manufacture, transportation, and assembly of prefabricated components, bringing about hazards such as quality defects of prefabricated components and inappropriate split of components. Studies of construction accidents and injuries suggest that even if sufficient safety equipment is placed at the construction site appropriately, the personal protective equipment itself cannot eliminate the risks and hidden dangers brought by the design [99]. It can be overcome when the designers are aware of this situation and fully consider the safety issues in the subsequent construction phase.

5.2. Implications for Practitioners

The transmission and interaction of safety risks in PCSRN make the prefabricated construction more threatening and challenging in terms of safety. For the sake of effective amelioration of prefabricated construction safety performance, managers ought to comprehensively uncover the critical safety risks at each construction phase and develop strategies specific to them.

On the one hand, to address management safety issues throughout the prefabricated construction process, setting up an interactive platform that promotes safety information exchange among participants is indispensable. Further, an innovative general contracting mode for prefabricated building projects is recommended to prompt all the project stakeholders to coordinate and collaborate prior to and during the construction [3]. At the same time, enhanced prefabricated construction safety performance can be obtained by continuously carrying out standardized and bespoke safety training programs for managers, designers, and front-line operators. Moreover, there is a prominent requirement to develop appropriate safety procedures and standards for strengthening dynamic inspection and management of materials, machinery, and construction quality. Proper modifications with considerations of design for safety (DFS) could have eliminated or alleviated the hazards and risks in the early phase [100]. For implementing the design for safety concept, design professionals ought to change the thinking method, take responsibility for safety, and participate in reinforcing site safety. Additionally, the government should also be on guard against problems related to the design of prefabricated constructions and issue more detailed and pertinent regulations. For example, *General Technical Conditions for Precast Part of Prefabricated Construction GB/T 40399-2021* issued by the Chinese government clearly stipulates the requirements for the structural design and connection design of prefabricated components.

On the other hand, the application of advanced digital technologies such as BIM (Building Information Modeling) is supposed to be an advisable means to improve the overall safety performance in prefabricated construction. More than offering new sights to aid safety risk identification through developing an automatic safety rule checking prototype during the design stage [101], BIM technology has a salient positive influence on reinforcing communication and facilitating coordination by storing, updating, and sharing construction information in one common data environment [102]. By integrating with VR technologies, BIM could also enable workers to envisage a virtual construction and achieve "immersive" technical clarification. Moreover, BIM can present a proactive optimization of the feasibility for the general layout of the construction site; identify the

collision point, conflict point, and other potential hazards in the layout scheme beforehand by integrating the use of GIS [103]. In addition to the advantages mentioned above, BIM multi-dimensional model allows repeated dynamic simulation of the hoisting and installation process of prefabricated components, reducing the damage of prefabricated components prompted by hoisting and installation errors [104]. In simpler terms, BIM technology could be utilized for the life cycle management of prefabricated constructions to mitigate risks, optimize safety decisions, and support project development.

6. Conclusions

This paper applies complex network theory to reveal the patterns of underlying interactions among safety risks in prefabricated construction and understand its safety performance. An analytical framework comprised of three parts is developed to build prefabricated construction safety risk network (PCSRN) and to dissect its inherent characteristic at different topological scales. The results confirm that PCSRN is both a small-world and a scale-free network where a small fraction of key nodes exert a global impact and play vital roles in the process of accident formation and development. After incorporating different ranking criteria, a more comprehensive list of critical safety risks is achieved and several corresponding strategies instrumental in retaining a high level of prefabricated construction safety are proposed.

The main original contributions of this study are twofold. The first one is the theoretical contribution. This paper provides a new perspective on prefabricated construction safety analysis by systematically exploring the correlation among safety risks rather than regarding safety risk factors as isolated elements. What is more, incorporating multiple relationships among safety risks into PCSRN is conducive to understanding the patterns of risk interactions, thereby broadening the quantitative application of complex network theory. The second one is practical contribution. Considering the capacity of diagnosing critical safety risks omitted in a single dimension criterion, the proposed method is supposed to be more scientific. It is feasible to extrapolate the method not only to other countries' prefabricated constructions but even to other types of constructions such as water conservancy and infrastructure. Simultaneously, the developed strategies specific to the pivotal safety risks will be instrumental in shaping the safety performance of this sector in the near future.

Despite these contributions, there are several limitations in the current work that deserve further study. Firstly, qualitative measurement of the interactions, i.e., the way of unweighted edges, is adopted in this paper. The potential interactions from unobserved safety risks as well as the quantification of correlation intensity among risks are not taken into consideration, which could exert influence on the topological property of PCSRN. Along with the accumulation of the dataset, the edge's weight based on frequency can be incorporated into the network of PCSRN for reinforcing the reliability of network construction. Secondly, the network is manually constructed on the basis of the edge relationships obtained from the questionnaire survey. In the future, data mining technology could be combined to automatically mine the association relationships among safety risks in accidents and map them into complex networks to achieve this goal.

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