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RISK ASSESSMENT OF COMPLEX ENGINEERING PROJECT BASED ON FUZZY PETRI NET UNDER THE PERSPECTIVE OF VULNERABILITY

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Abstract. Traditional engineering risk management has been unable to adapt to the complexity and variability due to its constituent elements and dynamic nature of internal and external environments. Vulnerability, as a concept closely related to risk, has been neglected in the traditional risk management due to its hidden characteristics. This study attempts to quantify and evaluate vulnerabilities of complex engineering projects independently and explore the transmission mechanism between risk and vulnerability factors. Twenty different types of large-scale engineering projects in China were selected as case studies from the Mega Project Case Study Center (MPCSC) of Tongji University. Vulnerability and risk factors of each project were identified and analysed. A mechanism model was developed to explore the impacts of vulnerabilities and risks through ta Fuzzy Petri Net. Four main vulnerability-risk critical paths were identified through the reverse labelling method. The overall evaluation of engineering project risks considering the impacts of vulnerabilities is the highlight of this paper. This study interprets the cognition and evaluation of complex engineering risks from a new perspective, enriches the connotation of engineering risk management, and provides a reference for risk management and decision-making of complex engineering projects.

Keyword: complex engineering project, risk assessment, vulnerability, fuzzy Petri net, project risk management.

Introduction

With rapid economic development, more and more megaprojects have emerged in China, such as Hong Kong-Zhuhai-Macao Bridge, Beijing Daxing Airport, Shanghai Tower, etc. Those complex and large-scale projects are usually playing an important role and having significant and far-reaching impacts on a country's economy, social stability, science and technology education, national defense, and environmental protection. Research on complex engineering has also become increasingly diversified (Ren, 2012). Contemporary complex engineering research urgently needs to re-recognize and understand the dynamic changes inside and outside the complex engineering project system and investigate the problems within complex engineering from multiple perspectives (Wu & Kairong, 2015).

A complex engineering project is a kind of complex system. In addition to its inherent characteristics such as uncertainty, predictability, evolution, and network correlation (Li et al., 2011), a complex project is restricted by rapid changes in the internal and external environment and affected by various non-systematic risks at different stages of development (Kermanshachi et al., 2016). There are many factors that affect the implementation of the complex project. The relationship between these factors is intricate and the dynamic nature of the system brings more uncertainties and risks to the project.

Previous studies on traditional engineering risk management have been focusing on the probability and severity of risks, while neglecting an important factor closely related to risk – vulnerability. As one of the basic characteristics of the complex system, vulnerabilities exists as inherent characteristics of the project, and it may cause potential loss of the project when the external disturbance occurs in different ways and degrees (Zhang, 2007). On the one hand, vulnerabilities make projects more likely to be exposed to harsh environments and hinders the ability of the project management team to respond to adverse external changes and prevents the spread of adverse cascad-

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ing effects. On the other hand, vulnerabilities are a type of attribute that is different from risks. It acts on the multi-dimensional goals of the project in different ways through different channels. Factors such as the defects of the project itself, market, policy, and stakeholders, etc., can have impacts on the probability of adverse events in the project. Some factors, such as management capabilities, project experience, human technology and financial resources, can affect the risk management and control of the project. The characteristics of the project itself, such as project scale, construction period, payment method, contract terms, and project management mode, are related to the severity of the risk after it occurs (Fidan et al., 2011). Vulnerabilities exist throughout the entire life cycle of complex engineering projects and closely relates to risks; however, it has always been neglected in contemporary project risk research due to its concealed characteristics. Vulnerability assessment and management could be introduced into the risk management to realize the cognition and evaluation of complex engineering risks from a new perspective.

This study is an extended work following the research on clarifying the connotation of fragility vulnerabilities of complex engineering projects published by the authors earlier (Qiao et al., 2020). Qiao et al. (2020) clarified the connotation of vulnerabilities of complex engineering projects from 50 key literature, and applied Wittgenstein's philosophy of family similarity and content analysis to show the connotation of the vulnerability of complex engineering projects by a sunflower model diagram. The authors found that four typical elements such as: project characteristics, sensitivity, adaptability and exposure can be generalized as the common elements for the vulnerabilities of complex engineering projects.

On the basis of the connotation of vulnerabilities in the previous research work, this study uses case study approach to identify the vulnerability and risk factors of 20 representative complex engineering cases selected from the Major Engineering Case Study and Data Center (MPCSC) of Tongji University. A fuzzy Petri net model is developed based on the mechanism of interactions between vulnerability and risk factors, to evaluate the reliability and anti-risk ability of specific projects. Vulnerability-risk transmission paths are identified by calculating relevant parameters and thus management issues in the practice of complex engineering projects are also identified. The model can help better understand on complex engineering from the dimension of vulnerabilities and provide a new perspective on the risk theory.

The significance of this research is embodied in the following two aspects:

(1) In theory, this study links vulnerabilities to risk management research on complex engineering projects. Vulnerability factors in the construction process of complex engineering projects are identified and extended to the traditional project risk analysis.

(2) In practice, this study identifies the key vulnerability factors and risk factors of typical complex engineering projects. The impact mechanisms between the vulnerabilities and risks of complex engineering projects are explored and the vulnerability-risk action paths are identified, which can ultimately provide practical implications in improving overall anti-risk capability of future complex engineering projects.

1. Vulnerabilities and risks

1.1. Vulnerability

The term of "vulnerability" was firstly proposed by Timmerman in 1981 (Timmerman, 1981). Since then, this concept has been widely used in disaster science, sociology, sustainability, and other areas. While the focus of research has been heterogeneous in in different fields, the definition and the connotation of vulnerabilities varies across subjects and can be roughly divided into the following categories.

As an intrinsic feature of the system, vulnerabilities will only be exposed when the system comes across external disturbances, however, the existence of it is not determined by the exposure to the disturbances. Smit and Wandel (2006) pointed out that a vulnerability is a characteristic of the system itself, and the existence of which will not be affected or transferred by whether the risk occurs or not, nor are they changed by the degree of external disturbance. Li believes that vulnerabilities are characteristics which can trigger changes on the system's function and structure, and is also a type of variability caused by insufficient system flexibility or tenacity (Li et al., 2008).

Vulnerability is similar to the two dimensions of traditional system risks: the probability and degree of the impact to a system. Some studies claim that vulnerabilities refer to the possibilities of a system being exposed to adverse effects or damages. For example, Gallopín (2006) showed that vulnerabilities is the possibilities of a system, or its subsystems exposed to external harsh environments. Turner et al. (2003) analyzed vulnerabilities from the perspective of impact degree and pointed out that it is a characterization of the damage level to the system. In the field of climate change, vulnerabilities are defined as the degrees of adverse effects caused by climate change. It is a function of adaptability and sensitivity, and depends on the joint effect of the speed, magnitude and variation characteristics of climate change (Field & Barros, 2014).

Vulnerabilities reflects a system's recover ability after being disturbed and plays a role as a mediating regulatory variable. Zhou et al. (2014) stated that if a system can return to its original state without any external assistance after being disturbed or damaged, then this kind of stable self-organization of the system is a form of vulnerabilities. Turner et al. (2003) pointed out that in social science, vulnerabilities can be used to characterize the comprehensive effect of external disturbance on people and people's own resilience and recovery ability.

Vulnerability is a relative concept and can only be shown in specific "vulnerable scenarios", and is related to contexts such as resilience, adaptability, and sensitivity. If using a fixed process to identify the possibility of system evolution, comparison will be involved from the perspective of getting better or worse. Usually, the "normal" status will be compared with, as it reflects the characteristics of relativity. The system only exhibits vulnerabilities under certain external conditions, while it exhibits stability under other environments (Lankao & Qin, 2011). However, vulnerabilities of the system are not enough to reflecting the response to all disturbances. If the system is not sensitive to some external disturbance, then the system is not vulnerable under this disturbance situation (Li & Zhang, 2011).

Vulnerabilities has been defined in different ways in different types of complex engineering projects. Huang et al. (2013), Deng et al. (2014), Qin (2016), Qiao et al. (2020) and Qiao (2020), etc., have all attempted to define and describe the vulnerabilities of complex engineering projects, however, there is no consistent and common terms for describing vulnerabilities, which could be used to guide the management and development of complex engineering projects activities.

1.2. Research on vulnerabilities and risks

Apostolakis and Lemon (2005) first applied the concept of vulnerability to the research on risk management of complex engineering projects. After that, scholars have tried to define the concept and connotation of vulnerabilities according to the characteristics of different types of engineering projects and built connections between vulnerability and risk theory. Theoretical research on project vulnerabilities is mainly divided into two categories, one is the "what" issue, which is related to the identification and analysis of the concept and factors of vulnerabilities. The other one is the "how much" issue, that is, sorting and quantifying vulnerabilities. This study is focusing the later one – the measurement and evaluation of vulnerabilities of engineering projects. It is an extended work on the basis of Qiao's et al. (2020) study which clarifies the connotation of vulnerabilities and identified four typical elements such as: project characteristics, sensitivity, adaptability and exposure of the vulnerabilities of complex engineering projects.

Zhang (2007) innovatively apply the concept of vulnerability in the event-consequence transmission chain in traditional risk management and proposed that vulnerability assessment can be carried out from the two dimensions: exposure and capacity. Following Zhang's study, Deng et al. (2014) divided the identified political vulnerability variables into a matrix based on the two dimensions and created a four-quadrant model to reflect the vulnerability profile of the international engineering project system. They suggested international construction companies to apply selective strategies to deal with international political risks based on the model and focus on actively controlling vulnerabilities with a greater impact. Fidan et al. (2011) expanded the concept of risk sources to link with the sources of vulnerabilities, pointed out that the sources of vulnerabilities could affect the transmission path of risk sources. They developed a model of the transmission path of risks under the role of vulnerability adjustment from the perspective of cost overrun, and the model was validated through a case study from Turkish contractors in international engineering projects.

Ozcan et al. (2011) proposed a risk path model which incorporated vulnerability-risk parameters and the relationships between the two. Their model assessed the magnitudes and threats of vulnerabilities by analyzing the impacts of changes in a specific vulnerability on the overall cost and duration of the project. Vidal and Marle (2012) considered project construction as a process of creating value. From the perspective of maintaining and increasing project value, he proposed a management process of vulnerabilities including identification, analyzing, responding, and controlling, in corresponding to risk analysis. Controlling and management methods were also proposed, such as vulnerability avoidance, mitigation, transfer, and retention. Johansson et al. (2013) looked at the interrelationship and impact of the location and function of highly technical infrastructure and pointed out that this interdependent characteristic should be considered in vulnerabilities. They developed a model to simulate a virtual electric railway network which was composed of five systems and provided valuable insights for the vulnerability analysis of interdependent systems. Guo et al. (2020) abstracted the project into a weighted directed network based on its topology and specific characteristics, and then adopted network metrics to assess project vulnerabilities and identified tasks and inter-task dependencies which were critical to project functionality. Correlation analysis was conducted to explore potential associations between the structural characteristics of the project and its vulnerabilities.

Additionally, given the wide application of digital services in the AEC industry, cybersecurity is becoming increasingly important to society. Some infrastructure incidents may occur significant economic and social impacts. Mantha proposed a Common Vulnerability Scoring System (CVSS) to determine the risk categories of different paths in building a network. The CVSS could help better understand and control its network vulnerability exposure and ultimately improve network security. Santolini et al. (2021) selected 14 different large-scale engineering projects to explore the network characteristics which affect the completion of projects and provided empirical evidence of dissemination events for large socio-technical engineering projects. They have demonstrated the link between the structure of the network and its underlying activity and overall project performance. Zhu et al. (2022) proposed a risk causation model for international construction projects (RCM_ICP), which links response measures to risk chains to identify and modify management failures, which could facilitate management level's thinking and gain relevant risk management lessons. Recently, Su and Khallaf

(2022) reviewed 54 related articles and found that there were four gaps in the research on risk assessment of engineering projects, one of which was lacking a method for accurate risk impact assessment.

In China, the vulnerability research of urban subway projects has been a hot topic in recent years. Yuan et al. (2012) decomposed the operational vulnerabilities of urban subway network into three categories: physical, structural and social functions, and analyzed the impact of different types of vulnerabilities on subway accidents through a case study. Xianguo et al. (2016) proposed a set of vulnerability analysis methods of subway network based on complex network theory, in order to deal with the serious impacts of node failures on the efficiency of subway operation. They used Pajek to construct the topology structure of subway network, and systematically analyzed the static and dynamic vulnerability levels of urban subway network under random and deliberate attacks. Wan (2016) analyzed vulnerabilities of subway station operation from the perspective of the relationships between customer behavior and accidents and the sensitivity of station operation to customer behavior. A causal diagram is constructed between abnormal behaviors and accidents to determine the variables and feedback structure of a System Dynamics model.

Based on the disaster chain and complex network theory, Li et al. (2021) developed an evolution model of the subway disaster chain complex network, evaluated the vulnerabilities of the key nodes and edges of the network, and proposed the key direction of risk control for subway disasters and contingency plan of disaster mitigation to pre-control the risks of subway operation. In addition, there have been increasing attention on vulnerability research of green buildings, major engineering projects and PPP projects. Qin (2016) defined and identified the vulnerability and risk factors of green building projects and used structural equation models to test the impact of the latent variables (collected by questionnaires) on the vulnerability-risk path. Xiang and Li (2016) identified the vulnerability factors of cross-regional major engineering projects through literature and case study analysis and developed a cross-regional model based on the complex network theory. A adjacency matrix of the vulnerability factors is used to simulate and analyze the vulnerabilities through network topology parameters such as node and edge betweenness. Ji et al. (2016) considered transportation PPP projects as a system composed of multiple dimensions, including functions, profitability, maintainability, and operability, etc. They used reliability theory to analyze the ability to self-regulate and recover of PPP projects against adverse events when exposed to adverse environments; Le et al. (2019) evaluated vulnerabilities of social systems in areas where major infrastructure projects are located from four aspects: social risk exposure, sensitivity, risk cognition, and coping ability. A vulnerability quantitative index evaluation system was constructed.

Xiang and Pang (2021) pointed out that a major engineering project is a complex system with both internal and external risks. Vulnerabilities represents the uncertainties existing in the project system, and threats represent the external risks of the system. Based on the system vulnerabilities and threats, an integrated risk measurement model for major engineering projects was developed. Cai and Wang (2021) reviewed research on vulnerability assessment methods in Natech risk management from the perspectives of relevance and uncertainty and found that most of the studies have used logistic regression, bow-tie diagrams, and Bayesian networks to explore the relationships between the influencing factors of vulnerabilities. To deal with uncertainty caused by missing data or human error, Monte Carlo simulation, Bayesian network, fuzzy theory, Rapid-N and other models have been used to increase the credibility of the assessment.

To sum up, research on vulnerabilities of engineering projects has been qualitative or quantitative. Though most of the studies have focused on evaluating the vulnerabilities of the project, there are limited research on incorporating vulnerabilities into risk management framework and assessing the overall project risks under the impacts of vulnerabilities. This paper is innovated from two aspects: first, the traditional Petri net cannot deal with the uncertainty and fuzziness of the evaluation index. Therefore, this paper combines the fuzzy theory with traditional Petri net to form a fuzzy Petri net system and defines the fuzzy inference rules of the fuzzy Petri nets to adapt to the characteristics of complex engineering projects. Second, in order to eliminate the subjectivity of expert experience and the limitation caused by the limited number of people, a randomly generated cloud model is used to process the expert evaluation results and simulate the approximate distribution of data in large sample cases.

2. Selection of leading cases of complex engineering project

Okudan et al. (2021) suggested that decision makers can retrieve similar projects in enterprise risk memory (e.g., databases, etc.) and use their related knowledge on risks as a starting point for current project risk management. Thus, this study identifies the vulnerability factors and risk factors of complex engineering projects based on case studies. The Mega Projects Case Study and Data Center (MPCSC) from the Complex Engineering Management Institute of Tongji University has established the most comprehensive database of complex engineering projects in China (Shi et al., 2018), it collects project reports and datasets across various types of complex projects and was the main data source for case analysis of this research.

In order to scope the "complex engineering" for this study, the case database was screened according to the following criteria: 1) Comprehensiveness: all candidate cases need cover multiple types of complex engineering projects; 2) Representativeness: it need to be representative within a specific type of complex project, mainly from the three aspects: investment amount, publicity and technical difficulty; 3) Completeness: the information of the selected cases need to be complete and sufficient to support the comprehensive and detailed analysis in this study. Based on the above three filtering criteria, twenty pilot projects were screened out for further in-depth case study analysis.

Case studies were conducted on the selected 20 leading cases. In addition to the relevant information in the database, news, reports, academic papers, and other median information of the 20 projects were searched on the web. The project number, name (type) and main issues were summarized (as seen in Table 1). The vulnerability and risk factors were identified, and the paths were described in Table 2. The entire process is shown in Table 2, where "*V*" represents the vulnerability factor, "*R*" represents the risk factor, and the fourth column shows the corresponding complexity and mechanism of risk factors identified in the project.

Table 3 summarizes the vulnerabilities "*V*" and risk factors "*R*" of the 20 projects. The interpretation and source of vulnerability factors could be found in Table 4.

Table 1. Selected 20 typical complex projects and major issues

No	Project Name	Type	Issues
1	North Water Transfer Project	Energy	– The project was proposed to solve the problem of uneven distribution of regional water resources and the shortage of electricity. – There was social controversy over the project. Large amount of relocation caused turbulence on residents' life and different attitudes of local governments along the route have led to disputes in the site selection of the project. – The ecological and geographical environment along the route is severe and water is severely polluted which increases the challenges in the construction. – Continuous changes in the scope and interface during the construction stage and conflicts of interest among multiple stakeholders. – No similar projects in China at that time so the contractors lacked experience in solving related problems, which led to an increase in additional workload, project delays, and cost overruns.
2	West-East Gas Pipeline	Energy	– This project aimed to solve the problem of uneven distribution of regional energy, to support the rapid development of the eastern region. – The long-term delay in resettlement affects the progress and brings negative social impacts. – Areas with rich gas resources were selected and connected as the project line. The pipeline traverses a variety of geographic, geomorphic, and cultural and economic units from west to east. The geological conditions along the line are complex and diverse. The environment and geological disasters seriously threaten the safety of the pipeline. – The construction environment was poor. – The air quality was degraded quickly due to soil erosion, forest and vegetation damage and dust by construction. – The supervision mode of Sino-foreign cooperation was adopted for the first time so the contractor has insufficient experience in similar projects. – The negotiation of the interests of all parties faced challenges. – Problems have arisen in terms of schedule payment, construction period, and cost.
3	Sichuan–East Gas Pipeline	Energy	– The Puguang Gas Field in Dazhou, Sichuan Province has abundant and high-quality natural gas reserves, which can be supplied to areas with short energy needs over long distances. – The local government had played a key role in the decision-making of the project. However, the relevant policies and regulations were not complete, which brought difficulties to the later implementation. – Limited access to resources, frequent corrosion in the pipeline and long construction period caused large-scale of rework. – Quality issues caused accidents. – Poor preliminary design considerations on the long pipeline laying distance, and serious soil and water loss during laying Drain phenomenon.
4	CCTV Headquarters Building	Skyscrapers	– The complexity of the project itself is very high. The design blindly pursued the appearance and less focused on the structural safety and fire resilience which brought serious hidden hazards. – Cheng Taining, an academician from the Chinese Academy of Engineering commented: "The CCTV headquarters building challenges the mechanics principle and the bottom line of fire safety for the needs of the structure". – The preliminary design was incomplete with low constructability. – There were major issues on the owner's preliminary requirements and contract terms. – Continuous changes in the project scoping during the construction process, and the participants negotiations were effective, which caused the tremendous additional workload and the project delay, and eventually led to serious investment overruns.

Continue of Table 1

No	Project Name	Type	Issues
5	Shanghai Center Building	Skyscrapers	– The project was located in a soft soil area. The significant rheological effect had a great impact on the surrounding environment and brought challenges to the survey and design. – Cross operation over a dozen professional units such as civil engineering, installation, curtain wall, and decoration under the design with low constructability brought great difficulty to the construction. – Mutual influences and constraints increased the difficulty in coordination work. – The construction site was small and restricted. The construction intensity was extremely high, with uneven investment on manpower and material resources. – The contract preparation was insufficient. – The vertical transportation of indoor construction for this super high-rise building greatly reduced the work efficiency.
6	Nanjing South Railway Station	Transportation Hub	– As the largest and leading interchange transportation hub in Asia at that time, Nanjing South Railway Station's integrated bus stations, high-speed rail stations, and subway stations and applied an innovative "small plot dense road network" model, and the project itself is extremely complex. – Ministry of Railways and Nanjing Municipal Government have communicated with experts; however, the pre-construction headquarters was not well managed and the original contract scope in the project contract was changed many times. The contractor's poor management ability caused repeated delays. – The 280-million-yuan rooftop photovoltaic project was left unused as a display, and the project was seriously overrun.
7	Wuhan Railway Station	Transportation Hub	– As an important transportation hub, it was highly affected by government. – The use of glass curtain wall structure for spatial separation at the entrance caused connection problem of the vibration structure of the curtain wall and the bridge track. – The structural design of the station building was complex. The truss is a spatial double-curved-double-arch structure, which was difficult to construct and delayed the construction period. – The "green station" concept proposed by the design had high requirements for energy conservation and environmental protection. – Insufficient experience led to project delays and overspending.
8	Hong Kong-Zhuhai-Macao Bridge	Bridge	– Greatly influenced by the governments of the three places. – Changeable ocean weather and strict height limit for offshore construction made the traditional erection of temporary tower crane unable to implement. – Difficulty in connection of bridge island tunnel project, low constructability of design due to the large scale and complexity of the project. – Difficulty in settlement of submarine immersed pipe and adverse impact on marine life and ecological and geographic condition due to construction blasting. – Injuries and deaths due to the sudden return of silt from the subsea foundation trench during the installation of the subsea tunnel. – Construction delays in the Hong Kong section caused overspending by more than 5 billion Hong Kong dollars.
9	Donghai Bridge	Bridge	– The first overseas bridge in China. At that time, there was no precedent for the design and construction of such long and large bridges in China. The completeness and constructability of the design were not high, which directly led to the lack of integrity of the contract and the change of the contract scope in the later period. – The bridge is located in the deep waters of Hangzhou Bay which is under strong corrosive environment, and the natural conditions are poor. – Due to regional factors, the availability of resources was also limited. – The project period was short with only two and half years It was completed to coincide with the commissioning of the first phase of the Xiaoyangshan Port Area. In addition, the contractor's lack of previous experience and management capabilities, resulted in a series of problems such as increased workload, delays, and overruns.
10	Wuhan-Guangzhou High Speed Rail	High-speed Rail	– Though the state vigorously supported the construction of high-speed rail to improve the transportation network and drive the economic development along the route; the project was highly subject to restrictions by the local governments along the route. – There was large engineering volume, complex engineering geology and high construction safety risks. – New technologies, new structures, new materials and new processes were used. Difficulty in construction increased due to high technical standards and low constructability in design. – Local governments misappropriated land requisition funds. There was serious budget overruns. – The owner's management capabilities were insufficient. Quality problems emerged during the construction. There were varying degrees of cavities, cracks, and missing blocks in the tunnel arches, no connection between embedded parts and steel bars, chaotic cable wiring, station buildings and platform canopies.

Continue of Table 1

No	Project Name	Type	Issues
11	Beijing-Shanghai high-speed rail	High-speed Rail	– Was one of the most difficult high-speed rail projects in China and was far more complex than similar projects by that time. – The owner's management team was inadequate. The requirements in contract were not clear and internal corruption occurred. – There was a problem of non-compliance in the tendering process during the construction, resulting in unclear contract terms. – Funding and financial management was unqualified, which caused misappropriated over 100 million yuan. There were multiple delays in progress payments and delays in project construction. – Corruption serious and project overruns occurred.
12	Three Gorges Project	Power station	– The project was proposed to promote the hydropower and meet the requirement of the national economic development strategy. – Resettlement was the biggest issue of the Three Gorges Project, residents have different attitudes to the project, and land acquisition and resettlement triggers a wide range of social issues. – The harsh ecological and geo-geological environment increased difficulty in construction and the construction also caused damage to the nature environment. – In terms of technology, various realistic conditions at that time cannot meet the technical requirements, and the project was very complex. – The scope of the project kept changing and the workload increased accordingly. In addition, the contractor had never undertaken a similar-scale project and lacked management capabilities, which caused almost 100 billion yuan overrun.
13	Gansu Jiuquan Wind Power Base	Power station	– The project aimed to solve the power supply issue in the western regions and promote the economy in the central and western regions. – The wind power base was located in the Hexi Corridor, a narrow area. the surface is dominated by Gobi and deserted beaches, and the construction environment is extremely difficult and dangerous. – The local residents' support for the construction of wind power bases was limited and the resolution of related relocation problems was hindered. – Due to the lack of practical experience in relevant large-scale wind power bases, conflicts have occurred many times during the implementation process and resulted in delayed payment of progress payments.
14	Beijing Daxing Airport	Airport	– In order to alleviate the huge pressure on the passenger flow of the original airport, and support Beijing's function as the national political and economic center. – the relocation issue of original residents was particularly prominent, and the support from residents on the project is very low. Delay in land acquisition and demolition work which caused the delay on the overall project progress. – Inaccurate investment calculations and great uncertainty in the construction process caused various risks. – The owner's requirements are not clear, and there were multiple and complicated issues on the preliminary design. Due to over competition during the design bidding period, unreasonable and underestimated contracting existed, which caused non-compliance of the contract in later stage and resulted in increased work, delays and overspending.
15	Kunming Changshui International Airport	Airport	– The Civil Aviation Administration of China proposed to build Kunming Changshui International Airport into a green airport demonstration project, which brought huge challenges to the preliminary design. – The residual red soil was easy to crack and deform, resulting in many unfinished matters in the preliminary survey and design. – Heavy fog due to the special geographical environment was frequent and the low-visibility weather increased the challenges in construction. – The early planning and design were improper, leading to major changes in the scope of the contract such as demolition and reconstruction in later stage. – The designer and the construction party had issues in communication, resulting in project delays and overruns on cost.
16	Ya Xi Expressway	Highway	– The Yaxi Expressway climbs from the edge of the Sichuan Basin to the highlands of the Hengduan Mountains, as the key road connecting Ya'an and Xichang. Because of the imperfect policies and regulations at the time, it was restricted highly by the government. – Crossing over the deep mountains and valleys with frequent geological disasters in the Southwest was realized through the highest technology in the world. – The terrain conditions were extremely steep, the geological structure was extremely complex, and the ecological environment was extremely fragile, which made the construction conditions extremely difficult. Mudslides and debris on the roads had caused several accidents, bringing damage and interruption on the project.

End of Table 1

No	Project Name	Type	Issues
17	Shanghai Yangshan Deepwater Port	Port engineering	– The deep-water shoreline and land area were created by reclaiming land from the sea thus involved huge amount of work. – During the demonstration of the scheme, many academicians have conducted demonstrations on the port construction scheme, but all unfinished due to the insufficient water depth of the channel. The research and demonstration was time-consuming and costly. – The unsatisfied matters in the early-stage lead to the unclear requirements in the process of signing the contract between the owner and the parties, which led to a series costing and schedule issues in later stage.
18	Shanghai World Expo	Large-scale event exhibition facilities	– The numerous organizational structures led to a certain degree of complexity in the project, the owner's lack of management capabilities, and the lack of clear requirements when signing the contract, led to unclear terms in the contract. – Imperfect construction procedures for some projects, and irregular bidding and contracting of engineering projects. – The contract scope has been changed many times, and communication between stakeholders was inconvenient and low efficient. – In the construction stage, the relevant management agencies have been abolished, merged, and changed many times, resulting in low management efficiency and fruitless multi-interest negotiation. – The project settlement method agreed in the individual project contract was not standard, which led to delays in payment. And some contracts are open contracts, causing serious project overruns.
19	China Expo Convention and Exhibition Complex	Large-scale event exhibition facilities	– It has the common problems as one of the convention and exhibition facility complex projects. The project volume was huge, and the building floor plan was large. It was composed of multiple single projects, and the units of each single project are different. – The design itself as not detailed enough when the contract was issued. The owner's requirements were not clear and there were too many project subcontractors which caused complicated cross working. The scope of contracting was frequently changed. Some contractors had insufficient business experience and wrangling conflicts happened. Unnecessary workload increased, resulting in project delays and cost overruns.
20	Qinghai-Tibet Railway	Railway Line	– It was proposed to improve the plateau area's long-term self-sufficient economy, however, the local governments along the route have different attitudes towards site construction. – The route crossed continuous permafrost regions, where the ecological and geographic geological environment was quite bad, and the construction site conditions were unfavorable. – Contractors had no experience in highly cold and oxygen-deficient construction environment has caused physical discomfort of builders during the construction process. After the reflection, the investment in the establishment of medical and health security points had increased a lot. – The expected extra workload: coupled with the contractor's lack of management capabilities, resulted in delays in the overall construction period and increased costs.

Table 2. Typical case analysis table

No	Project Name	Type	Factors and Path	
1	North Water Transfer Project	Energy	*V*:	$V_1, V_2, V_3, V_5, V_6, V_7, V_8, V_{10}, V_{11}, V_{12}, V_{14}, V_{15}, V_{16}, V_{17}, V_{18}, V_{19}, V_{20}$
			R:	$R_{21}, R_{22}, R_{24}, R_{26}, R_{27}, R_{28}, R_{29}, R_{30}$
			MP:	$(V_5 + V_6 + V_7) \to V_{10} \to V_{14} + (V_{15}) \to R_{21} + (V_{17}) \to R_{22} + (V_{18}) \to R_{27} + (V_{19}) \to R_{28} + (V_{20}) \to R_{30}$
2	West-East Gas Pipeline	Energy	*V*:	$V_1, V_2, V_3, V_5, V_6, V_{10}, V_{11}, V_{14}, V_{15}, V_{16}, V_{18}, V_{19}$
			R:	$R_{21}, R_{22}, R_{24}, R_{26}, R_{29}, R_{30}$
			MP:	$(V_5 + V_6) \to V_{10} \to V_{14} + (V_{15}) \to R_{21} \to R_{22} + (V_{18}) \to R_{26} \to R_{28} \to R_{30}$
3	Sichuan–East Gas Pipeline	Energy	*V*:	$V_3, V_4, V_5, V_6, V_9, V_{11}, V_{14}, V_{15}, V_{16}, V_{19}$
			R:	$R_{21}, R_{22}, R_{23}, R_{27}, R_{28}, R_{29}, R_{30}$
			MP:	$(V_7 + V_8) \to V_{11} \to R_{23} \to R_{29} \to R_{30}$
4	CCTV Headquarters Building	Skyscrapers	*V*:	$V_1, V_2, V_3, V_4, V_6, V_8, V_9, V_{12}, V_{13}, V_{16}, V_{17}, V_{18}, V_{19}, V_{20}$
			R:	$R_{22}, R_{23}, R_{25}, R_{26}, R_{27}, R_{28}, R_{30}$
			MP:	$(V_3 + V_4) \to V_9 \to V_{13} + (V_{12}) \to V_{17} \to R_{22} \to R_{25} + (R_{26}) \to R_{28} \to R_{30}$

End of Table 2

No	Project Name	Type		Factors and Path
5	Shanghai Center Building	Skyscrapers	*V*:	V_2, V_3, V_4, V_6, V_7, V_9, V_{10}, V_{12}, V_{13}, V_{15}, V_{17}, V_{18}, V_{20}
			R:	R_{21}, R_{22}, R_{25}, R_{26}, R_{28}, R_{30}
			MP:	$(V_3 + V_4) \to V_9 \to V_{13} \to V_{17} + (V_{12}) \to V_{20} + (R_{28}) \to R_{30}$
6	Nanjing South Railway Station	Transportation Hub	*V*:	V_1, V_2, V_3, V_6, V_7, V_8, V_{12}, V_{16}, V_{17}, V_{18}, V_{19}
			R:	R_{22}, R_{27}, R_{28}, R_{30}
			MP:	$(V_2 + V_3) \to V_{12} \to V_{17} \to R_{22} + (V_{18}) \to R_{27} + (V_{19}) \to R_{28} \to R_{30}$
7	Wuhan Railway Station	Transportation Hub	*V*:	V_1, V_3, V_4, V_6, V_7, V_8, V_9, V_{10}, V_{13}, V_{17}, V_{18}
			R:	R_{25}, R_{26}, R_{28}, R_{30}
			MP:	$(V_3 + V_4) \to V_9 \to V_{13} \to V_{17} \to R_{22} \to R_{25} + (R_{26}) \to R_{28} \to R_{30}$
8	Hong Kong-Zhuhai-Macao Bridge	Bridge	*V*:	V_3, V_5, V_6, V_7, V_{10}, V_{13}, V_{14}, V_{15}, V_{16}, V_{17}, V_{19},V_{20}
			R:	R_{21}, R_{22}, R_{27}, R_{28}, R_{29}, R_{30}
			MP:	$(V_5 + V_6 + V_7) \to V_{10} \to V_{14} + (V_{15}) \to R_{21} \to R_{22} \to R_{27} + (V_{19}) \to R_{28} \to R_{30}$
9	Donghai Bridge	Bridge	*V*:	V_3, V_4, V_9, V_{11}, V_{12}, V_{13}, V_{15}, V_{16}, V_{17}, V_{18}, V_{19}
			R:	R_{22}, R_{26}, R_{27}, R_{28}, R_{30}
			MP:	$(V_3 + V_4) \to V_9 \to V_{13} \to V_{17} \to R_{22} + (V_{18}) \to R_{26} \to R_{28} \to R_{30}$
10	Wuhan-Guangzhou High Speed Rail	High-speed Rail	*V*:	V_2, V_3, V_6, V_7, V_{10}, V_{11}, V_{13}, V_{14}, V_{15}, V_{18}, V_{19}
			R:	R_{21}, R_{22}, R_{23}, R_{25}, R_{28}, R_{30}
			MP:	$(V_6 + V_7) \to V_{10} \to V_{14} + (V_{15}) \to R_{21} \to R_{22} \to R_{25} \to R_{28} \to R_{30}$
11	Beijing-Shanghai high-speed rail	High-speed Rail	*V*:	V_2, V_3, V_7, V_8, V_{12}, V_{16}, V_{17}, V_{18}
			R:	R_{22}, R_{25}, R_{28}, R_{30}
			MP:	$(V_2 +V_3) \to V_{12} \to V_{17} \to R_{22} + (V_{18}) \to R_{27} \to R_{28} \to R_{30}$
12	Three Gorges Project	Power station	*V*:	V_1, V_2, V_3, V_4, V_5, V_6, V_7, V_8, V_{10}, V_{14}, V_{15}, V_{16}, V_{18}, V_{19}
			R:	R_{21}, R_{22}, R_{25}, R_{26}, R_{27}, R_{28}, R_{30}
			MP:	$(V_5 + V_6) \to V_{10} \to V_{15} + (V_{14}) \to R_{21} \to R_{22} + (V_{18}) \to R_{27} + (V_{19}) \to R_{28} \to R_{30}$
13	Gansu Jiuquan Wind Power Base	Power station	*V*:	V_1, V_3, V_5, V_6, V_{10}, V_{13}, V_{14}, V_{15}, V_{18}
			R:	R_{21}, R_{22}, R_{25}, R_{26}
			MP:	$(V_5 + V_6) \to V_{10} \to V_{14} + (V_{15}) \to R_{21} \to R_{22} + (V_{18}) \to R_{26} + (R_{25}) \to R_{28} \to R_{30}$
14	Beijing Daxing Airport	Airport	*V*:	V_1, V_2, V_3, V_4, V_5, V_6, V_7, V_8, V_9, V_{10}, V_{12}, V_{13}, V_{16}, V_{17}, V_{18}, V_{19}, V_{20}
			R:	R_{22}, R_{25}, R_{26}, R_{27}, R_{28}, R_{30}
			MP:	$(V_5 + V_6 + V_7) \to V_{10} \to V_{15} \to R_{21} + (V_{17}) \to R_{22} + (V_{18}) \to R_{27} + (V_{19}) \to R_{28} \to R_{30}$
15	Kunming Changshui International Airport	Airport	*V*:	V_3, V_4, V_7, V_9, V_{10}, V_{13}, V_{15}, V_{17}, V_{18}
			R:	R_{21}, R_{22}, R_{26}, R_{28}, R_{30}
			MP:	$(V_3 + V_4) \to V_9 \to V_{13} \to V_{17} + (R_{21}) \to R_{22} + (V_{18}) \to R_{26} \to R_{28} \to R_{30}$
16	Ya Xi Expressway	Highway	*V*:	V_1, V_3, V_4, V_6, V_7, V_8, V_{10}, V_{11}, V_{14}, V_{15}, V_{17}
			R:	R_{21}, R_{22}, R_{23}, R_{28}, R_{29}, R_{30}
			MP:	$(V_7 + V_8) \to V_{11} \to R_{23} \to R_{29} \to R_{30}$
17	Shanghai Yangshan Deepwater Port	Port engineering	*V*:	V_2, V_3, V_8, V_{10}, V_{12}, V_{16}, V_{17}, V_{18}, V_{19}, V_{20}
			R:	R_{21}, R_{22}, R_{25}, R_{26}, R_{28}, R_{30}
			MP:	$(V_2 + V_3) \to V_{12} + (V_{17}) \to V_{20} +(R_{28}) \to R_{30}$
18	Shanghai World Expo	Large-scale event exhibition facilities	*V*:	V_2, V_3, V_4, V_7, V_9, V_{12}, V_{13}, V_{16}, V_{17}, V_{19}, V_{20}
			R:	R_{22}, R_{24}, R_{25}, R_{26}, R_{27}, R_{28}, R_{30}
			MP:	$(V_2 + V_3) \to V_{12} + (V_{13}) \to V_{17} \to R_{22} \to R_{25} + (R_{26}) \to R_{28} + (V_{20}) \to R_{30}$
19	China Expo Convention and Exhibition Complex	Large-scale event exhibition facilities	*V*:	V_1, V_2, V_3, V_{12}, V_{13}, V_{16}, V_{17}, V_{18}, V_{20}
			R:	R_{22}, R_{25}, R_{26}, R_{27}, R_{28}, R_{30}
			MP:	$(V_2 + V_3) \to V_{12} + (V_{13}) \to V_{17} \to R_{22} + (V_{18}) \to R_{27} \to R_{28} + (V_{20}) \to R_{30}$
20	Qinghai-Tibet Railway	Railway Line	*V*:	V_1, V_3, V_6, V_7, V_8, V_{10}, V_{14}, V_{15}, V_{16}, V_{18}, V_{19}
			R:	R_{21}, R_{22}, R_{24}, R_{27}, R_{30}
			MP:	$(V_6 + V_7) \to V_{10} \to V_{14} + (V_{15}) \to R_{21} \to R_{22} + (V_{18}) \to R_{27} + (V_{19}) \to R_{28} \to R_{30}$

Table 3. Summary of vulnerability and risk factors

No	Description	No	Description	No	Description
V_1	Market Operation	V_{11}	Resource availability	R_{21}	Unfavorable site conditions
V_2	Capability of the project owner	V_{12}	Clarity of the owner's requirements	R_{22}	Change of project scope
V_3	Project Complexity	V_{13}	Constructability of design	R_{23}	Decreased project quality
V_4	Capability of survey and design team	V_{14}	Ecological environmental conditions	R_{24}	Increased price of materials
V_5	The public's attitude towards the project	V_{15}	Geographical conditions	R_{25}	Delayed payment
V_6	National macroeconomic conditions	V_{16}	The scale of the construction project	R_{26}	Conflicts of stakeholders
V_7	Attitude of local governments	V_{17}	Completeness of contract terms	R_{27}	Increased extra work
V_8	Policies and regulations	V_{18}	Contractors' experience	R_{28}	Project delays
V_9	Completeness of design	V_{19}	Contractors 'management capabilities	R_{29}	Safety incident
V_{10}	Site selection	V_{20}	Payment type of contract	R_{30}	Overrun of project cost

Table 4. The interpretation and source of vulnerability factors

No		Definition	Related cases and references
V_1	Market	The construction market and upstream and downstream industries will certain impacts on the project.	Cases: 1, 2, 4, 6, 7, 12, 13, 14, 16, 19, 20 References: Fidan et al. (2011), Ozcan et al. (2011), Abd El-Karim et al. (2017)
V_2	Ability of the project owner	From the perspective of project management, the owner's organizational and management ability is a key factor that affects the success of the project.	Cases: 1, 2, 4, 5, 6, 10, 11, 12, 14, 17, 18, 19 References: Ozcan et al. (2011), Abd El-Karim et al. (2017)
V_3	Project complexity	Including three elements: the complexity of project structure, the complexity of technical implementation and the complexity of organizational structure.	Cases: 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20 References: Fidan et al. (2011), Le et al. (2019), Yildiz et al. (2014)
V_4	Qualification of survey and design team	Most of the complex engineering projects are located in special geographical locations, so they are greatly affected by the preliminary survey and design.	Cases: 3, 4, 5, 7, 9, 12, 14, 15, 16, 18 References: Fidan et al. (2011), Ozcan et al. (2011)
V_5	The public's attitude towards the project	The public's attitude towards the project will affect the establishment of the project through different ways such as public hearings.	Cases: 1, 2, 3, 8, 12, 13, 14 References: Fidan et al. (2011), Ozcan et al. (2011), Le et al. (2019)
V_6	National macroeconomic conditions	Some projects are affected by the country's macroeconomic regulation and control at the time of their initiation, or at certain stage or certain regions.	Cases: 1, 2, 3, 4, 5, 6, 7, 8, 10, 12, 13, 14, 16, 20 References: Deng et al. (2014), Le et al. (2019), Yildiz et al. (2014)
V_7	Attitude of local governments	Regional landmark projects are affected by the support from the local government.	Cases: 1, 5, 6, 7, 8, 10, 11, 12, 14, 15, 16, 18, 20 References: Fidan et al. (2011), Ozcan et al. (2011), Yildiz et al. (2014)
V_8	Policies and regulations	National or local government policies and regulations has an regional impacts on complex projects.	Cases: 1, 4, 6, 7, 11, 12, 14, 16, 17, 20 References: Deng et al. (2014), Le et al. (2019), Yildiz et al. (2014)
V_9	Completeness of design	Completeness of the preliminary design of a complex project determines a series of contract issues during project construction.	Cases: 3, 4, 5, 7, 9, 14, 15, 18 References: Fidan et al. (2011), Ozcan et al. (2011), Yildiz et al. (2014)
V_{10}	Site selection	The site selection of the project affects regional resource and environmental conditions.	Cases: 1, 2, 5, 7, 8, 10, 12, 13, 14, 15, 16, 17, 20 References: Fidan et al. (2011), Ozcan et al. (2011), Le et al. (2019)
V_{11}	Resource availability	Refers to the availability and quality of regional human resources, materials, and machines.	Cases: 1, 2, 3, 9, 10, 16 References: Deng et al. (2014), Abd El-Karim et al. (2017), Yildiz et al. (2014)
V_{12}	Clarity of the owner's requirements	The degree of clarity on the owner's requirements in the contract is closely related to the follow-up schedule and other related issues.	Cases: 1, 4, 5, 6, 9, 11, 14, 17, 18, 19 References: Deng et al. (2014), Abd El-Karim et al. (2017), Yildiz et al. (2014)
V_{13}	Constructability of design	The constructability of the design directly affects the completion of the construction work.	Cases: 5, 7, 8, 9, 10, 12, 13, 14, 15, 18, 19 References: Deng et al. (2014), Abd El-Karim et al. (2017), Fidan et al. (2011)

End of Table 4

No		Definition	Related cases and references
V_{14}	Ecological environmental conditions	The ecological environment conditions of the project are one of the sources of risk events during the construction process.	Cases: 1, 2, 3, 8, 10, 12, 13, 16, 20 References: Deng et al. (2014), Fidan et al. (2011), Le et al. (2019)
V_{15}	Geographical conditions	It determines whether the environmental conditions are favorable or not together with the survey and design capabilities.	Cases: 1, 2, 3, 5, 8, 9, 10, 12, 13, 15, 16, 20 References: Fidan et al. (2011), Ozcan et al. (2011), Le et al. (2019)
V_{16}	The scale of the construction project	Refers to the relative construction scale of a specific type of project. The larger the scale, the greater the uncertainty of the project.	Cases: 1, 2, 3, 4, 6, 8, 9, 11, 12, 14, 17, 18, 19, 20 References: Deng et al. (2014), Fidan et al. (2011), Abd El-Karim et al. (2017)
V_{17}	Completeness of contract terms	Contract terms are one of the key factors affecting project quality, duration, cost, safety and other critical issues.	Cases: 1, 4, 5, 6, 7, 8, 9, 11, 14, 15, 16, 17, 18, 19 References: Ozcan et al. (2011), Abd El-Karim et al. (2017), Yildiz et al. (2014)
V_{18}	Contractors' experience	The previous similar project experience of the contractors affects the completion of the project objectives.	Cases: 1, 2, 4, 5, 6, 7, 9, 10, 11, 12, 13, 14, 15, 17, 19, 20 References: Abd El-Karim et al. (2017), Yildiz et al. (2014)
V_{19}	Contractors' management capabilities	The organization and management ability of the contractors affects the completion of project objectives.	Cases: 1, 2, 3, 4, 6, 8, 9, 10, 12, 14, 17, 18, 20 References: Abd El-Karim et al. (2017), Yildiz et al. (2014)
V_{20}	Payment type of contract	The contract payment type will affect the risk severity and consequences after a risk event occurs.	Cases: 1, 4, 5, 8, 14, 17, 18, 19 References: Ozcan et al. (2011), Abd El-Karim et al. (2017), Yildiz et al. (2014)

3. Basic principles of fuzzy Petri nets

Fault tree analysis (FTA) has been frequently used in analysis of risk occurrence mechanism and FTA has been used with event tree analysis (ETA) for probabilistic risk assessment (PRA) (Guo et al., 2016). However, these methods can only conduct static analysis of accident structure and rely on a large amount of basic failure rate data.

3.1. Definition and characteristic analysis of fuzzy Petri net

Petri net was first proposed by German scholar Carl Adam Petri in the field of computer communication in 1962 (Petri, 1962). It has strong capability in distribution description and analysis due to characteristics of parallelism, uncertainty and asynchrony. Petri net is a network model that could graphically depict the dynamic process of information flow and composed of two types of nodes: place and transition. Tokens are used to indicate status information in conditions and events. And tokens could also reflect the dynamic running process of the system according to the evolution of the status which is driven by certain rules (flow relationships).

Fuzzy Petri net has been used as a tool to optimize the system operation in various fields such as control systems (Mu, 2010), artificial intelligence (Shen et al., 2015; Gao et al., 2019), model construction (Hamed, 2018; Chen et al., 2019), transportation (Mu, 2010) and fault detection (Ren, 2017), etc. and the model itself has become more and more diversified during evolution. And it might be worth to explore the use of it in risk assessment considering that its fuzzy characteristic might be capable to capture the uncertainty of risks.

This study used Petri nets to model and analyze the formation and evolution process of vulnerabilities and risks in complex projects, considering the suitability of Petri nets in modelling abstract factors through diverse inference rules. In Petri nets, an intermediate place can be regarded as the result of its multiple forward places, and it can also be regarded as one of the causes of its backward places. Therefore, based on the relationship between abstract factors, a logic distributed system can be clarified. In the system, the inference rule is defined by algorithm and calculation is usually based on fuzzy mathematics.

The "0–1" rule in the traditional Petri net can only be used for the judgment of objective things. This study uses fuzzy mathematics to enrich the calculation form of the relationship between abstract factors and to extend the application of Petri nets. On the basis of basic tuples such as place P, transition T and flow relation F, a 9-tuple fuzzy Petri Net (Fuzzy Petri Net, FPN) is defined, and its character code and meaning are shown in Table 5.

The fuzzy Petri nets defined in this paper have the following characteristics:

(1) Compared with the basic Petri net, FPN obfuscates the place value and the transition value, and breaks the limitation of original "0–1 rule" judgment. The traditional computer field and other natural sciences have focused on the complexity of programming and modelling, thus only "0–1" assignments are made to the places and transitions. While this study introduced it into the social science research and made it compatible with the uncertainty analysis, by increasing two fuzzy indicators of the truthfulness of the propositions and the credibility of changes in the places.

Table 5. Definition and identification of FPN

Code	Name	Description
P	Place	$P = \{p_1, p_2, ..., p_n\}$ represents a finite set of places, p_i is a specific vulnerability and n is the total number of places;
T	Transition	$T = \{t_1, t_2, ..., t_m\}$is a finite set of transitions, t_i is the transition process of an abstract factor i, m is the number of transitions;
D	Propositions	a finite set of propositions, each proposition is unique and responding to only one place, for the first three elements, there is always: $P \cap T \cap D = \varnothing$, $\lvert P\rvert = \lvert D\rvert$;
I	Input Function	Input function which defines the directed arc from place to transition, $I = \{\alpha_{ij}\}$ when there is a directed arc from place p_i to the transition t_j, $\alpha_{ij} = 1$, otherwise;
O	Output Function	Defines the directed arc from transitions to place, $O = \{\beta_{ij}\}$, when there is a directed arc from transition t_j to place p_i, $\beta_{ij} = 1$, otherwise $\beta_{ij} = 0$;
W	Truth Degree	Indicates the truthfulness of the proposition in the library, $W(p_i) = w_i$, $w_i \in (0,1]$;
F	Confidence level	Indicates the degree of confidence in the change, that is, the degree of theoretical support for the transition by the propositions in the library, $F(t_j) = \mu_j$, $\mu_j \in (0,1]$;
R	Relation Function	Represents the bijective correlation function of place P and proposition D;
M	Marking	Represents the initial state matrix, $M(k)$ is the state matrix after Kth iteration.

(2) In the basic Petri net model, the place stands for a unique identification. In this paper, in order to adapt the established model to the vulnerability-risk evaluation system of complex engineering projects, the place identification in the fuzzy Petri net was divided into Vulnerability (V) and Risk (R) places respectively.

(3) Since the places of vulnerabilities and risks are defined separately, the following situations may occur in the fuzzy Petri nets based on the relationships between vulnerabilities and risks:
Case 1: $V \to V$, that is, one vulnerability can cause or be caused by the other, as shown in Figure 1a;
Case 2: $V + V \to V$, that is, one vulnerability can be the result of multiple vulnerabilities, as shown in Figure 1b;
Case 3: $R \to R$, that is, one risk can cause or be caused by the other, as shown in Figure 1c;
Case 4: $R + R \to R$, that is, one risk can be the result of multiple risks, as shown in Figure 1d;
Case 5: $V + R \to R$, that is, one risk can be the result of one (or more) types of places interacting with others, as shown in Figure 1e.

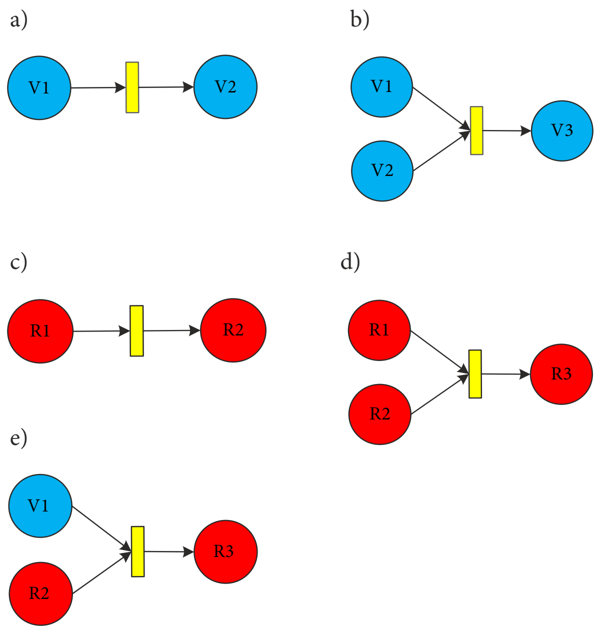

Figure 1. Several cases of fuzzy Petri nets

3.2. Inference rules of fuzzy Petri net

Inference rules which are suitable for vulnerability and risk evolution were defined in this study, based on the basic Petri net theory and existing applications (Ding et al., 2005; Amin & Shebl, 2014). Assuming there is matrix $(A,B,C,D)_{n\times q}$ and matrix $E_{n\times 1}$, we define two rules:

Maximizing Rule:

$A \oplus B = C \Leftrightarrow C_{ij} = \max(a_{ij}, b_{ij}), i = 1,2,\cdots,n; j = 1,2,\cdots,q;$

Multiplying Rule:

$E \otimes B = D \Leftrightarrow e_{ij} = d_i \times b_{ij}, i = 1,2,\cdots,n; j = 1,2,\cdots,q.$

Besides, the two basic relationships: that multiple propositions may correspond to a single transition or a single proposition may correspond to multiple transitions, are defined: logical "and" relations are represented by "$\vee$", and logical "or" relations are represented by "$IF\ d_1 \vee d_2 \vee \cdots \vee d_n\ THEN\ d_k$". Therefore, four types of IF-THEN calculations for proposition D in the FPN model are defined:

Type 1: As seen in Figure 2a,

$$IF\ d_1 \wedge d_2 \wedge \cdots \wedge d_n\ THEN\ d_k,$$
$$\text{and } w_k = (w_1 \oplus w_2 \oplus \cdots \oplus w_n) \otimes \mu_j. \quad (1)$$

Type 2: As seen in Figure 2b,

$$IF\ d_k\ THEN\ d_1 \wedge d_2 \wedge \cdots \wedge d_n,$$
$$\text{and } w_1 = w_2 = \cdots = w_n = w_k \otimes \mu_j. \quad (2)$$

Type 3: As seen in Figure 2c,

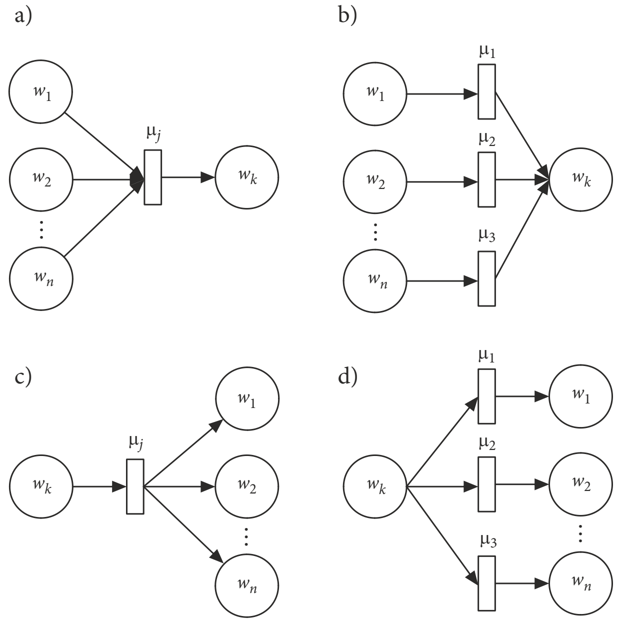

Figure 2. Calculation types of fuzzy Petri nets

IF $d_1 \vee d_2 \vee \cdots \vee d_n$ *THEN* d_k,

and $w_k = (w_1 \otimes \mu_1) \oplus (w_2 \otimes \mu_2) \oplus \cdots \oplus (w_n \otimes \mu_n)$. (3)

Type 4: As seen in Figure 2d,

IF d_k *THEN* $d_1 \vee d_2 \vee \cdots \vee d_n$,

and $w_k = w_k \otimes \mu_i, i = 1, 2, \cdots, n$. (4)

After defining the relevant fuzzy inference rules, the vulnerability-logic inference process was transformed into the FPN model, and the data source of the initial identification and confidence level was clarified.

Determination of $M_0(m_{ij}^0)$: Using expert knowledge, the truth degree (W) of the proposition in the initial place was determined, thus the initial state matrix M_0 was defined.

Determination of confidence level μ: An evaluation form was designed to determine the support level of the place to transition through expert knowledge scoring. In addition, in order to avoid the subjectivity of expert scoring, a cloud model was introduced to achieve fuzziness and eliminate the bias caused subjectivity in the study.

As the level of existence and influence of each factor was given by expert experience and the subjectivity and randomness during this process may not truly reflect the characteristics of the project itself, a cloud model is used to determine the initial degree of membership. The cloud model can be expressed by three quantitative indicators: expectation (E_x), entropy (E_n) and super entropy (H_e). The expectation represents the position of the cloud drop, the entropy represents the confusion degree of the cloud drop, and the super entropy reflects the thickness and degree of dispersion of the cloud layer. The three numerical characteristics in the cloud model can be calculated as follows:

$$E_x = \overline{X} = \frac{1}{n}\sum_{i=1}^{n} x_i; \quad (5)$$

$$E_n = \sqrt{\frac{\pi}{2}} \times \frac{1}{n}\sum_{i=1}^{n} |x_i - E_x|; \quad (6)$$

$$H_e = \sqrt{S^2 - E_n^2}. \quad (7)$$

In order to be compatible with the Likert 5-level scale of the questionnaire, a 5-level evaluation was defined. According to the characteristics of the model, the evaluation standard cloud model simplifies the original index calculation as

$$\begin{cases} E_x = (C_{\min} + C_{\max})/2 \\ E_n = (C_{\max} - C_{\min})/6. \\ H_e = k \end{cases} \quad (8)$$

Here, the value of k is 0.01. Based on this, the evaluation standard cloud map was obtained, as shown in Figure 3.

The initial state matrix can be obtained by using the cloud model. The steps to determine the initial membership degree of each proposition in the initial place are as follows:

(1) If there are n experts scoring the initial affiliation level of factors, the set of cloud drops will be $\{x_1, x_2, ..., x_n\}$;
(2) The arithmetic average of the expert scores is calculated according to Eqn (5);
(3) Replace the average value of the expert's score with an ordinary cloud drop, and calculate the confidence degree obtained by Eqn (9) as the degree of membership:

$$\mu(\overline{X}) = \exp\left(\frac{-(\overline{X} - E_x)^2}{2(E_n')^2}\right). \quad (9)$$

As shown in Figure 4, by comparing the propositions in each initial place with the standard evaluation cloud chart, the evaluation value under the maximum membership degree was obtained. The value of the maximum membership ordinate in the cloud chart was reversed to search for the corresponding abscissa value.

Linear interpolation was used to define the degree of membership of the evaluation value. If the evaluation value $x_i \in [C_{\min}, C_{\max}]$, where $C_{\min}$, $C_{\max}$ are the upper and lower limits of evaluation equivalence, then the degree of membership is calculated according to the following formula:

$$\theta_l = C_{\max} - x_i \rightarrow C_{\min}; \quad (10)$$

$$\theta_{l+1} = x_i - C_{\min} \rightarrow C_{\max}. \quad (11)$$

The membership degrees of the remaining evaluation levels were set to 0.

The defuzzification method to solve the fragility in the reverse direction was specified:

$$S_w = \sum_{l=1}^{5} \theta(l) \bullet l. \quad (12)$$

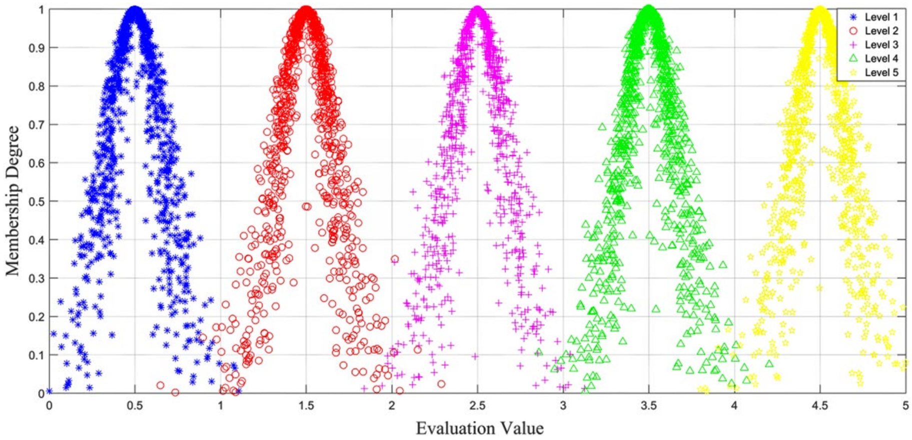

Figure 3. Evaluation standard cloud map

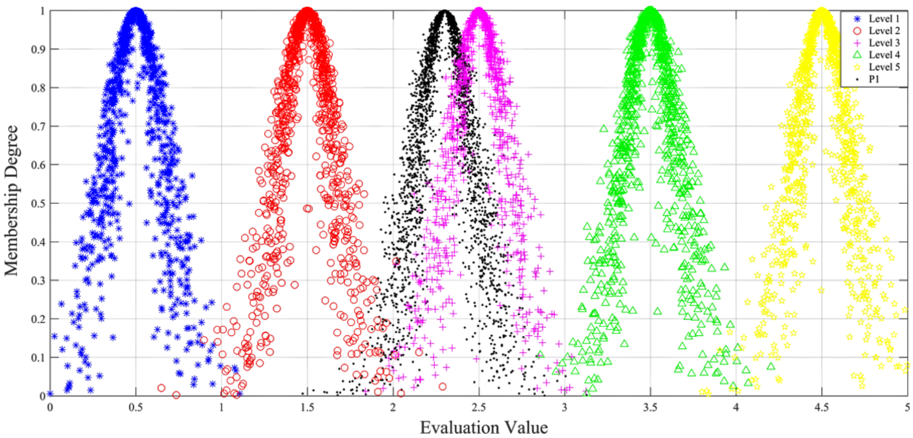

Figure 4. Proposition compared with standard evaluation of cloud

4. Vulnerability-risk model based on fuzzy Petri net

4.1. Modelling category

To increase the adaptability of the research object and the model and unify the consistent changes of vulnerabilities and risks, this paper only considered the unfavorable changes in the system. That is, vulnerabilities and risks are defined as the negative impacts when the system is affected by external factors. On this basis, the meaning of the propositions in the library is all the adverse effects caused by the occurrence. For example, the proposition for the "market operation status" in the place P_1 is defined as "the overall operation status of the construction market or its corresponding construction market is not good". As for the point of view, since the definition of the point is relatively clear, it can be considered that the point of the place is the proposition itself.

Considering that complex projects is one of the research categories of construction engineering and having the universal feature of the traditional construction projects and spatial characteristics of complex engineering projects, the modeling scoping of complex engineering project FPN models is explained as follows:

(1) Time scoping: The fuzzy Petri net model represents a series of abstract inference processes from vulnerability exposure to occurrence of various risk events in different time during the project construction period. The factors that need to be considered in the operation stage are usually more complicated, and in recent years, most of the complex engineering projects have been in the construction or preliminary operation stage. Research on the operation stage has been increasing, but a broad consensus has not yet been formed. Therefore, this paper will use the construction stage of the project as the timing scoping of modeling.

(2) Factor scoping: As it is not practical to include all potential factors. The selection of factors in this study was mainly based on case studies and literature which means some factors might be so omitted. More attention was put into the specification of complex engineering projects as well as the universality and representativeness of traditional construction projects. General factors that can represent most complex engineering projects are firstly selected in order to provide a general paradigm for thinking about problems for the management of complex engineering projects.

(3) Logic Scoping: In this paper, the guiding mechanism of the compound action of multiple factors was considered, rather than just the transmission of a single factor. As shown in Table 2, although there may be a single factor transmission in a specific project, when multiple factors work together in the pilot case, the path of multiple factors transmission was set as the node setting in the model logic. For example, in Case 1, the path of (V_5 + V_6 + V_7) → V_{10} in Case 1 indicated public's attitude towards the project (V_5), national macroeconomic (V_6) and local government's attitude (V_7) determines the site selection the project (V_{10}) mutually; while in Case 2 the path is (V_5 + V_6) → V_{10}, that only the public's attitude towards the project (V_5) and the country's macroeconomic (V_6) affect the site selection of the project (V_{10}). In this case, in order to maintain the integrity of the path, Case 1 was used as the standard flow of drawing the Petri net model, that is, the combined effect of more complex factors was used as priority in the logical identification. It can also be inferred from the logic of fact that different representations appearing in different projects are accidental. Therefore, a wide range of project types and detailed data information are particularly important in the logic scoping.

Based on the above three modeling scoping, the identified factors are matched with the Petri net model according to logic rules, as shown in Table 6. To facilitate calculation and characterization, this study defines "project cost overrun" as a target place. Propositions such as "project delays" and "safety accidents" can all point to this proposition through different degrees of transitions. The basic model of the Petri net is as shown in Figure 5. The places without an input arrow are called the "initial place". There are a total of 10 initial places which include P_1, P_2, P_3, P_4, P_5, P_6, P_7, and P_8 at the bottom and also P_{18} and P_{19}. P_{30} were the "terminal places" and the rest are "intermediate places". The three transitions t_{13}, t_{19} and t_{20} which relate to the terminal place are called "terminal transitions".

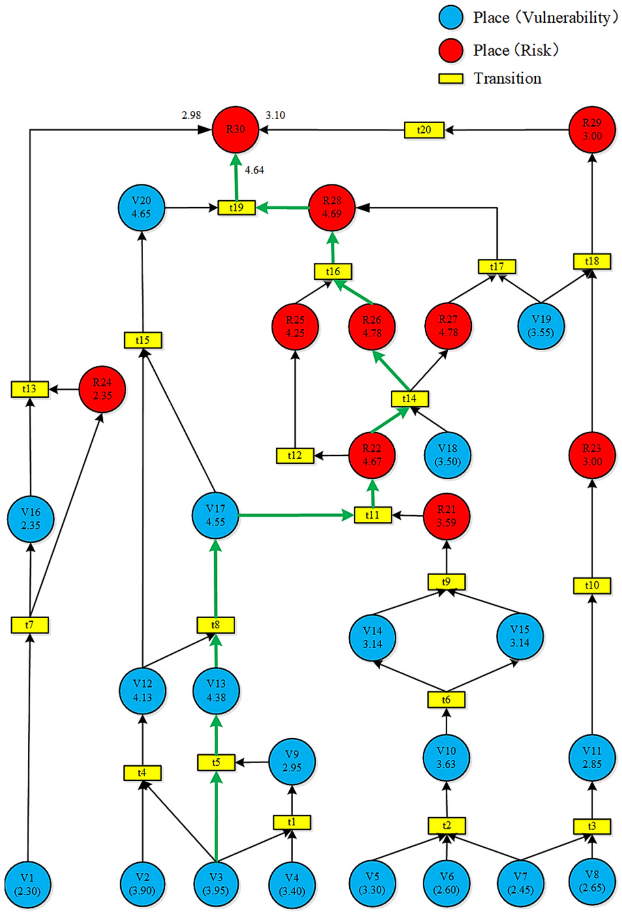

Figure 5. Fuzzy Petri net model of complex engineering project

Table 6. The corresponding table of propositions in each place and *V*/*R* factors

Place (*P*)	Vulnerability/Risk	Place (*P*)	Vulnerability/Risk
P_1	V_1 Market Operation	P_{16}	V_{16} The scale of the construction project
P_2	V_2 Capability of the project owner	P_{17}	V_{17} Completeness of contract terms
P_3	V_3 Project Complexity	P_{18}	V_{18} Contractors' experience
P_4	V_4 Capability of survey and design team	P_{19}	V_{19} Contractors 'management capabilities
P_5	V_5 The public's attitude towards the project	P_{20}	V_{20} Payment type of contract
P_6	V_6 National macroeconomic conditions	P_{21}	R_{21} Unfavorable site conditions
P_7	V_7 Attitude of local governments	P_{22}	R_{22} Change of project scope
P_8	V_8 Policies and regulations	P_{23}	R_{23} Decreased project quality
P_9	V_9 Completeness of design	P_{24}	R_{24} Increased price of materials
P_{10}	V_{10} Site selection	P_{25}	R_{25} Delayed payment
P_{11}	V_{11} Resource availability	P_{26}	R_{26} Conflicts of stakeholders
P_{12}	V_{12} Clarity of the owner's requirements	P_{27}	R_{27} Increased extra work
P_{13}	V_{13} Constructability of design	P_{28}	R_{28} Project delays
P_{14}	V_{14} Ecological environmental conditions	P_{29}	R_{29} Safety incident
P_{15}	V_{15} Geographical conditions	P_{30}	R_{30} Overrun of project cost

4.2. Calculation in the fuzzy Petri net model

The relevant parameters of the FPN model were calculated based on the inference rules defined in the above sections. Double-layer fuzzy inference and calculation rules were adopted. The first layer of fuzzy is the processing of expert knowledge. As the number of experts interviewed is small, randomly generated cloud drops were used to simulate the approximate distribution of large population when processing the expert knowledge in the cloud model; the second layer of fuzzy is to use fuzzy membership to process the relationships between places and transitions in the Petri net, and the defuzzification method was used to return to the identification and judgment of the original path after the fuzzy calculation. The calculation process is shown in Figure 6.

The specific calculation steps of the FPN model are as follows:

Step 1: Distribute the expert questionnaire. The questionnaire was divided into three parts: background investigation, existence, and influence. Experts were invited to score the authenticity of the propositions for the 10 initial places and the confidence level of the 20 transitions. The nature of the questions determines that the respondents of the questionnaire should have relative high qualifications in the industry, so only a small number of people met the requirements. A total of 21 questionnaires were distributed, 17 were returned, and 16 valid questionnaires were selected, which met the basic statistical requirements of the expert questionnaire survey. The relevant information of the experts is summarized in Table 7. It can be seen that most of the interviewed experts have relatively high academic qualifications, long years of working experience, and deep professional knowledge background.

Step 2: Use the cloud model to process the scoring of experts. Due to the small number of data samples, the number of potential samples was expanded by computer simulation to generate random numbers. 3000 cloud drops were set, that the computer would generate 3000 random numbers (Liang et al., 2019). The cloud parameters of the 10 initial locations were calculated and the corresponding cloud diagrams were drawn, as seen in Figure 7; in the same way, the confidence levels of 20 transitions were calculated, as shown in Figure 8.

Step 3: The initial proposition membership vector was calculated according to Eqns (10) and (11), as seen in Table 8; in the same way, the membership vector of all transitions was calculated, see Table 9.

Step 4: the membership degree vectors of the intermediate places were calculated according to the inference rules by Eqns (1)–(4). The membership degree vectors of the propositions in all places are shown in Table 10.

Step 5: According to Eqn (12), the defuzzification value of each location node is shown in Table 11, where the initial location is marked with "()". The calculation results are also reflected in the fuzzy Petri net model diagram in Figure 5.

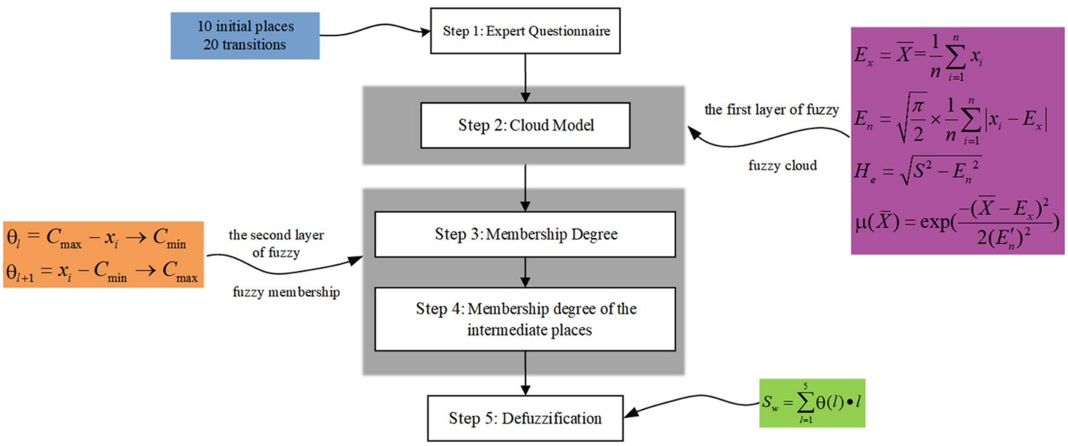

Figure 6. Fuzzy Petri net calculation process

Table 7. Statistics of background information of the interviewed experts

Education Level	Diploma 1 (6.25%)	Bachelor 6 (37.50%)	Master 3 (18.75%)	PhD 6 (37.50%)	
Working organisation	Academic institute 8 (50.00%)	Government organization 1 (6.25%)	Contractor company 3 (18.75%)	Design company 2 (12.50%)	Construction company 2 (12.50%)
Working experience in construction	1 Year 0	2 Years 2 (12.5%)	3 Years 1 (6.25%)	4 Years 0	>= 5 Years 13 (81.25%)
Number of projects involved	1 3 (18.75%)	2 7 (43.75%)	3 4 (25.00%)	4 0	>= 5 2 (12.50%)

Table 8. Membership vector of propositions in the initial place

Initial propositions	Evaluation Value	Membership	Initial propositions	Evaluation Value	Membership
P_1	2.30	(0, 0.7, 0.3, 0, 0)	P_6	2.60	(0, 0.4, 0.6, 0, 0)
P_2	3.90	(0, 0, 0.1, 0.9, 0)	P_7	2.45	(0, 0.55, 0.45, 0, 0)
P_3	3.95	(0, 0, 0.05, 0.95, 0)	P_8	2.65	(0, 0.35, 0.65, 0, 0)
P_4	3.40	(0, 0, 0.6, 0.4, 0)	P_{18}	3.50	(0, 0, 0.5, 0.5, 0)
P_5	3.30	(0, 0, 0.7, 0.3, 0)	P_{19}	3.55	(0, 0, 0.45, 0.55, 0)

Table 9. Membership vector of transitions

Transition	Evaluation Value	Membership	Transition	Evaluation Value	Membership
t_1	2.50	(0, 0.5, 0.5, 0, 0)	t_{11}	4.55	(0, 0, 0, 0.45, 0.55)
t_2	2.85	(0, 0.15, 0.85, 0, 0)	t_{12}	3.45	(0, 0, 0.55, 0.45, 0)
t_3	3.65	(0, 0.35, 0.65, 0, 0)	t_{13}	3.60	(0, 0, 0.4, 0.6, 0)
t_4	4.15	(0, 0, 0, 0.85, 0.15)	t_{14}	3.55	(0, 0, 0.45, 0.55, 0)
t_5	2.80	(0, 0.2, 0.8, 0, 0)	t_{15}	4.45	(0, 0, 0, 0.55, 0.45)
t_6	3.65	(0, 0.35, 0.65, 0, 0)	t_{16}	4.15	(0, 0, 0, 0.85, 0.15)
t_7	2.40	(0, 0.6, 0.4, 0, 0)	t_{17}	3.85	(0, 0, 0.15, 0.85, 0)
t_8	4.25	(0, 0, 0, 0.75, 0.25)	t_{18}	3.00	(0, 0, 1, 0, 0)
t_9	4.05	(0, 0, 0, 0.95, 0.05)	t_{19}	3.80	(0, 0, 0.2, 0.8, 0)
t_{10}	3.15	(0, 0, 0.85, 0.15, 0)	t_{20}	3.20	(0, 0, 0.8, 0.2, 0)

Table 10. Membership degree of propositions in each place

Place	Membership degree vector	Place	Membership degree vector
P_1	(0, 0.7, 0.3, 0, 0)	P_{16}	(0, 0.65, 0.35, 0, 0)
P_2	(0, 0, 0.1, 0.9, 0)	P_{17}	(0, 0.1125, 0.3375, 0.625, 0.1625)
P_3	(0, 0, 0.05, 0.95, 0)	P_{18}	(0, 0, 0.5, 0.5, 0)
P_4	(0, 0, 0.6, 0.4, 0)	P_{19}	(0, 0, 0.45, 0.55, 0)
P_5	(0, 0, 0.7, 0.3, 0)	P_{20}	(0, 0.0563, 0.1688, 0.625, 0.3063)
P_6	(0, 0.4, 0.6, 0, 0)	P_{21}	(0, 0.175, 0.3563, 0.5125, 0.025)
P_7	(0, 0.55, 0.45, 0, 0)	P_{22}	(0, 0.0875, 0.1782, 0.5375, 0.3563)
P_8	(0, 0.35, 0.65, 0, 0)	P_{23}	(0, 0.225, 0.75, 0.075, 0)
P_9	(0, 0.25, 0.55, 0.2, 0)	P_{24}	(0, 0.65, 0.35, 0, 0)
P_{10}	(0, 0.35, 0.775, 0.15, 0)	P_{25}	(0, 0.0438, 0.3641, 0.5438, 0.1782)
P_{11}	(0, 0.45, 0.65, 0, 0)	P_{26}	(0, 0.0438, 0.475, 0.5938, 0.1782)
P_{12}	(0, 0, 0.05, 0.9, 0.075)	P_{27}	(0, 0.0438, 0.475, 0.5938, 0.1782)
P_{13}	(0, 0.225, 0.675, 475, 0)	P_{28}	(0, 0.022, 0.3125, 0.7219, 0.1641)
P_{14}	(0, 0.35, 0.7125, 0.075, 0)	P_{29}	(0, 0.1125, 0.875, 0.0375, 0)
P_{15}	(0, 0.35, 0.7125, 0.075, 0)	P_{30}	t_{13}(0, 0.325, 0.375, 0.3, 0) t_{19}(0, 0.028, 0.2563, 0.7625, 0.1531) t_{20}(0, 0.0563, 0.8375, 0.1188, 0)

Table 11. Fuzzy values of solutions of propositions in each place

Place	Defuzzification value	Place	Defuzzification value
P_1	(2.30)	P_{16}	2.35
P_2	(3.90)	P_{17}	4.55
P_3	(3.95)	P_{18}	(3.50)
P_4	(3.40)	P_{19}	(3.55)
P_5	(3.70)	P_{20}	4.65
P_6	(2.60)	P_{21}	3.59
P_7	(2.55)	P_{22}	4.67
P_8	(2.65)	P_{23}	3.00
P_9	2.95	P_{24}	2.35
P_{10}	3.63	P_{25}	4.25
P_{11}	2.85	P_{26}	4.78
P_{12}	4.13	P_{27}	4.78
P_{13}	4.38	P_{28}	4.69
P_{14}	3.14	P_{29}	3.00
P_{15}	3.14	P_{30}	$2.98(t_{13})$ $4.64(t_{19})$ $3.10(t_{20})$

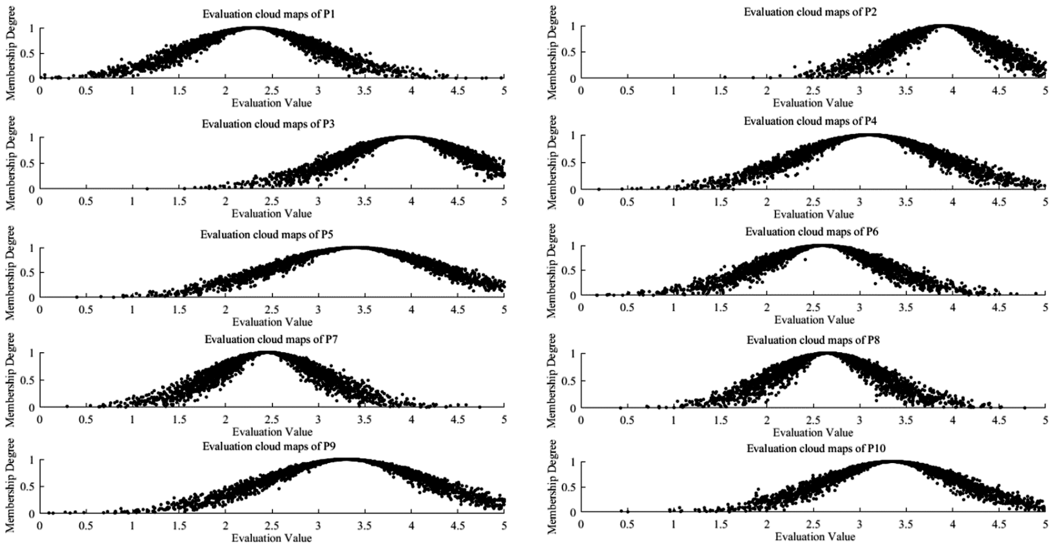

Figure 7. Evaluation cloud maps of the 10 initial place

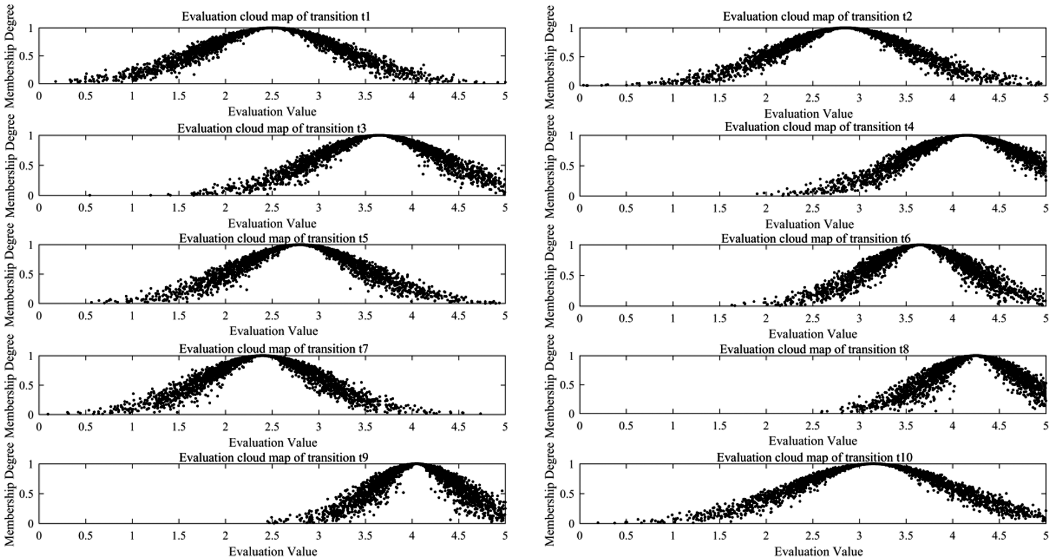

Figure 8. Evaluation cloud maps of the 20 transitions

5. Vulnerability-risk path identification and analysis

The labeling method in the double-code network diagram is a method of calculating node parameter values and inferring the critical path in reverse. The reverse labeling method was used to solve the vulnerability-risk transmission path. The defuzzification value of each place node in Table 10 is regarded as the vulnerability. From the Petri Net diagram, the destination place P_{30} belongs to the three destination transitions t_{13}, t_{19} and t_{20}. The critical path is starting from the terminal node P_{30} and determined in reverse along the three paths of the three terminal transitions. Since the nodes are divided into vulnerabilities and risks, application of the reverse labeling method in this study needs to pay attention to the following aspects:

- If the defuzzification values (vulnerabilities) are the same for the same set of backward places, they are regarded as the same path converging on their common backward transitions.
- If forward places of a transition contain both vulnerability and risk nodes, it must include risk nodes for pruning, so that vulnerability can be regarded as a supplementary effect on the risk.

According to the distribution of the evaluation standard cloud map (Figure 4), qualitative evaluation language of vulnerabilities is defined as follows:

- When the defuzzification value is between (0, 1], the risk is very low; when the defuzzification value is between (1, 2), the risk is low.
- When the defuzzification value is between (2, 3], the risk is in the middle; when the defuzzification value is between (3, 4), the risk is high.
- When the defuzzification value is between (4, 5), the risk is very high.

The paths inferred from the three end-point transitions are as follows.

Path 1: Belonging to the terminal transition t_{13}, as shown in Figure 9. When the market operation (V_1) is not good, such as the shortage of materials will bring the rise of construction resources such as labor, material, and machinery (R_{24}); at the same time, the market operation will also affect the scale of the construction project (V_{16}). When the price of resources rises, project cost overruns may happen (R_{30}). Obviously, if the scale of the construction project is large and the price of resources rises, the overall cost of the project will be overrun more significantly, vice versa. According to Eqn (12), the vulnerability of this path is S (0, 0.325, 0.375, 0.3, 0) = 2.98. It is in the middle level, that is, the risk of each factor propagating along the path to the project system is medium.

Path 2: It belongs to the end point transition t_{19}. According to Eqn (12), the vulnerability of the path is S (0, 0.028, 0.2563, 0.7625, 0.1531) = 4.64, which is relatively high, that is, the factors are propagated to the project system along the path and cause high risks. According to the distribution, path 2 is divided into two sub-paths and analyzed separately.

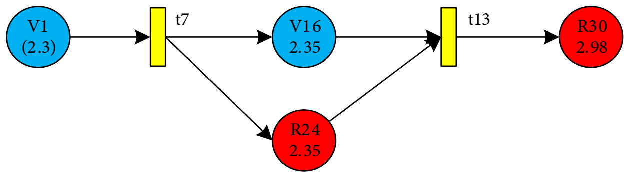

Figure 9. Vulnerability – Risk path 1

Sub-path 2-1: as shown in Figure 10. When the complexity of the project (V_3) is high and the ability of the owner (V_2) is insufficient, the clarity of the owner's requirements (V_{12}) will be reduced. The insufficient capability of the survey and designer (V_4) will result in a decrease in the completeness of the design (V_9), which, together with the complexity of the project, leads to a decrease in the constructability of the design (V_{13}); unclear requirements of the owner and poor constructability of the design will lead to unclear contract terms (V_{17}); in the case of unclear requirements of the contract by the owner, the choice of contract payment type (V_{20}) faces difficulties. Due to the uncertainty of the early design and contract, the unit price and total price contracts have different impacts on the later contract payment and changes and the project delay risk (R_{28}), which collectively leads to project cost overruns (R_{30}).

Sub-path 2-2: As shown in Figure 11, the public's attitude towards the project (V_5), the national macroeconomic (V_6) and the local government's attitude (V_7) will all affect the site selection of a complex project (V_{10}); The ecological environment conditions (V_{14}) and geo-geological conditions (V_{15}) of the construction project will change due to different site selection. The combined effects of them may lead to unfavorable construction site conditions (R_{21}). In addition, if the contract requirements are not clear. (V_{17}), a variation in the scope of the project (R_{22}) may be caused; here, the change in the scope of the project is an important node, which can lead to the delayed payment of the progress payment (R_{25}), or conflicts between stakeholders (R_{26}) or additional workload increase (R_{27}), spatially when contractor's business experience is insufficient. Obviously, when the scope of the project changes, it will have less impact on the project if contractors with rich previous practical experience; Delayed payment of progress payments and stakeholder conflict can both lead to project delays (R_{28}); and when the additional workload increases, the degree of project delays depends on the contractor's management capabilities (V_{19}).

Path 3: Belong to the end transition t_{20}, as shown in Figure 12. Because the availability of resources (V_{11}) has a certain regionality, it is affected by the attitude of the local government (V_7) and the perfection of policies and regulations (V_8); if the quality of the resources is poor, it will directly lead to the decline in project quality (R_{23}), which determines the probability and severity of a safety incident (R_{29}) together with the contractor's management capability (V_{19}), and finally leads to project cost overruns

(R_{30}). According to Eqn (12), the vulnerability of the path is S (0, 0.0563, 0.8375, 0.1188, 0) = 3.10, that is, the risks of various factors propagating along the path to the project system is relatively high.

From the perspective of the Petri net graphics, the inverse labelling method is used to solve the critical path of the fuzzy Petri net, that is, looking for the most vulnerable node starting from R_{30} and going against the arrow line, and so on, until the initial place is found. This line is the critical line in the Petri net. As shown by the thick green solid line in the fuzzy Petri net model in Figure 5, $V_3 \rightarrow t_5 \rightarrow V_{13} \rightarrow t_8 \rightarrow V_{17} \rightarrow t_{11} \rightarrow R_{22} \rightarrow t_{14} \rightarrow R_{26} \rightarrow t_{16} \rightarrow R_{28} \rightarrow t_{19} \rightarrow R_{30}$ is the critical line, and same of $P_3 \rightarrow t_5 \rightarrow P_{13} \rightarrow t_8 \rightarrow P_{17} \rightarrow t_{11} \rightarrow P_{22} \rightarrow t_{14} \rightarrow P_{26} \rightarrow t_{16} \rightarrow P_{28} \rightarrow t_{19} \rightarrow P_{30}$. The nodes on the critical lines become "key nodes", which are V_3 (P_3), V_{13} (P_{13}), V_{17} (P_{17}), R_{22} (P_{22}), R_{26} (P_{26}), R_{28} (P_{28}), R_{30} (P_{30}).

From the critical lines and key nodes, the complexity of the project (V_3) may lead to poor constructability of the design (V_{13}). As design is normally not capable to fully consider the technical feasibility, there might be incompleteness of the contract terms (V_{17}) when signing the contract and lead to changes in the scope of the construction project (R_{22}) during the implementation of the project, and in turn triggers conflicts between stakeholders (R_{26}), which is not conducive to the progress of the project. When there are stakeholder conflicts, the project's construction period may be delayed (R_{28}), which may lead to project cost overruns (R_{30}) to varying degrees.

Events such as conflicts between stakeholders are highly vulnerable nodes in complex engineering projects, which have occurred in 13 out of the 20 selected cases. Complex engineering system exhibit unique characteristics, including complex interactions between the project and society, economy and environment, complexity of scale, technology and organization, uncertainty in depth, and multi-subjectivity. These characteristics will inevitably cause some issues or risks such as: poor constructability of the project due to complicated design in the early stage, unclear requirements of the project owner, lack of similar engineering projects which can be used for reference, incomplete contract terms, complex cross-work due to excessive number of project subcontractors, and frequent changes in the scope of contracting. Inexperienced con-

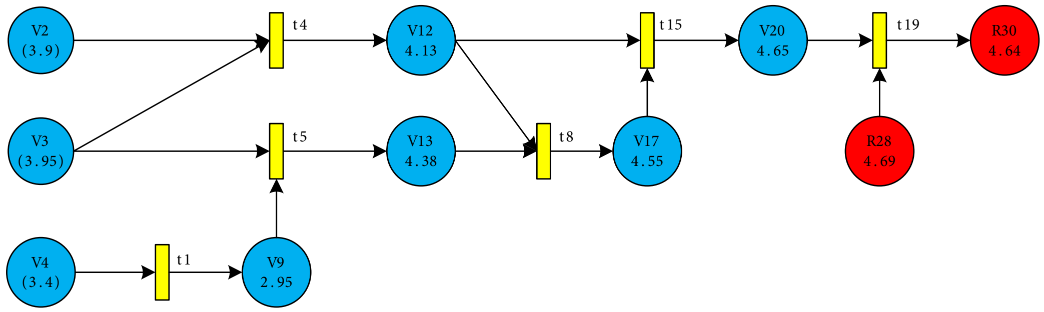

Figure 10. Vulnerability – Risk path 2-1

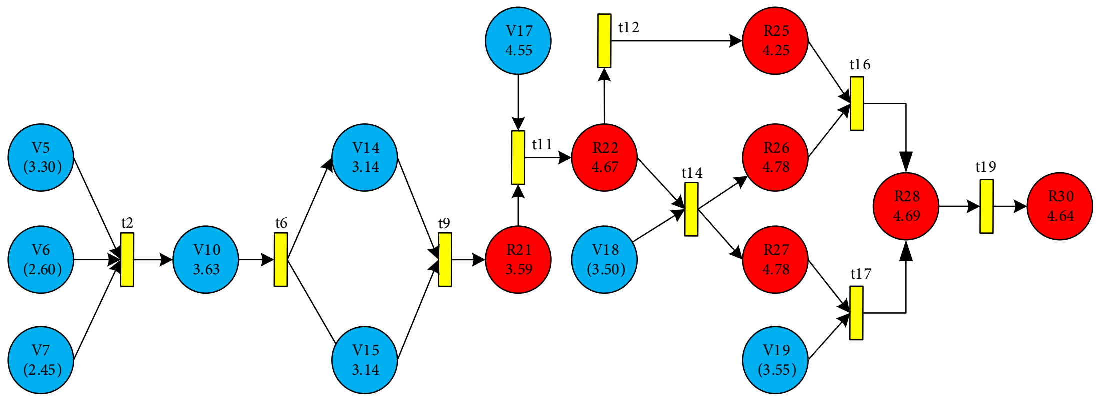

Figure 11. Vulnerability – Risk path 2-2

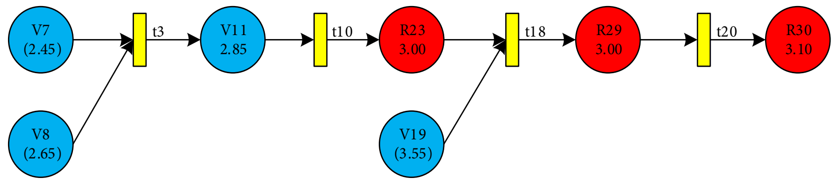

Figure 12. Vulnerability – Risk path 3

tractors will intensify the wrangling among stakeholders and in turn lead to conflicts. Risks, such as delays in construction and project cost overruns may arise correspondingly. This study analysed typical events which occurred in the selected 20 typical cases, it was found that vulnerabilities exist in the project as an attribute of the system itself, such as project scale, construction period, payment method, contract terms, project participants, project experience, management capabilities and project management models, etc. Those attributes affect the potential loss of the project after the disturbance event occurs in different ways and degrees, and they also affect the severity of the risks after the occurrence of those disturbance events. Identification and analysis of vulnerabilities from those 20 typical complex projects could help stakeholders of similar type of projects better understand the potential risks, The analysis and results from this study could provide early warning to the stakeholders of the project, thereby improving the stakeholders' ability to deal with internal and external adverse changes and the project's overall anti-risk ability.

This study separated vulnerabilities from the concept of risk and established a mechanism model of the impact mechanism between vulnerabilities and risks in complex engineering projects. Vulnerability factors are identified independently of risk factors, and a Petri network model was developed to explore the role path of vulnerabilities in the project implementation from the perspective of project development time. Xiang and Li (2016) combined 15 trans-regional major engineering project cases and identified 20 trans-regional major vulnerability factors. Similarly, Ji et al. (2016) analysed 20 typical domestic transportation PPP projects and identified 27 vulnerability factors. However, the vulnerability factors identified in the two study were similar to traditional risk factors and the mechanism and relationships between vulnerabilities and risks were not addressed.

Conclusions and discussion

This paper identified 20 vulnerabilities and 10 risk factors from the and related documents of 20 leading complex engineering projects and clarified the logical relationship between them. The fuzzy Petri net identification and other related concepts applicable to complex engineering projects are defined and a vulnerability-risk fuzzy Petri net model of complex engineering projects was developed. The basic characteristics and fuzzy inference rules which meet the characteristics of complex engineering projects were defined. By collecting expert knowledge and a cloud processing model, the confidence level of the initial place in the FPN model and the membership of the transitions were determined. MATLAB was used to calculate the relevant parameters of the model. From the perspective of the combination of graphics and logic, four main transmission paths converging to three end-point transitions were divided, and the critical lines and key nodes on the lines were determined by the reverse labeling method. Accordingly, managers of complex engineering projects are warned that they should pay more attention to the complexity of the project (V_3), the constructability of the design (V_{13}), and the completeness of contract terms (V_{17}) in the early stages of the project, so as to avoid relevant risk events such as changes in the scope of the project (R_{22}), stakeholder conflicts (R_{26}), project delays (R_{28}) and others.

The contribution of this study is to separate the vulnerabilities from the risk concept and develop a model of the impact mechanism between vulnerabilities and risks of complex engineering projects. The basic identification and fuzzy inference rules of fuzzy Petri nets which are suitable for complex engineering projects are defined, and the model is designed from the perspectives of three dimensions: time sequence, factor, and logic. Vulnerability and risk factors are introduced into the Petri net model as place identifications. The focus of the research is to show the role of vulnerabilities in the project implementation process from the perspective of time series development, and to improve the evaluation method in the traditional risk management which just simply multiplies the probability of risk occurrence and the severity after occurrence.

As mentioned earlier, this study is an extended work following the research on clarifying the connotation of fragility vulnerabilities of complex engineering projects published by the author earlier (Qiao et al., 2020). The next step will be focusing on developing a reliability model of vulnerabilities and risks based on the failure theory and function limit theory, using the multi-value corresponding hierarchical relationship between the 20 vulnerability factors and each risk dimension identified in this study. The fuzzy Petri net model using data from subjective expert knowledge and the reliability model based on objective case analysis will be further compared and discussed.

However, there are some limitations in this study. One is that the number of cases is not enough, and may not be able to fully reveal all the vulnerability and risk factors involved in complex projects, e.g., the impact of the project and the entire society. On the other hand, though the fuzzy Petri net performs double-layer fuzzy processing on subjective data, using cloud model to process expert knowledge may not be able to completely eliminate the uncertainty of expert subjectivity. In order to make the model more scientific and the data more accurate, a wider case database which collates previous risk knowledge and risk management experience can be established and used as the starting point of current project risk management.

In addition, the current research mainly focuses on the vulnerabilities during construction stage of complex engineering projects rather than the entire project life cycle. Therefore, future research could extend the vulnerability analysis to the entire life cycle of the project to better understand the impacts of vulnerability factors at different stages.

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