

Article

Structural Adjustment and Effect Evaluation of Governance on Critical Quality and Safety Risks in Nuclear Power Plant Construction Projects

Bingdong Sun ^{1,2}, Xiang Wang ^{1,*}  and Yuliang Zhao ³

¹ School of Management Engineering, Qingdao University of Technology, Qingdao 266520, China; sunbingdong89@163.com

² Haiyang Nuclear Power Project Department, China Nuclear Industry Fifth Construction Co., Ltd., Yantai 265122, China

³ Urban and Rural Construction Service Center of Linyi City, Linyi 276000, China

* Correspondence: engineer_wangxiang@163.com

Abstract

Quality and safety incidents in nuclear power plant construction can result in severe socio-economic losses. Thus, controlling core quality and safety risks that trigger major accidents is urgent. Stakeholders involved in risk control form structures with distinct social-network features. This study adopts social network analysis to build a core risk governance network model. It analyzes individual and overall network metrics to identify core stakeholders. The key stakeholders include project owners, contractors, supervision institutions, equipment manufacturers, and government regulatory authority. However, effective collaborative governance among these parties remains a challenge. The study then adjusts the organizational network structure and evaluates its effectiveness. This study helps mitigate stakeholders' governance role risks and improves collaborative governance outcomes.

Keywords: nuclear power; quality control; safety; social network analysis; governance structure adjustment

1. Introduction

Rapid social development has made energy shortages a global concern that requires urgent attention. Traditional fossil energy sources are nearing depletion. However, their use poses challenges, including pollution and global warming. Developing sustainable clean energy is an urgent priority for human society, and nuclear power is a clean and highly efficient energy source. It plays a pivotal role in global energy restructuring and carbon reduction [1]. However, the construction of nuclear power plants is a high-risk engineering project. Major quality and safety accidents result in significant economic losses. They also trigger severe and long-lasting social repercussions [2].

1.1. Core Concept Definition

This study defines core quality and safety risks as potential hazards that may cause major casualties, huge economic losses, or serious environmental impacts during nuclear power plant construction, including nuclear island civil construction risks, main equipment manufacturing and installation risks, pipeline welding risks, and commissioning risks. Through statistical analysis of 37 global nuclear power construction accidents from 2010 to



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2024 and semi-structured interviews with 12 industry experts, 12 core quality and safety risks were identified (Supplementary Material S4 for the complete list).

The construction of nuclear power plants requires strict governance of core quality and safety risks. Uncontrolled risks can escalate into severe quality and safety-related accidents. Such accidents inflict substantial losses and disrupt project delivery and wider society. Compared with conventional projects, nuclear plant construction has a more complex organizational structure. It involves a large number of stakeholders [3]. Engineering practice identifies 11 core stakeholder groups in nuclear-plant construction. These groups cover all the key nodes across the full construction value chain. The core parties include owners, contractors, insurers and insurance intermediaries. They also include survey institutions, design firms, and supervision institutions. Equipment manufacturers and important material suppliers are also key stakeholders. Government regulatory authority and quality supervision agencies complete this framework. This classification aligns with the established construction management standards [4].

Most traditional project management research has focused on contracts and organizational structures. It generally frames project organizations as formal, stable hierarchical systems [5]. Complex megaprojects fundamentally differ from ordinary engineering projects. They comprise diverse, self-organizing entities with conflicting interests. These entities interact through networked relationships rather than linear relationships. They collectively form a dynamic, composite, and open large-scale system [6]. Nuclear power plant projects exhibit the defining features of complex megaprojects. They have exceptional complexity and strategic significance. Accordingly, core risk governance in nuclear power plant construction forms a temporary social network [7]. A network perspective supports a systematic analysis of this governance structure. This enables a more comprehensive and objective depiction of the structural characteristics.

1.2. Research Gaps and Objectives

Existing research suffers from three core gaps: (1) most nuclear power project risk governance studies focus on single entities or stages, neglecting the complex network relationships among multiple stakeholders; (2) traditional relationship-strength measurement frameworks fail to account for the strong regulatory characteristics unique to the nuclear power industry, resulting in insufficient applicability; (3) there is a lack of quantitative research on the structural adjustment of nuclear power project risk governance networks.

To address these gaps, this study proposes the following research questions: (1) What are the structural characteristics of the core quality and safety risk governance network in nuclear power plant construction projects? (2) Which stakeholders occupy the core positions in the network? (3) How can risk governance effectiveness be improved through alliance-based structural adjustments? The objectives are to construct a social network model of core risk governance, identify key stakeholders, and propose relatively optimal governance structure adjustment strategies.

This study employs social network analysis (SNA) as the core research method. A social network model of core quality and safety risk governance was constructed. The model covers all stakeholders in nuclear power plant construction projects. It analyzes stakeholder interactions, connections, and group features within the network. It also assesses the mutual influence of various governance strategies [8]. This study aims to enhance the regulation of stakeholder risk prevention behaviors. This ultimately improves the success rate of core quality and safety risk governance.

2. Theoretical Background

2.1. Quality and Safety Risk Management in Nuclear Power Plant Construction Projects

Most studies on nuclear construction quality and safety risk governance adopt two perspectives. The first focuses on the quality control of a single entity during construction. It also covers risk control at one or more project stages. For example, one study analyzed the welding quality control for main steam pipes and supports [9]. Similarly, fuel cladding integrity research focuses on local component quality management [10]. These studies rarely elaborate on the checks and balances among relevant parties. They also fail to address the core essence of governance.

The second is the integrated risk management theory for engineering projects. This theory emphasizes the integration of risk management processes, objectives, and the entire life cycle. It also highlights the strengthened internal integration of project organizations in risk practices [11]. Previous studies have proposed process-based risk management integration. Most adopt the perspectives of owners or consultants. Such frameworks aim to adapt risk management across project life cycle stages [12]. However, existing research on integrated risk management is limited to model construction. Few studies have explored how to fully integrate project organization members. The practical application of integrated risk management has also been understudied.

Overall, existing studies neglect the interwoven network ties between multiple project stakeholders. They rarely examine the inherent risks embedded in stakeholder governance networks [13]. Consequently, these studies fail to address core issues of project risk governance. Therefore, it is necessary to identify stakeholder network relationships from a social network perspective.

2.2. Development and Typical Practical Application of SNA in General Construction Projects

Social network analysis (SNA) first appeared in construction engineering research in 1997. Loosemore studied organizational communication during construction crises [14]. In 2005, scholars applied SNA to construction alliance governance analyses. Pryke's work marked a key milestone in this research direction [15]. Since then, SNA has gained popularity in project governance research.

Relevant studies on construction social networks fall into two main research categories. One stream constructs social network models based on project management concepts and social science variables [16]. The other applies SNA to analyze the dynamics and barriers of network strategies in public construction projects [17]. Some scholars have extended SNA research to engineering, procurement, and construction (EPC) general contracting projects. They first established a socio-organizational relationship model for EPC projects using network indicators and formulas. They then quantitatively analyzed core metrics, including network density, centrality, and cohesive subgroups. They also assessed the strength of organizational ties and the influence of each participating entity. The research findings provide theoretical support for organizational optimization and adjustment [18].

Existing studies also apply SNA from the whole-network and ego-network perspectives. They identified agent construction and design units as core stakeholders. Targeted regulatory measures have been proposed for project owners and government authorities [19]. In addition, scholars have applied SNA to public-private partnership (PPP) project governance research. They constructed relational network models for PPP project governance mechanisms. These studies further proposed policy reflections and optimization recommendations [20].

2.3. Research Orientation on the Application of SNA in Nuclear Power Plant Construction Projects

Existing studies have applied social network analysis (SNA) to project risk governance practices. They provide valuable methodological references for the three core dimensions. These include the construction of a network indicator system, structural optimization logic, and stakeholder interaction mechanism analysis. Such approaches inform SNA-based core quality and safety risk governance for nuclear power plant construction projects [21]. Nuclear power plant construction projects have distinct and inherent characteristics. These include high technological intensity, large investments, long durations, and significant social impacts [22]. Their quality and safety directly support the full life cycle of safe operations of nuclear facilities, which involves multiple stakeholders and diverse objectives during implementation. Thus, coordinating and regulating stakeholder relationships is a critical task. It determines the success of core quality and safety risk governance in nuclear power plant construction projects.

2.4. Theoretical Contributions of This Study

This study makes three main theoretical contributions: (1) it is the first to apply SNA to the field of core quality and safety risk governance in nuclear power projects, addressing the gap of neglecting the high-safety requirements of the nuclear power industry in existing research; (2) it constructs a four-dimensional measurement framework of stakeholder relationship strength adapted to nuclear engineering scenarios, adding the unique “transaction and supervision” dimension to traditional frameworks; (3) it proposes a governance structure adjustment idea based on core stakeholder alliances, providing a new theoretical perspective for collaborative risk governance of complex engineering systems. Compared with PPP and EPC projects, nuclear power projects have fundamental differences in irreversible accident consequences, full-process government supervision, and long-term safety determined by equipment quality, which require safety-oriented and multi-party collaborative governance networks.

Digitally enabled social network analysis is a robust tool for quality and safety control in nuclear power construction projects. It has three core characteristics: relationship visualization, insight quantification, and control predictability. This represents far more than a mere technological upgrade. This signals a fundamental paradigm shift in management philosophy. The focus shifts from “individuals and events” to “systems and relationships”. This approach fosters a more resilient, intelligent, and efficient quality and safety-defense system. Such systems operate within the ultra-complex nuclear power construction ecosystem [23].

This approach aligns with the nuclear power industry’s unwavering pursuit of safety and excellent performance. This marks an inevitable direction for the intelligent and refined management of nuclear power engineering construction projects. Accordingly, this study employs SNA to construct a social network for nuclear power plant construction projects. The network focuses on core quality and safety-risk governance. Targeted governance recommendations are proposed based on core stakeholder alliance adjustment outcomes [24].

3. Model Development and Hypotheses

The strength of stakeholder relationships acts as the edge value in the social network of core quality and safety risk governance. It captures the degree of closeness between the two connected parties. Traditional measurement frameworks usually cover three dimensions: task interdependence, information sharing, and emotional attachment. This attribute directly shapes the interaction capacity of the actors within the network.

3.1. Relationship Strength Measurement Framework

Based on a systematic literature review and semi-structured interviews with 12 senior nuclear power industry experts (average 15 years of experience), this study measures stakeholder relationship strength from four dimensions: trust (TR) [25], transaction and supervision (TS), cooperativeness (CO) [26], and contact duration (CD). The contact duration dimension, characterized by the frequency of formal and informal interactions, is a core component of interorganizational relationship strength in engineering project alliances [27]. These four dimensions cover institutional basis (TS), relational foundation (TR), task interdependence (CO), and interaction frequency (CD), fully reflecting the dual attributes of “contract supervision + relational cooperation” in nuclear power construction governance. This framework integrates the project trust scale from Pinto et al. and the supply chain cooperation strength scale from Kumar et al. and adds the unique “transaction and supervision” dimension for the strong regulatory nuclear power scenario, addressing the limitation of traditional scales in highly regulated engineering fields. The scientific validity of the framework was verified using an expert content validity test (CVI = 0.89).

3.2. Analytic Network Process (ANP) Method

The analytic network process (ANP) is a multi-criteria decision-making method that is suitable for complex systems with interdependent elements. It constructs a supermatrix by establishing pairwise comparison judgment matrices between elements, and calculates the relative weights of each element through matrix operations. Compared with the analytic hierarchy process (AHP), the ANP can better handle the interdependence between dimensions, making it more suitable for the complex relationship system of nuclear power project risk governance.

3.3. Measurement Validation

The reliability and validity of the questionnaire measurement instrument were tested using SPSS (version 26.0). These statistics assess the measurement quality of relationship strength rather than the structural stability of the aggregated network. The reliability test results showed that the Cronbach’s alpha coefficient of the overall questionnaire was 0.872, and the alpha coefficients of each dimension were trust (0.825), transaction and supervision (0.793), cooperativeness (0.811), and contact duration (0.768), all of which were greater than 0.7, indicating good internal consistency. For validity testing: (1) content validity was verified through expert review (CVI = 0.89); (2) the convergent validity test showed that all factor loadings were greater than 0.6, and the average variance extracted (AVE) of each dimension was greater than 0.5; (3) the discriminant validity test showed that the square root of the AVE of each dimension was greater than the correlation coefficient between dimensions, indicating good convergent and discriminant validity (Supplementary Material S3 for factor analysis results).

A questionnaire was developed for an empirical investigation based on the relationship strength indicators in Table 1. This study did not confine its survey to specific projects. It targets entities involved in core quality and safety risk management of nuclear power plant construction. Respondents rated the strength of the relationship between their organization and ten other stakeholder types. The ratings covered four dimensions: trust, transaction and supervision, cooperativeness, and contact duration [28]. The full questionnaire is provided in Supplementary Material S1. It includes instructions, demographic items, and eight Likert-scale items. The questionnaire was pretested by 15 industry experts. Minor wording adjustments were made to the individual items based on expert feedback.

Table 1. Measurement Indicators of Stakeholder Relationship Strength.

Measurement Dimension	Measurement Indicators	Indicator Description
Trust	TR1	Believe that the cooperative party has the ability to complete the core quality and safety risk governance on time, ensuring quality and quantity.
	TR2	Believe that the cooperative party will fully consider the interests of the project when making important decisions.
Transaction and supervision	TS1	Have a contractual relationship with this partner.
	TS2	Have a supervisory relationship with the party.
Cooperativeness	CO1	Has a strong task dependency relationship with this partner.
	CO2	Have a strong resource dependence relationship with this partner.
Contact duration	CD1	Frequent formal communication with this partner.
	CD2	Frequent informal communication with this partner.

3.4. Data Collection and Sample Description

The baseline network in this study reflects the average relationship structure of stakeholders throughout the construction period. Considering the significant differences in core risks at different stages, the dynamic adjustment of alliance focus is required in practice. A purposive sampling method was adopted to distribute 120 questionnaires to 11 types of core stakeholders in six under-construction nuclear power projects in China from March to June 2025. A total of 76 valid questionnaires were collected, with an effective response rate of 63.3%. The sample characteristics are as follows: (1) Gender: 82.9% male, 17.1% female; (2) Age: 76.3% aged 30–50; (3) Work experience: 89.5% with more than 5 years of experience, 52.6% with more than 10 years; (4) Position: 23.7% project managers, 35.5% department heads, 40.8% technical backbones; (5) Organizational distribution: 18.4% owner units, 22.4% contractors, 14.5% equipment manufacturers, 11.8% government regulatory authorities, 32.9% others.

The sample covers core positions in the entire nuclear power construction industry chain, consistent with the characteristics of industry expert samples, and accurately reflects the industry-level stakeholder relationship structure. This study constructs an industry-level stakeholder relationship network rather than an individual-level network of a single project, so the key informant method is adopted. The nuclear power industry has high entry barriers and strong standardization, and core practitioners have a high consensus on an interorganizational relationship model. A total of 76 valid samples from six representative projects covered all core links of the industrial chain, which is equivalent to the sample size of similar SNA studies in high-threshold engineering fields. The permutation test further verified that the network structure was not randomly formed, which effectively reduced the impact of subjective bias. The sample size is comparable to that of similar SNA studies in high-threshold engineering fields, which usually adopt 60–100 expert samples for industry-level network research. The high entry threshold and strong standardization of the nuclear power industry ensure a high consensus on inter-organizational relationship models among core practitioners, so 76 valid samples can effectively reflect the industry-level network structure.

3.5. Edge Value Calculation Process

The specific steps are as follows: (1) Construct a judgment matrix of interdependence between dimensions, and invite 12 experts to pairwise compare the importance of dimensions; (2) Calculate the supermatrix and conduct a consistency test, with the overall consistency ratio $CR = 0.078 < 0.1$, meeting the requirements; (3) Obtain the final weights of each dimension: trust (0.35), cooperativeness (0.30), transaction and supervision (0.20), and contact duration (0.15) (Supplementary Material S2 for ANP judgment matrix and supermatrix).

A five-point Likert scale was adopted to assess the alignment between indicator descriptions and actual scenarios, with five levels defined as {High, Above-average, Average, Below-average, Low} with corresponding scores of {5, 4, 3, 2, 1}. Specifically, “High” denotes full alignment, “Above-average” indicates substantial alignment, “Average” represents moderate alignment, “Below-average” signifies limited alignment, and “Low” denotes minimal alignment.

The edge value calculation formula is as follows:

$$\text{Edge}_{ij} = 0.35 \times \text{TR}_{ij} + 0.30 \times \text{CO}_{ij} + 0.20 \times \text{TS}_{ij} + 0.15 \times \text{CD}_{ij}$$

where TR_{ij} , CO_{ij} , TS_{ij} , and CD_{ij} are the average scores of trust, cooperativeness, transaction and supervision, and contact duration between stakeholders i and j , respectively.

A binary relational gate serves as a preceding step for all dyad evaluations. Each stakeholder pair is first checked for four direct tie types: contractual, supervisory, cooperative, and regular contact. Dyads with none of these ties receive an edge value of 0 and fall outside the Likert scale’s measurement range. Only pairs with confirmed direct ties were included in the weighting calculation procedure. After averaging the valid questionnaire responses, a standardized hierarchical adjustment of ± 0.5 points was applied to the weighted raw scores. The adjustment follows three uniform rules derived from nuclear industry organizational norms: (1) $+0.5$ for dyads with direct administrative subordination; (2) $+0.5$ for dyads with general contracting-subcontracting or core contractual ties; (3) -0.5 for dyads with only indirect business connections. This rule-based procedure avoids subjective discretion on a case-by-case basis. The adjusted values were rounded to integers to produce the final edge values. For example, the raw weighted score between the project owner and contractor is 3.6. It is adjusted upward by 0.5 according to the core contract rule and rounded to 4. The weighted relationship matrix formed by the above scoring and adjustment rules is shown in Table 2.

Table 2. Core stakeholder relationship matrix.

Stakeholder (Code)		I	II	III	IV	V	VI	VII	VIII	IX	X	XI
Project Owner	I	-	4	3	4	3	1	3	3	4	3	1
Contractor	II		-	0	0	0	4	4	3	3	2	4
Insurer	III			-	3	0	1	2	0	0	3	0
Insurance Intermediary Institution	IV				-	1	1	0	0	0	2	0
Survey Institution	V					-	3	0	3	0	0	0
Design Institution	VI						-	0	2	0	3	0
Supervision Institution	VII							-	3	3	3	0
Government Regulatory Authority	VIII								-	0	3	0
Quality Supervision Agency	IX									-	0	0
Equipment Manufacturer	X										-	0
Key Material Supplier	XI											-

Note: This table presents the upper triangle of the symmetric adjacency matrix. The lower triangle entries are identical to the upper triangle entries owing to network symmetry. This matrix supports the full replication of all the indicators listed in Table 3.

This study constructs an undirected weighted network. Edge weights represent the strength of bilateral relational ties between stakeholders. Contractual and supervisory ties carry directional semantic meaning but no topological directionality in engineering practice.

Additionally, the undirected weighted social network structure of core quality and safety risk governance was visualized using NetDraw 2.16 software (Figure 1).

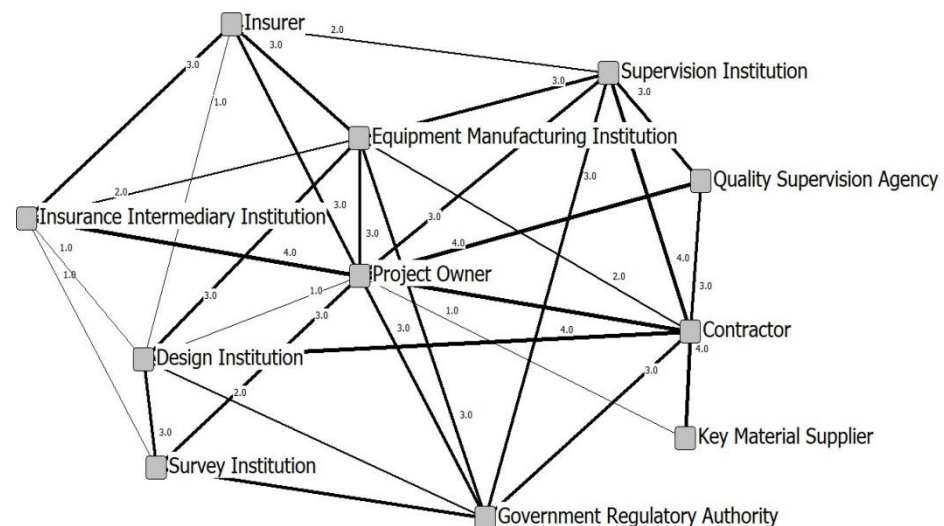


Figure 1. Social network relationships of nuclear power plant construction projects. Note: This figure visualizes the undirected weighted governance network. Larger node size and more connected lines indicate stronger network influence of the stakeholder. The figure clearly shows that the project owner (I) and contractor (II) are the two largest nodes, located at the center of the network with the most connections to other nodes.

To fully characterize the interconnections among entities in the core quality and safety risk governance structure, this study selects four types of indicators for analysis, i.e., overall network density, centrality metrics, structural hole indicators, and clique analysis metrics, which are widely adopted core topological indicators in stakeholder risk network research of construction projects [29]. These indicators can describe the overall network state, identify core entities, and evaluate the effectiveness of the structural adjustments.

4. Network Results Analysis

4.1. Overall Network Density and Centralization

The risk status of the overall social network is assessed using two key structural indicators: overall network density and network centralization. These metrics were computed using UCINET 6.750 software, and the results are summarized in Table 3.

Table 3. Core network structure indicators of the overall social network.

Indicator	Indicator Value
Network Density	0.564
Degree Centralization	41.390%
Betweenness Centralization	24.490%
Closeness Centralization	66.750%

Note: (1) Network density: Reflects the tightness of connections between nodes in the network, ranging from 0 to 1; higher values indicate closer connections between nodes. (2) Degree centralization: Measures the concentration of relational influence across the network, with higher values indicating a more uneven distribution of network power among stakeholders. (3) Betweenness centralization: This measures the concentration of nodes acting as information intermediaries in the network. (4) Closeness centralization: This measures the difference in the convenience of nodes to obtain information in the network.

The overall network density in this governance network is 0.564. This indicates that the network has a moderate connection level. Stakeholders face weak structural constraints and enjoy high decision-making autonomy, and the degree of centralization reaches 41.39%, representing a moderate level of centralization. The network has clear core nodes; however, an absolute monopoly by a single node has not been formed, and the betweenness centralization is 24.49%, which remains low. Few nodes act as intermediaries

for information and resource flows. The closeness centralization reaches 66.75%, the highest of all indicators. Peripheral members obtain core information through indirect network paths. This lowers the overall communication efficiency and timeliness [30].

4.2. Statistical Significance Test of Overall Network Structure

A permutation test with 1000 iterations was conducted using UCINET software. The results showed that the overall network density was significantly higher than that of random networks ($p < 0.01$), indicating that the network constructed in this study was not randomly formed but had real structural characteristics.

4.3. Analysis of Centrality Indicator Measurements

To identify the core stakeholders in the governance of core quality and safety risks, the “Centrality” function in UCINET was employed to assess the centrality of stakeholders across the entire risk governance process (Table 4).

Table 4. Weighted Degree Centrality Index of Core Stakeholders.

Stakeholder Code	Point Centrality		Betweenness Centrality	Closeness Centrality	
	Absolutely	Relatively		Absolutely	Relatively
I (Project Owner)	29	72.5	12.2	10	100
II (Contractor)	24	60	3.867	13	76.923
X (Equipment Manufacturer)	19	47.5	1.617	13	76.923
VII (Supervision Institution)	18	45	1.667	14	71.429
VIII (Government Regulatory Authority)	17	42.5	1.283	14	71.429
VI (Design Institution)	15	37.5	2	13	76.923
III (Insurer)	12	30	0.533	15	66.667
IV (Insurance Intermediary)	11	27.5	0.583	15	66.667
IX (Quality Supervision Agency)	10	25	0	17	58.824
V (Survey Institution)	10	25	0.25	16	62.5
XI (Key Material Supplier)	5	12.5	0	18	55.556

4.4. Statistical Significance Test of Node Centrality

The permutation test results showed that the degree centrality of the top five core stakeholders was significantly higher than that of the other nodes ($p < 0.05$), verifying the statistical significance of their core positions.

Five stakeholders record the highest degree centrality: owner, contractor, equipment manufacturer, supervisor, and regulator. These entities hold extensive network connections and exert dominant influence on governance outcomes. The owner and contractor also show high betweenness centrality, serving as core hubs for information and resource flows.

The government regulatory authority ranks highly in several centrality measures. However, its regulatory focus remains mainly on the project owner and contractor. Oversight of other peripheral stakeholders is relatively limited. This pattern has a clear underlying cause. Many external entities belong to the broader stakeholder ecosystem. Yet they do not participate directly in construction activities. Instead, the project owner and contractor select and engage them. Thus, government supervision of these indirect stakeholders is largely indirect. It operates through monitoring and accountability mechanisms. These mechanisms are imposed on the project owner and contractor.

4.5. Structural Hole Analysis

We measured structural hole indices to assess the extent of structural holes in the network. A larger effective size indicates greater node autonomy and fewer constraints on action. Efficiency is equal to the effective size minus network redundancy. This reflects the efficiency of a node’s interaction. Higher efficiency values indicate better information processing and coordination. The constraint index measures the extent to which an actor is restricted from using structural holes. A lower constraint value indicates a stronger

ability to access non-redundant information. This also indicates a better ability to act as a relationship broker. Thus, the constraint index is the most critical indicator in structural hole analyses. Hierarchy reflects the concentration of constraints on a single stakeholder. Higher hierarchy means more centralized control over structural advantages. Table 5 presents the calculated structural hole index. These indices apply to core quality and safety risk governance social networks. The network is derived from nuclear power plant construction projects.

Table 5. Structural hole indicators in social networks.

Stakeholder Code	Effective Size	Efficiency	Constraint	Hierarchy
Project Owner	5.800	0.580	0.329	0.036
Contractor	3.571	0.510	0.462	0.069
Insurer	1.800	0.360	0.627	0.024
Insurance Intermediary Institution	1.800	0.360	0.627	0.024
Survey Institution	1.500	0.375	0.740	0.021
Design Institution	3.000	0.429	0.470	0.026
Supervision Institution	2.667	0.444	0.532	0.043
Government Regulatory Authority	2.333	0.389	0.536	0.023
Quality Supervision Agency	1.000	0.333	0.926	0.000
Equipment Manufacturer	2.714	0.388	0.472	0.014
Key Material Supplier	1.000	0.500	1.125	0.000

(1) The project owner has the lowest constraint score. This indicates extensive connections, strong information advantages, and a significant influence on resource flows. The project owner also shows a large effective size and low redundancy. It occupies a strategically structural hole position. These factors collectively enhance the capacity to coordinate and govern core risks. The contractor, design unit, and equipment manufacturer also hold advantageous positions. However, their structural advantages are comparatively weaker.

(2) Insurance intermediaries and insurers have identical structural hole metrics. This indicates highly overlapping network positions and their functional roles. They also show strong substitutability. Both have small effective sizes, low efficiencies, and high constraint levels. This implies limited access to non-redundant information and weak brokerage capacity. These findings confirm that both actors have a marginal influence on the core quality and safety risk governance network. They cannot effectively fulfill their potential roles in risk monitoring and control.

(3) Quality supervision institutions and key material suppliers each have an effective size of one. This classifies them as extremely peripheral actors in a network. This suggests that they are structurally “locked” into a single relational tie. They lack alternative connections or strategic flexibility. As a result, they have minimal autonomy and negligible influence on decision-making processes. They are also disproportionately exposed to network risks. This makes them particularly vulnerable to the governance system.

4.6. Cliques and Factions Analysis

This study employs a core-periphery analysis. It examines the subgroup structure in the core quality and safety risk governance social network of nuclear power plant construction projects. This study aims to identify key central stakeholders and peripheral actors. No universally standardized method exists for identifying core-peripheral structures. This study applies the continuous core-periphery model in UCINET. It estimates the coreness score for each stakeholder. This approach enables the quantitative ranking of actors. The ranking is based on proximity to the network core. This reflects their relative influence and integration into the governance system. Table 6 presents the resulting core scores and corresponding rankings.

Table 6. Core quality safety risk governance social network core–periphery analysis.

Stakeholder Code	Core Degree	Structural Division
Project Owner	0.515	Core Structure
Contractor	0.421	
Supervision Institution	0.345	
Equipment Manufacturer	0.333	
Government Regulatory Authority	0.315	
Design Institution	0.245	Periphery Structure
Quality Supervision Agency	0.223	
Insurer	0.205	
Insurance Intermediary Institution	0.189	
Survey Institution	0.171	
Key Material Supplier	0.108	

This study strictly adopts the output results of the UCINET continuous core–periphery model and divides nodes into core structure (core degree > 0.3) and periphery structure (core degree ≤ 0.3). Five stakeholders were identified as the structural core with coreness scores above 0.3: the project owner, contractor, supervision institution, equipment manufacturer, and government regulatory authority. Given their critical structural and functional positions in risk governance, these core stakeholders are selected as subjects for subsequent alliance structure adjustments.

(1) Core structure analysis

According to the UCINET continuous core–periphery model, stakeholders with coreness > 0.3 are classified as the structural core, including the project owner, contractor, supervision institution, equipment manufacturer, and government regulatory authorities.

The quantitatively identified structural core is highly consistent with the functional core of risk governance summarized in engineering practice. All five core stakeholders undertake irreplaceable regulatory, technical, or management responsibilities in core quality and safety risk control, jointly forming the structural hub of the entire governance network.

The equipment manufacturer produces critical components for nuclear power plants. It independently manages its production process. Its product quality directly affects the installation performance of on-site contractors. It also determines the long-term operational safety and reliability of the plant. It acts as a “technical gatekeeper” in the nuclear energy supply chain. It also serves as the “primary bearer of safety responsibility.” Its strategic interests align with the safe and economic operation of the plant. This dual role reinforces its irreplaceable position in the core network.

The supervision institution is an independent, third-party risk manager. Appointed by the project owner, its authority stems from specialized expertise. This knowledge-based authority enables effective risk management. This contributes to improved overall governance outcomes. Collectively, these actors’ capabilities and structural positions create mutual project value. They also enhance the overall effectiveness of core-risk governance. Accordingly, the core of the risk governance network consists of five key stakeholders. The stakeholders are the project owner, contractor, supervision institution, equipment manufacturer, and government regulatory authority.

(2) Marginal structure analysis

Stakeholders in the marginal structure are auxiliary actors in the risk governance network. They can be further classified into two categories based on their relational patterns. The first category maintains ties with both core and peripheral actors in the network. Examples include surveying and designing units. These stakeholders have relatively more connections in the governance networks. They function as “network brokers” or facilitators. They enhance the information flow and coordination between the

core and peripheral nodes. Their integrative role improves the coherence and resilience of the governance system.

The second category includes stakeholders with substantial resource endowments. Insurers are typical examples of this category. They do not actively participate in the daily risk management activities. Their direct involvement in governance is thus limited. However, they provide critical, intellectual, and institutional support. This includes risk assessment, financial safeguarding, and contingency planning. They mainly offer support to project owners and contractors. This indirect but strategic contribution strengthens the governance frameworks. It also mitigates systemic uncertainties in the project.

(3) Community division based on faction indicators

Extensive research has demonstrated that social network nodes often form cohesive subgroups. This clustering occurs because of shared interests, functional interdependence, or institutional linkages. This clustering creates a network with dense internal sub-group connections. The connections between the different subgroups were relatively sparse. Such subgroups are commonly called “communities” [31]. Members of a community interact more frequently than cross-community members. Each community typically forms around a central influential stakeholder. This study uses the “Factions” algorithm in UCINET to determine the optimal community number. The algorithm maximizes the within-group density and minimizes the between-group ties. Using this method, we partitioned the risk governance network into two distinct communities. The network focuses on the core quality and safety risks in nuclear power plant construction (Figure 2).

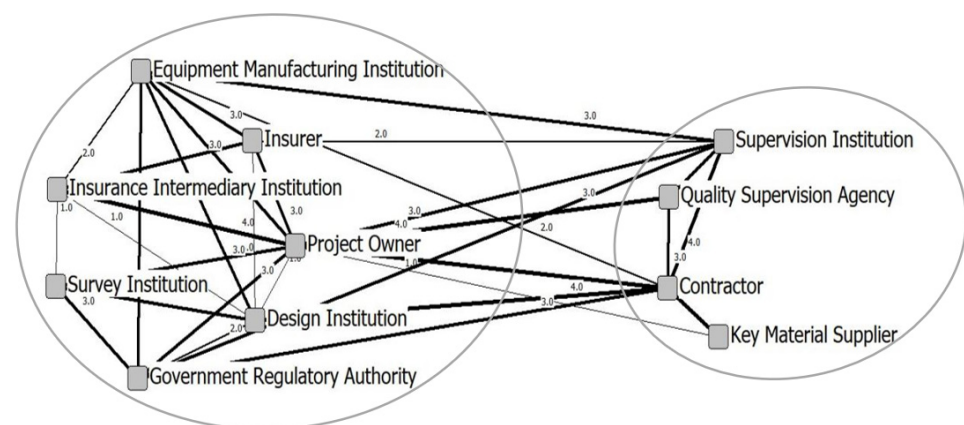


Figure 2. Community member centrality measure graph. Note: Community C1 is located in the left cluster, with the project owner as the core; Community C2 is located in the right cluster, with the contractor as the core. The figure clearly shows a bipartite community structure with sparse connections between the two groups.

The visualization clearly shows the bipartite community structure. Community C1 includes the project owner, insurers, insurance intermediaries, survey units, design units, government regulatory authorities, and equipment manufacturers. Community C2 includes the contractor, key material suppliers, quality supervision institutions, and supervision institutions. Notably, these two communities are anchored by different core stakeholders. Community C1 is anchored by the project owner. Community C2 is anchored by contractors. This reflects the dual governance centers in the organizational architecture of the project. Table 7 presents the inter- and intra-community density matrices. This matrix quantifies the structural cohesion of the groupings.

Table 7. Social network group density matrix.

Group	C1	C2
C1	0.81	0.36
C2	0.36	0.67

This indicates strong connectivity and close relationships within each community. In contrast, the inter-community density was significantly lower. This reflects the weak structural ties between the two groups. Consequently, information sharing, coordination, and joint decision-making are constrained. These are the key components of effective collaborative governance. This structural fragmentation hinders the implementation of integrated risk management. Consequently, this increases the overall risk exposure of the governance system.

4.7. Robustness Analysis

Three robustness tests were conducted to verify the stability of the research conclusions, covering weight, sampling, and edge assignment rule dimensions (Table 8 presents detailed test configurations and quantitative results), indicating that the core conclusions of this study have good robustness.

Table 8. Results of Robustness Tests.

Test Type	Test Configuration	Network Density Change Rate	Core Stakeholder Ranking Consistency	Conclusion Stability
Weight sensitivity analysis	ANP dimension weights adjusted by $\pm 10\%$	3.8%	Fully consistent	Unchanged
Sampling stability analysis	50 samples randomly extracted for recalculation	4.2%	Fully consistent	Unchanged
Edge value assignment test	Hierarchical adjustment removed, raw mean used as edge value	3.3%	Fully consistent	No significant change

5. Structural Adjustment and Effect Evaluation of Governance Network

5.1. Alliance Structure Design and Effect Evaluation

This study did not perform global optimization across all possible alliance combinations but designed three typical alliance structures based on practical engineering scenarios and evaluated their structural effects to identify a relatively better scheme for each scenario. The social network analysis results identified five core stakeholders in the network: project owners, government regulatory authorities, contractors, supervision institutions, and equipment manufacturers. The project owner and contractor are the two primary actors in risk governance, and their roles have been clearly established; they can be treated as independent decision-making entities, allowing the formulation of distinct alliance strategies.

This study does not include the five-party full alliance model because the independence of government regulatory authorities is the premise of effective supervision. An excessively close alliance with owners and contractors may weaken the impartiality of supervision. Therefore, three typical tripartite alliance models were designed to correspond to core governance scenarios, balancing coordination efficiency and regulatory independence. Based on the core-periphery analysis results, this study selected the top five core stakeholders—owners, contractors, supervisors, equipment manufacturers, and government regulatory authorities—to construct alliance structures. Considering that the owner and contractor are the dual cores of the governance network, three typical alliance models are designed, corresponding to three core governance scenarios: (1) Model 2: Owner–

Contractor–Supervision Institution Alliance (for construction quality control scenarios); (2) Model 3: Owner–Contractor–Equipment Manufacturer Alliance (for equipment quality control scenarios); (3) Model 4: Owner–Contractor–Government Regulatory Authority Alliance (for compliance control scenarios).

Moderate centralization helps improve decision-making efficiency and coordination effectiveness, but excessive centralization may lead to information monopolies, slow decision-making, and reduced network resilience. The alliance structure proposed in this study is a balance between centralization and resilience, which drives the governance efficiency of the entire network through the collaboration of core nodes while retaining the independence and flexibility of the other nodes.

By evaluating key social network indicators under various strategic configurations, a relatively optimal alliance structure can be determined. Second, government regulatory authorities, supervision institutions, and equipment manufacturers occupy central positions within the network, and their roles should be further reinforced to enhance systemic coordination. Third, the relationship between the project owner and contractor represents the foundational and most critical dyadic linkage in the project. Therefore, building alliances around this core dyad by integrating either the supervision institutions, key suppliers, or government regulatory authority provides a strategic basis for exploring alternative governance arrangements. Figure 3 illustrates the network structure when core stakeholders implement these alliance strategies.

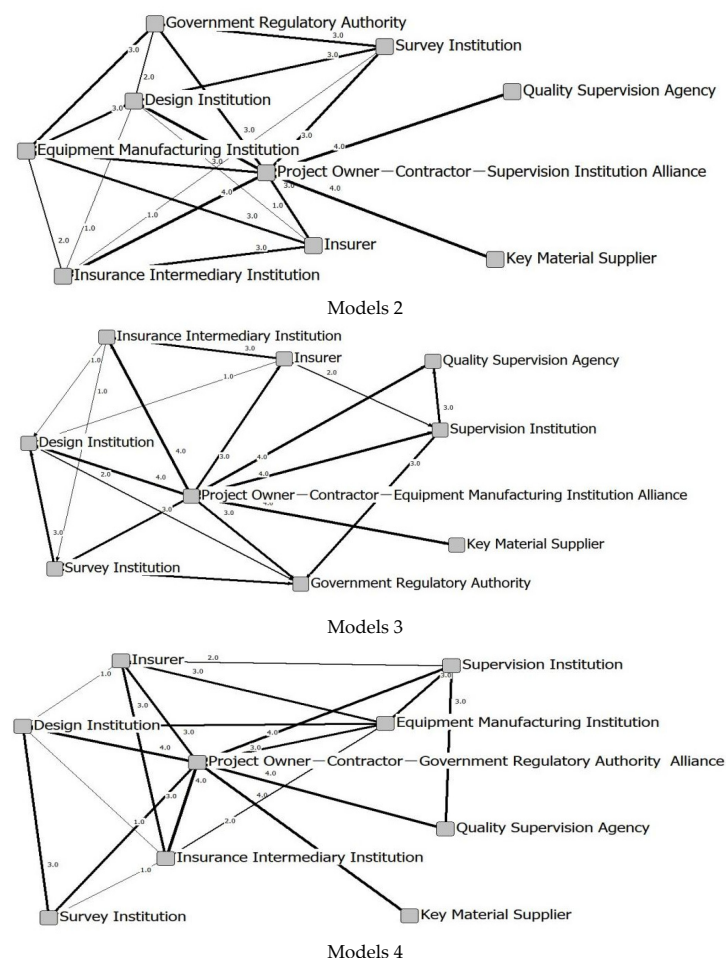


Figure 3. Network regulation structure of different alliance strategies. Note: Merged nodes in the figure represent alliance entities. The figure shows that after the formation of the alliance, the alliance node becomes the new structural core of the network with a significantly enhanced influence.

Based on the above analysis, Model 1 represents the original social network structure (Figure 1). It serves as the baseline network configuration without any alliance strategies. Models 2 to 4 represent alternative network configurations. These configurations correspond to different alliance strategies. We calculate overall network density and centralization for each model using UCINET. The calculation results are presented in Table 9.

Table 9. Core structure indicators of networks under different alliance strategies.

Indicator	Models 1	Models 2	Models 3	Models 4
Network Density	0.564	0.528	0.500	0.528
Degree Centralization	41.390%	65.180%	70.980%	68.300%
Betweenness Centralization	24.490%	64.000%	45.540%	45.980%
Closeness Centralization	66.750%	71.750%	75.930%	72.430%

The data analysis in Table 9 indicates that.

(1) After implementing alliance strategies, overall social network density slightly decreased. Network centralization increased significantly. This indicates a more concentrated power distribution within the network. When the owner, contractor, and equipment manufacturer formed an alliance, the network density reached its lowest level. Network centralization peaked simultaneously. Betweenness centralization dropped to its minimum value. This suggests the tripartite alliance became the network's structural core. It acquired enhanced authority and superior information control. It also gained stronger decision-making influence.

(2) For the project owner, forming alliances enhances its network centrality. This gives the owner greater control over critical network resources. It also improves its ability to respond to core quality and safety risks. We use UCINET to compute three key centrality measures. These measure information exchange capacity, control, and independence. The measures are degree, betweenness, and closeness centrality. We conduct a comparative analysis across the four models. This analysis shows how alliance strategies reshape the governance network. Results are presented in Tables 10–12.

Table 10. Degree centrality index.

Stakeholder Code	Degree Centrality							
	Models 1		Models 2		Models 3		Models 4	
	Absolutely	Relatively	Absolutely	Relatively	Absolutely	Relatively	Absolutely	Relatively
Project Owner	29	72.5	—	—	—	—	—	—
Contractor	24	60	—	—	—	—	—	—
Equipment Manufacturer	19	47.5	14	43.75	—	—	14	43.75
Supervision Institution	18	45	—	—	12	37.5	12	37.5
Government Regulatory Authority	17	42.5	11	34.375	11	34.375	—	—
Design Institution	15	37.5	14	43.75	11	34.375	12	37.5
Insurer	12	30	10	31.25	9	28.125	12	37.5
Insurance Intermediary Institution	11	27.5	11	34.375	9	28.125	11	34.375
Quality Supervision Agency	10	25	4	12.5	7	21.875	7	21.875
Survey Institution	10	25	10	31.25	10	31.25	7	21.875
Key Material Supplier	5	12.5	4	12.5	4	12.5	4	12.5
Alliance: Models 2	—	—	28	87.5	—	—	—	—
Alliance: Models 3	—	—	—	—	29	90.625	—	—
Alliance: Models 4	—	—	—	—	—	—	29	90.625

Table 11. Betweenness centrality index.

Stakeholder Code	Betweenness Centrality			
	Models 1	Models 2	Models 3	Models 4
Project Owner	12.200	—	—	—
Contractor	3.867	—	—	—
Equipment Manufacturer	1.617	0.583	—	0.667
Supervision Institution	1.667	—	1.333	1.000
Government Regulatory Authority	1.283	0.250	0.833	—
Design Institution	2.000	1.167	1.000	0.667
Insurer	0.533	0.000	0.833	0.667
Insurance Intermediary Institution	0.583	0.583	0.333	0.667
Quality Supervision Agency	0.000	0.000	0.000	0.000
Survey Institution	0.250	0.250	0.333	0.000
Key Material Supplier	0.000	0.000	0.000	0.000
Alliance: Models 2	—	14.167	—	—
Alliance: Models 3	—	—	13.333	—
Alliance: Models 4	—	—	—	13.333

Table 12. Closeness centrality index.

Stakeholder Code	Closeness Centrality							
	Models 1		Models 2		Models 3		Models 4	
	Absolutely	Relatively	Absolutely	Relatively	Absolutely	Relatively	Absolutely	Relatively
Project Owner	10	100.000	—	—	—	—	—	—
Contractor	13	76.923	—	—	—	—	—	—
Equipment Manufacturer	13	76.923	11	72.727	—	—	11	72.727
Supervision Institution	14	71.429	—	—	12	66.667	12	66.667
Government Regulatory Authority	14	71.429	12	66.667	12	66.667	—	—
Design Institution	13	76.923	10	80.000	11	72.727	11	72.727
Insurer	15	66.667	12	66.667	12	66.667	11	72.727
Insurance Intermediary Institution	15	66.667	11	72.727	12	66.667	11	72.727
Quality Supervision Agency	17	58.824	15	55.333	14	57.143	14	57.143
Survey Institution	16	62.500	12	66.667	12	66.667	13	61.538
Key Material Supplier	18	55.556	15	55.333	15	53.333	15	53.333
Alliance-models 2	—	—	8	100.000	—	—	—	—
Alliance-models 3	—	—	—	—	8	100.000	—	—
Alliance-models 4	—	—	—	—	—	—	8	100.000

The results presented in Tables 10–12 indicate the following:

(1) From Models 1 to 4, the project owner and alliance group show consistent results. They have the highest degree and betweenness centrality values. They also have the lowest closeness centrality across all models. This demonstrates their strongest transactional capacity in the network. They occupy the central position in all network interactions. These findings confirm the project owner’s dominant governance role. The owner maintains control over critical project resources. It serves as the primary decision-making entity in the system.

(2) The four-party alliance achieves the highest degree and betweenness centrality values. This alliance includes the owner, contractor, equipment manufacturer, and government regulator. Its values significantly surpass those of non-allied stakeholders. This indicates alliance members assume core hub roles in the network. They have a greater number of direct relational ties. As a result, these alliances gain key strategic advantages. These include information dissemination, resource coordination, and risk mitigation.

(3) When the owner, contractor, and equipment manufacturer form an alliance, other stakeholders’ betweenness centrality rises relative to other alliance configurations. This implies that the tripartite alliance strengthens intermediary control over resource flows. Key material suppliers and quality supervision agencies recorded zero betweenness centrality across all alliance models. This reflects their limited brokerage capacity and weak governance influence, placing them at the network’s structural periphery.

(4) When the owner and contractor ally with three other core stakeholders, the closeness centrality of non-allied actors slightly decreases. This indicates alliance strategies improve information exchange efficiency among central actors. Consequently, the owner and contractor perform their routine responsibilities. They become inherently influenced by their alliance partners. This interdependence improves core risk governance efficiency and effectiveness. It also reduces overall project-level risk exposure.

5.2. Management Recommendations

The traditional risk management model relies on independent risk identification and management, which is no longer adequate for nuclear power plant construction projects [32]. Establishing a social network for core risk governance forms a foundational framework that enables governance structure analysis and improves risk management outcomes.

First, core risk stakeholders must shift from an individualistic to a collaborative governance mode. A 2025 mid-year nuclear power plant weld joint accident validates our network analysis. Accident investigations showed that the manufacturer had only a 3-point relationship strength with the owner and contractor. Insufficient information exchange caused a delayed detection of unqualified welders. As a structural counterfactual inference, the proposed owner-contractor-manufacturer tripartite alliance can strengthen inter-organizational information sharing. It is expected to structurally reduce the probability of such quality hazards. This case comes from one of six investigated nuclear power projects. It aligns with industry-level network structure characteristics. Previous studies emphasize that risk management requires a systemic perspective. It should not be limited to isolated organizational viewpoints [33]. Core quality and safety risks have complex causes and catastrophic potential losses. No single entity can bear these losses alone. Thus, collaborative governance is absolutely essential.

Second, the project owner occupies a central position in the governance network. It exercises substantial control over critical project resources. This structural dominance creates a key responsibility for the owner. It must proactively raise risk governance awareness among all stakeholders. The owner should clearly communicate these risks' direct consequences and externalities. It should also explain collaborative governance's advantages over fragmented approaches. These include improved coordination, reduced redundancy, and enhanced system resilience.

Third, equipment manufacturers are not formally principal responsible parties in nuclear construction. Their strategically important role is still frequently underestimated. Equipment quality deficiencies directly compromise on-site construction integrity. They also jeopardize the plant's long-term operational safety. These entities currently have limited structural power in the network. However, centrality indicators show their influence is growing. Thus, manufacturers must be recognized as indispensable governance participants. Integrating them into strategic alliances enables direct engineering coordination. It facilitates seamless technical integration and quality assurance. It also supports schedule alignment across project phases. These measures mitigate equipment-related quality and safety risks. To maximize governance effectiveness, manufacturers need formal inclusion. They should join owner- and contractor-led decision-making processes. Engineering practice confirms that critical nuclear equipment defects cause severe issues. They directly trigger nuclear safety hazards and major schedule delays [34].

Fourth, dynamically adjust the governance alliance focus according to different construction stages: (1) Construction stage: Strengthen the tripartite alliance of owner-contractor-supervisor, focusing on controlling on-site construction quality risks; (2) Equipment installation stage: Incorporate equipment manufacturers to form a four-party alliance, focusing on controlling equipment quality and installation connection risks; (3) Commis-

sioning stage: Strengthen collaboration with government regulatory authorities to ensure that the commissioning process meets safety standards.

6. Conclusions

6.1. Main Findings

Core risk governance effectiveness in nuclear construction depends on two key factors. First is the responsibility level each stakeholder assumes. Second is how their network positions influence other stakeholders. This study analyzes stakeholder interdependence using key network metrics. These include density, centralization, structural holes, and faction formation. The findings identify five core functional stakeholders. These are the owner, contractor, supervisor, regulator, and manufacturer.

Social networks in nuclear construction are characterized by asymmetric relationships. Stakeholders with weak structural positions face a high risk of resource exclusion. Previous studies suggest the owner can mitigate these imbalances. It should strengthen collaborative ties with marginalized actors. This facilitates shared resource access and improves their resilience. The owner holds a central role in coordination and resource control. It has both strategic position and institutional responsibility. It should implement alliances to enhance stakeholder coordination. These alliances also improve overall cooperation efficiency.

This study first conducts a structural analysis of the core quality and safety risk governance network. It further evaluates network configurations generated by various alliance strategies among identified core stakeholders. Results show that the tripartite alliance forms the relatively optimal network structure. This alliance comprises the project owners, contractors, and equipment manufacturers. It provides superior integration, enhanced information flow, and stronger resilience in risk management.

6.2. Limitations and Future Research

This study has the following limitations: (1) The sample size was relatively small and mainly concentrated on nuclear power projects along the eastern coast of China. Future research should expand the sample scope to include global nuclear power projects. (2) Static network analysis is adopted, and the dynamic changes in the network at different stages of nuclear power construction (design, construction, and commissioning) are not considered. Future research can construct a dynamic network model to analyze the evolution of risk governance networks at different construction stages. (3) Only questionnaire perception data are used, and verification is not combined with actual project safety performance data. (4) Only the reliability and validity of the measurement instrument are verified. The structural stability of the aggregated network is not tested via multi-source data. Future research can combine actual accident cases and safety performance indicators to verify the effectiveness of alliance governance strategies. Cross-validation with multiple data sources can enhance the robustness of network structure inferences.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/buildings16142772/s1>, Supplementary Material S1: Questionnaire; Supplementary Material S2: ANP Judgment Matrix and Supermatrix; Supplementary Material S3: Factor Analysis Results; Supplementary Material S4: Core Quality and Safety Risk List.

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Informed Consent Statement: Verbal informed consent was obtained from all the anonymous respondents involved in the study. All data were used exclusively for academic research and were kept strictly confidential.

Data Availability Statement: The data presented in this study are available on request from the corresponding author, as part of the data related to the quality and safety of nuclear power plant engineering is classified confidential.

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