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Research article

Integrating FRAM and BN for enhanced resilience evaluation in construction emergency response: A scaffold collapse case study

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ABSTRACT

The construction system's complexity can generate substantial uncertainties during emergencies. Resilience, as a new perspective on emergency response, can significantly mitigate these challenges. This paper introduces an innovative model to assess the resilience of construction emergency response processes utilizing a scaffold collapse scenario as a demonstrative case study. Grounded in resilience engineering, our model integrates the merits of the Functional Resonance Analysis Method (FRAM) with the probabilistic strengths of Bayesian Networks (BNs). The process commences with FRAM, mapping out the emergency response in qualitative terms by identifying functions, variabilities, and couplings. This culminates in a topological network which serves as a foundational structure for the directed Complex Network (CN) and the BN model. Thereafter, the Delphi method and the modified K-shell (MKS) decomposition algorithm guide the computation of prior probabilities for root nodes and the conditional probability table within the BN model. Subsequently, the BN model is subjected to a simulation using the AgenaRisk software, executing both forward and backward propagation as well as sensitivity analyses. Our findings pinpoint "Intersectoral Coordination and Linkage" as the most crucial function, with rapidity being the most sensitive aspect influencing resilience during a scaffold collapse emergency response process.

1. Introduction

Despite its significant contribution to the national economy, the construction industry is riddled with hazardous and demanding activities, leading to a considerably higher rate of fatalities and injuries than other sectors [1]. The intricacies of construction units, frequent personnel changes, swift modifications to worksites and environment, and other related factors can escalate the consequences of safety incidents, including fatalities, property damage, extended construction periods, project delays, and potential adverse effects on regional economic and social development. Statistics indicate that the risk of death in the construction industry is five times higher, and the risk of severe injury is 2.5 times greater than in the manufacturing sector [2]. As construction projects become larger, the

Abbreviations: FRAM, Functional Resonance Analysis Method; BNs, Bayesian Networks; CN, Complex Network; MKS, modified K-shell; DAG, directed acyclic graph; CPT, conditional probability table.

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fatality rate among workers escalates, with an average of 124 deaths per million workers reported due to safety accidents by 2019 [3]. Economic losses from construction injuries are also significant, with both fatal and non-fatal injuries estimated to cost over $10 billion annually in direct and indirect expenses [4]. These concerning figures underline the need for effective emergency measures to reduce accident rates. Hence, it is crucial to enhance the focus on emergency response within the construction industry.

The construction systems are commonly recognized as complex tech-social systems that involve various stakeholders, presenting significant challenges and uncertainties during emergency situations. Generally, the process of construction emergency response involves four major stakeholders. Firstly, the construction site itself, comprising workers and equipment, plays an essential role in promptly providing emergency message and executing urgent response measures. The second includes the management entities, such as owners and construction management companies. Their task is to strike a balance between economic interests and safety, a process that can introduce potential variabilities and uncertainties into the emergency response. Another critical stakeholder comprises local and national authorities, like the National Emergency Management Department and the Safety Production Supervision Administration, responsible for formulating and executing emergency response operations through the development of relevant laws and regulations. The final stakeholder includes technical support agencies, such as professional emergency response associations and organizations, who develop emergency response plans aligned with the emergency's objectives, thereby providing crucial technical support to the overall emergency response operation. Effective planning, coordination, and ongoing management are critical for the swift activation of emergency response. Despite having comprehensive emergency response plans in the construction industry, the success of emergency operations heavily depends on stakeholder cooperation. Given the unstandardized nature of the emergency response process, which is often assessed qualitatively post-completion, there is a notable absence of tools or techniques for quantitative analysis. Consequently, integrating resilience, defined as the ability to manage unforeseen events, adapt to changes, and recover from emergencies, into the assessment of construction emergency response is vital. While resilience plays a significant role in enhancing emergency response capabilities, most existing research leans towards qualitative analysis. Quantifying resilience's contribution remains a substantial challenge that hinders practical implementation. Consequently, this study integrates the Functional Resonance Analysis Method (FRAM), Bayesian Networks (BNs), and Modified K-Shell (MKS) decomposition algorithms to establish a comprehensive methodology that incorporates both qualitative descriptions and quantitative analysis for evaluating the resilience of the construction emergency response process. The validity of the proposed methodology is confirmed through a case study of a scaffold collapse.

The structure of this study is as follows. Section 2 provides a literature review. Section 3 presents the application of the proposed methodology. Section 4 describes its application to a scaffold collapse emergency scenario that took place in China, followed by analysis and discussion of the results. Finally, Section 5 concludes the study and proposes future work.

2. Literature review

2.1. Construction emergency response

The construction industry is frequently associated with unsafe working environments, primarily due to its dynamic nature involving the utilization of various resources and the need for coordination among diverse contractors, subcontractors, and operators, as well as challenging work conditions [5]. This necessitates a rigorous approach to construction safety and emergency management. In response to these challenges, Pham et al. [6] utilized Building Information Modeling (BIM) technology to simulate and visualize safety facilities. This application of BIM enabled the automatic planning of workspaces for temporary safety facilities in construction activities, thereby enhancing the emergency response capabilities of construction sites. Luo et al. [7] proposed a three-layer Bayesian model based on workers' near-warning response to safety hazards to predict construction safety hazards, and ensured workers' safety through a timely warning system. ZHANG et al. [8] developed the B-FERO2 ontology model tailored for building emergency response, which was founded upon a detailed clarification of the building ontology's study scope along with its extensive range and depth.

While prompt and efficient emergency response is vital for lessening the adverse effects of an accident, the fundamental requirement lies in making well-informed emergency decisions. This encompasses the scientific methods, means, or solutions adopted in response to urgent needs and emergencies. Decision-makers must rapidly gather accident-related information within a confined time frame, appraise the evolving accident scenario, and modify emergency response plans accordingly. Various decision-making methodologies have been employed in the context of construction emergencies. For instance, Li et al. [9] proposed a heterogeneous large-scale swarm decision-making method grounded in fuzzy cluster analysis, which, when applied to the selection of emergency rescue solutions, notably improved the matching speed of these solutions. Xia et al. [10] developed a method for emergency decision-making that combined Case-Based Reasoning (CBR) with a cloud model to effectively mitigate risk. Additionally, Sun and Turkan [11] devised a simulation framework that incorporates a fire dynamics simulator and intelligent agent-based modeling, utilizing Building Information Modeling (BIM) to assess fire development and evacuation procedures in various spatial layouts, thereby offering valuable insights for fire scenario decision-making. BIM technology is increasingly integral in the realm of building construction emergencies, as it provides a comprehensive view of a building's interior, thereby aiding safety managers in crafting precise decisions and efficient emergency rescue plans [12–14].

Efficient emergency operations are underpinned by not only emergency decision-making but also by other critical factors such as the allocation and dispatch of emergency resources, adherence to established communication protocols, and effective interdepartmental coordination mechanisms. Su et al. [15] emphasized the importance of rapid emergency resource allocation to reduce human and economic losses in rescue operations, and proposed a multi-constrained integer linear programming model to solve the emergency resource allocation of concurrent events. Furthermore, effective communication is essential for coordinating emergency responses, particularly in unstable conditions [16]. The efficiency of the emergency response systems is greatly enhanced by timely information access and a robust information infrastructure among response organizations [17]. Moreover, Hu and Kapucu [18] emphasized that effective information exchange is a key aspect of emergency management. Coordination mechanisms, which are crucial for team-based decision-making [19] and for managing joint response operations [20], depend on the efficient and timely sharing of information across communication networks.

2.2. Emergency response resilience evaluation method

Originally introduced by Holling [21] in his examination of ecosystems, the concept of resilience pertains to a system's ability to endure alterations in environmental variables. Since then, this concept has found application across diverse systems such as organizational [22], physical [23], social [24], and tech-social systems [25]. While a universally accepted definition of resilience remains

Table 1
Contributions and limitations of related articles.

Paper	Authors	Contribution	Limitations
Modelling performance variabilities in oil spill response to improve system resilience	Aguilera, M. V. C et al. [32]	The paper integrates Functional Resonance Analysis Method (FRAM) with ergonomic field studies to systematically assess the resilience of oil spill emergency response systems. It demonstrates how variations in planning, preparedness, execution, resources, economics, and human factors contribute to the efficacy of response operations. The methodology offers strategic insights for enhancing system resilience in handling oil spill emergencies.	The paper did not incorporate quantitative metrics for evaluating the performance of the emergency response system, such as response time, spill containment efficacy, cost-effectiveness, or recovery rates. Without quantitative analysis, generalizing the study's outcomes to different scenarios becomes challenging, as does adjusting solutions to fit the scale and magnitude of the oil spill incident.
A resilience perspective on water transport systems: The case of Eastern Star	Wang, Y et al. [33]	The paper presents a comprehensive reflection on the Eastern Star incident and conducts a qualitative assessment of the emergency response's resilience using traditional analytical methods. This approach yields valuable insights into the complexities of waterborne transportation risks and the significance of resilience in ensuring safety.	The paper qualitatively discusses the resilience of the emergency response process, yet it allocates insufficient focus to quantitative modeling and methods. This oversight may restrict the precision of the risk assessment proposed.
Using qualitative types of risk assessments in conjunction with FRAM to strengthen the resilience of systems	Bjørnsen, K et al. [34]	The paper delineates a novel methodology that merges qualitative risk assessment with the FRAM to bolster system resilience. This integration is especially beneficial for intricate systems where conventional quantitative risk assessment methods fall short.	The paper emphasizes qualitative methods, omitting quantitative data integration, a potential limitation for validating the methodology or benchmarking it against other risk assessment techniques. Moreover, the inherently subjective qualitative assessment could impact the consistency and reliability of the outcomes.
Application of a CREAM based framework to assess human reliability in emergency response to engine room fires on ships.	Ahn, S. I., & Kurt, R. E [29].	The paper introduces a methodology grounded in the cognitive reliability and error analysis, applied to evaluate maritime man-made fault in specific scenarios, particularly focusing on the reliability of personnel during an emergency response to a fire in a ship's engine room.	Time constraints and public opinion pressures complicate the interplay among human, organizational, and technological factors in the emergency response process, introducing inherent uncertainty, non-linearity, dynamics, and complexity. The method struggles to precisely delineate the pertinence of the emergency process.
Integration of Resilience and FRAM for Safety Management	Smith, D. et al. [35]	The paper presents a novel methodology that synergizes quantitative system performance metrics with qualitative insights derived from the FRAM to evaluate the resilience capabilities of industrial operations.	The article offers a hypothetical case to demonstrate the methodology, yet it stops short of examining its transferability to various industries or distinct models. Furthermore, although the hypothetical case facilitates understanding, it falls short of furnishing empirical evidence to substantiate the method's real-world efficacy.
The use of Functional Resonance Analysis Method (FRAM) in a maritime accident: A case study of Prestige	Salihoglu, E., & Beşikçi, E. B [36]	The paper scrutinizes the "Prestige" oil spill, a significant environmental disaster, using the FRAM framework. The objective is to decipher the variability of events leading to the accident, propose research recommendations, and elucidate potential causes of the incident.	The use of FRAM in this paper is based on subjective judgment, the value of the analyst and the quantitative valuation of the measurable effect, which has a certain subjectivity and cannot achieve the objective quantification of the accident
Safety analysis of anti-terrorism emergency response in offshore exploration based on STAMP model	Han et al. [37]	The article employs the System-Theoretic Accident Model and Processes (STAMP) model, predicated on systems theory, to examine the security of emergency response protocols for offshore exploration in the context of terrorism. This contemporary approach extends past conventional safety analysis techniques such as fault trees or event trees.	The reliability of the STAMP model is contingent upon the quality and comprehensiveness of the data utilized in the analysis. Data that are inaccurate or incomplete can yield results that are less dependable.

elusive [26], the broad consensus posits that resilience equips a system with the capacity to absorb damage, adapt to shifting environments, and recover from adverse or anomalous states [27]. In tech-social systems, where human operators and technology tools work together to manage unforeseen events, and the need for resilience in managing unexpected emergencies was highlighted after the 9/11 World Trade Center attacks. Researchers have since studied resilience in emergency management from a multidisciplinary perspective, including crisis and disaster research, which aims to understand the causes of events and encourage decision makers and public administrators to adopt more resilient approaches [28]. The emergency response mechanism within construction is characterized as a multifaceted techno-social system, attributable to the cooperative essence of construction tasks that involve a network of contractors, subcontractors, and operators interdependent on one another. The interplay between the human, organizational, and technical aspects of construction becomes intricate during emergency response due to time constraints and public opinion pressures, resulting in inherent uncertainty, non-linearity, dynamism, and complexity. Traditional qualitative methods such as CREAM analysis [29], analytic hierarchy processes [30], and FMEA [31] inadequately capture the multifaceted interrelationships of stakeholders in the emergency response process and fail to provide quantitative descriptions. Table 1 lists seven significant articles pertinent to our study, in which we assess their key contributions and limitations. Through dialectical analysis, we establish a solid foundation for the innovative methodology proposed in this study.

The limitations of the papers shown in Table 1 mainly include three aspects: (1) Lack of quantitative assessment: Many articles do not include quantitative methods and data, which affects the precision of the evaluation and limits the universality of the results and the ability to adjust solutions to fit accidents of different scales. (2) Insufficiency of qualitative analysis: Some qualitative analysis methods have difficulties depicting the relevance of the emergency response process, and subjective judgments may affect the objectivity and reliability of the evaluation results. (3) Insufficient empirical validation of the methodology: The new methodologies proposed in the research have not been sufficiently empirically studied in the real world to prove their effectiveness. Therefore, considering the limitations of the papers shown in Table 1, to fill this gap, this study proposes a comprehensive method that combines FRAM with the Bayesian network model, aiming to integrate the depth of qualitative analysis with the precision of quantitative assessment, to comprehensively evaluate the resilience in the emergency response process. To dissect the complex interactions characteristic of the emergency response process, an initial qualitative analysis is conducted using the Functional Resonance Analysis Method (FRAM). This analysis sets the stage for subsequent quantitative evaluations performed through Bayesian networks (BNs), which have gained prominence for their application in resilience assessment and decision support across various domains. Yodo et al. [38] employed dynamic BNs to predict the resilience of complex systems in uncertain and adverse environments. Building on this approach, Cai et al. [39] integrated time-dependent variables into dynamic BNs to refine system resilience assessments. Qiao et al. [26] adopted a fuzzy Bayesian network to measure resilience in the context of the North Sea Route. Hossain et al. [40] identified key factors that enhance the resilience of port infrastructure systems through BNs. Chen et al. [41] devised a comprehensive Bayesian network model that amalgamates social, economic, organizational, and technological factors to evaluate the static resilience of urban transportation systems.

2.3. Contribution and innovation of the study

This study proposes an integrated evaluation methodology designed to address the identified gaps in the literature review. The methodology synergistically utilizes the Functional Resonance Analysis Method (FRAM), Bayesian Networks (BNs), and a modified k-shell (MKS) decomposition algorithm. FRAM is first applied to dissect the emergency response process, pinpointing its various functions and the variability within them, and then amalgamating these variations to examine how each function interrelates. Subsequently, the FRAM model is assembled by integrating these variabilities and serves as a foundational prototype for the directed complex network (CN). Next, the functions in the FRAM model are selected using resilience theory as a way to construct the BN framework, and the probabilities in the BN model are calculated using the Delphi method and the MKS Decomposition Algorithm. A case study on scaffold collapse accident, a frequent occurrence in construction projects, is presented to validate the proposed integrated evaluation methodology's effectiveness. The innovations and contributions of the proposed methodology are summarized as follows.

(1) Theoretical exploration of the construction emergency response process was conducted through the lens of resilience engineering and the FRAM principle, examining the interrelationships among the process elements to inform and advance research in emergency response resilience theory.
(2) A comprehensive methodology has been developed to address the lack of quantitative resilience evaluation tools for emergency response processes in construction. This methodology integrates FRAM, BNs, and MKS, with its validity confirmed through a case study on scaffold collapse accident.
(3) Integration of FRAM and BNs is used to assess the resilience of the construction emergency response process, eliminating traditional potential biases induced by experts and compensating for the shortcomings of FRAM in quantitative analysis, which can effectively address the issues of uncertainty and variability encountered by emergency managers in decision-making.
(4) Utilizing BNs effectively addresses the lack of detailed statistical data in the emergency response phase. Moreover, BNs facilitate the incorporation of the latest information to update their parameters, thereby enhancing the robustness of emergency response strategies in construction.

3. Methodology

3.1. Functional resonance analysis method

FRAM is a functionally based systems methodology that is utilized to investigate security-related issues and challenges that arise in complex tech-social systems [42]. Unlike traditional approaches that emphasize physical aspects, FRAM explains how these systems operate by focusing on functional aspects, dynamic interactions, and performance variability [43]. To achieve optimal functionality and output, FRAM utilizes four fundamental principles, which are delineated as follows [42]:

(1) **The equivalence of successes and failures:** Success and failure occur in the same way, meaning that the potential causes for both outcomes are the same, and the same mechanisms lead to expected results or accidents.
(2) **Approximate adjustment:** In order to complete a task (to execute system functions and meet system requirements), it is necessary to make appropriate adjustments to the task under existing conditions (such as time, manpower, information, resources, etc.), and the adjustments will be approximate rather than precise.
(3) **Emergent outcomes:** Accidents are the result of the emergence of small changes in the system, which may come from the variability associated with daily adjustments, rather than the result of the combined forces.
(4) **Functional resonance:** Weak variability of some interrelated tasks/functions may exacerbate each other and lead to amplified variability of the whole system.

The three main steps for modeling and analyzing complex tech-social systems using FRAM, as shown in Fig. 1, are as follows:

(1) Description of basic system function;
(2) Identification of variability;
(3) Aggregation of variability.

In FRAM modeling, the first step involves identifying and defining the functions, as depicted in Fig. 1. These functions are outcomes of cooperation among technologies, humans, and organizations. They can be described based on the following six dimensions:

- **Input:** The essentials required for executing a function. The input forms a link with the previous function and can be transformed or used by the function to generate output.
- **Output:** The consequences of a function, encompassing a range of results like modifications in information or the sequence of events.
- **Precondition:** The system requirements that need fulfillment before a function can be performed. (including other processes, steps, and specific conditions.)
- **Resource:** The consumable resources that are necessary conditions for performing a function. (such as human resources, equipment, electricity, fuel.)

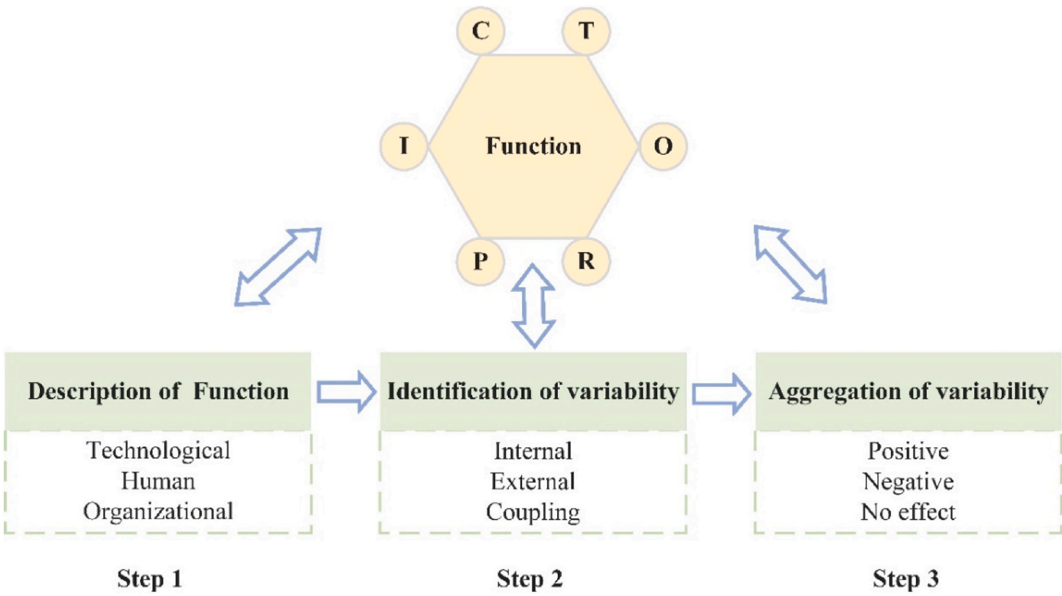


Fig. 1. General procedure for FRAM modelling.

- **Control:** The limitations to performing a function. (such as guidelines, plans and procedures.)
- **Time:** The specific time requirements for performing a function.

The second step in building the FRAM model involves identifying the potential or actual variability of the function, as shown in Fig. 1. It is important to note that the latter is preferred for instantiation. In complex systems, the three primary sources of variability stem from technological, human, and organizational functions [44]. The characterization of functional variability is indispensable to comprehend how functions intertwine and how variability from upstream functions impacts downstream ones. Consequently, particular emphasis must be placed on variability of function outputs, which can arise from three sources: endogenous factors, exogenous factors, and the interplay between upstream and downstream. Table 2 furnishes a synopsis of the fundamental principles of variability identification, classifying functions as technological, human, and organizational [36,45].

The concluding step encompasses aggregating variability, essentially forming interlinks among various functions. Fig. 2 illustrates that coupling is where the output of one function can be linked to different aspects of other functions (inputs, prerequisites, resources, controls or time). This step explains the impact of one function's variability on others, and how the interaction between two or more functions can intensify instability, culminating in unforeseen outcomes. Depending on the principle of functional resonance [42], the influence of variability in upstream functions on downstream functions can manifest as positive, negative, or may have no impact at all.

3.2. Construction of the emergency response resilience framework

Resilience serves as a vital trait that allows emergency management systems to function optimally, effectively addressing both foreseeable and unforeseen disruptions in emergency response procedures [32]. Zhou et al. [46] earmarked five facets for appraising the effectiveness of emergency response maneuvers. Concurrently, Son et al. [47] pinpointed four crucial dimensions of emergency management resilience. Extending from these findings, Qiao et al. [45] combined their work to design a resilience assessment framework. To bolster this framework further, the current study incorporates four metrics—robustness, redundancy, resourcefulness, and rapidity—from the technological, organizational, social, and economic dimensions to quantify emergency response systems' resilience. The objective is to gauge the resilience of varying analysis units and foster a more comprehensive comprehension of the complex interrelations among various elements within emergency response procedures [33]. Table 3 delineates the factors deduced for evaluating emergency response resilience.

This study evaluates the resilience of the emergency response process utilizing the criteria of robustness, redundancy, resourcefulness, and rapidity, as depicted in Fig. 3. It is important to note that these aspects are not independent but largely interrelated and complementary, as illustrated in Table 3.

3.3. Principles of inference using Bayesian Networks

3.3.1. Overview of the Bayesian Networks approach

Bayesian Networks (BNs) utilize directed acyclic graphs (DAGs) and conditional probability tables (CPTs) to model complex systems, integrating both qualitative and quantitative analyses. The DAGs visually depict causal relationships among variables, while CPTs encode variable states' probabilities based on their antecedent variables. This blend of qualitative and quantitative aspects facilitates robust modeling and analysis, aiding in reasoning and inference amidst uncertainty. A standout attribute of Bayesian networks (BNs) is their prowess for deductive reasoning. Unlike traditional regression algorithms, BN models are unfettered by constraints on the direction of inference, facilitating both forward and backward analysis. Contrasting with tree models such as Decision Trees [48] and Random Forest [49], BNs undertake deductive inference devoid of the necessity to predetermine a minimum cut set, thereby considerably augmenting computational efficiency.

(1) **Forward Analysis:** The probability of each root node serves as a known condition to compute the probability of leaf node T, represented by $P(T=t)$, based on the pre-defined CPT. The computation process is illustrated by Equation **(1).**

$$P(T=t)=P(T=t|X_1=x_1,\dots,X_n=x_n)\times P(X_1=x_1,\dots,X_n=x_n) \quad (1)$$

Table 2
Fundamental principle of variability identification.

Type	Source of variability	Description
Technological	Internal	The internal functional principles of technology are hard to comprehend or the functionality of technological facilities degrade.
	External	The variability results from improper maintenance or severe environmental circumstances.
Human	Internal	The variability related to humans resulting from psychological and physiological factors.
	External	The variability due to the influence of technology, organization, and society on human behavior.
Organizational	Internal	The variability related to intra-organizational communications, architecture, and culture
	External	The variability caused by external factors of the organization such as user demands and regulatory intensity.
Coupling	The variability of downstream functions is influenced by the variability of upstream functions.	

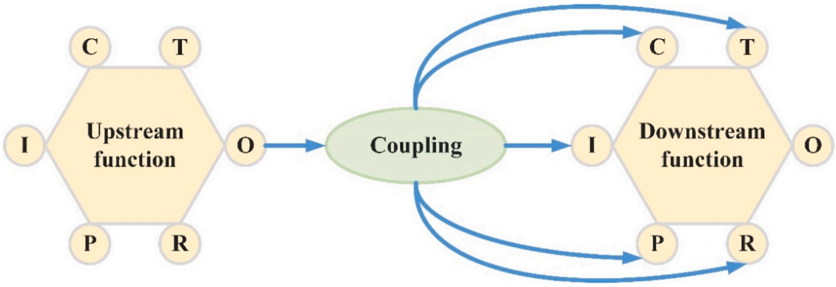


Fig. 2. Coupling process.

Table 3
Factors for emergency response resilience evaluation.

	Technological	Organizational	Economic	Social
Robustness	Ensure the functionality of critical emergency equipment and prevent damage	Mobilize rescue teams within 1 h and establish an adequate emergency organization	Estimate preliminary damage within 1 h of the event	Prevent deaths due to insufficient response capacity and secondary disasters
Redundancy	Maintain a degree of flexibility in on-site emergency activities	Establish division of duties and information exchange between departments for emergency response activities	Implement measures to restore economic viability	Use alternative resources to provide basic services
Resourcefulness	Provide availability of damage detection technologies and methods, other information technologies, and decision support systems	Implement emergency management plans and response strategies effectively	Input disaster prevention funds and equipment before an accident occurs	Estimate disaster assistance needs and submit formal disaster declaration requests
Rapidity	Ensure all technologies required for command, control, coordination, and critical response tasks are operational	Minimize the time required to start and complete critical response tasks	Resume construction and production activities within three days	Provide medical emergencies rapidly for injured personnel

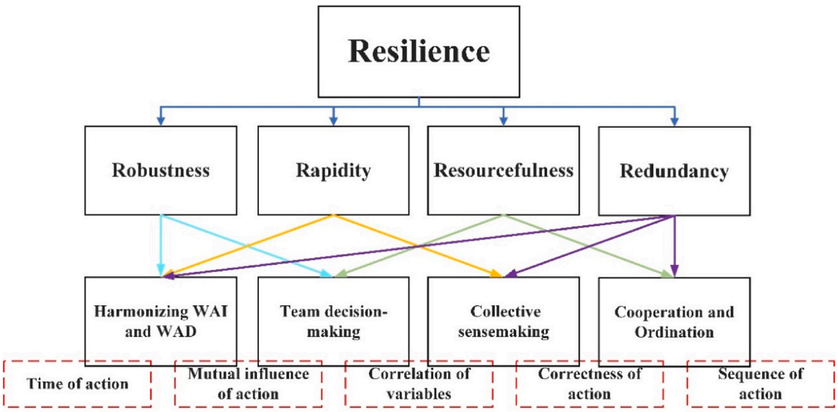


Fig. 3. Emergency response resilience assessment framework.

where $t = t_1, t_2, \ldots, t_p$ is a range of P states for the node T; $x = x_1, x_2 \ldots x_n$ is the variables; $P(T = t|X_1 = x_1, \ldots, X_n = x_n)$ denotes the conditional probability distribution of T; $P(X_1 = x_1, \ldots, X_n = x_n)$ represents the joint probability distribution of X_i.

(2) **Backward Analysis:** By manipulating the probability distribution of leaf nodes based on the pre-defined CPT, one can note alterations in the posterior probability of each node in the model, thereby identifying the key variables impacting the leaf nodes. Equation **(2)** outlines the formula for calculating the posterior probability of variable X_i, given the posterior probability $P(T = t)$ of the leaf node.

$$P(X_i|T = t) = \frac{P(X_i = x_i)P(T = t|X_i = x_i)}{P(T = t)} \tag{2}$$

where $i = 1, 2, ..., n$. The implementation of backward analysis can provide decision-makers and managers with an effective way to enhance resilience of the emergency response process from the perspective of system.

3.3.2. Modified K-shell decomposition algorithm

The k-shell decomposition algorithm is a coarse-grained decomposition method that uses the global structure of the network to determine the strength of relationships between nodes based on their positions within the network. The process of this method is illustrated in Fig. 4. In this study, we have introduced the concept of weighted degree (which fundamentally considers the strength of relationships between nodes and takes into account the varying importance of connected neighbors, measured by the potential influence of the edges) to refine the coarse-grained judgment of the k-shell method. This improvement compensates for the flaw that neighbors contribute equally, resulting in a more precise identification, as shown in Equation **(3).**

$$WK(i) = \sum_{j \in N_i} I_{ij} k_s(j) + \sum_{j \in N_i} w_{ij} \tag{3}$$

where I_{ij} represents the influence coefficient of edges between nodes i and j, as shown in Equation **(4)**. $k_s(j)$ represents the level in which j is after k-shell decomposition. N_i represents the set of all neighbors of node i. w_{ij} is the weight of edges between nodes i and j. as shown in Equation **(5)**.

$$I_{ij} = \frac{|N_i \cap N_j| + 1}{|N_i \cup N_j| + 1} \tag{4}$$

where N_i and N_j represent the set of neighboring nodes of node i and node j, $N_i \bigcap N_j$ represents the same neighbors of nodes i and j, and $N_i \bigcup N_j$ represents the total neighbors of i and j and does not include nodes i and j.

$$w_{ij} = K_i + K_j \tag{5}$$

where K_i and K_j represent the degree values of nodes i and j.

3.3.3. Determination of prior probability by delphi method

The prior probability of the root node was determined through expert consultation, following the Delphi method. Given the lack of extensive statistical data during emergency responses, this approach proves to be efficient for establishing the root node probability in Bayesian Networks (BNs). For networks with 10–20 nodes, two to five rounds of surveys involving three to five experts are typically recommended [50]. The consistency and reliability of the collected data, as indicated in Equation **(6)** and **(7)**, were verified using the coefficient of variation and Cronbach's coefficient, adhering to the criteria of $\alpha > 0.9$ for reliability [51].

$$V_j = \frac{\sigma_j}{\overline{x_j}} \tag{6}$$

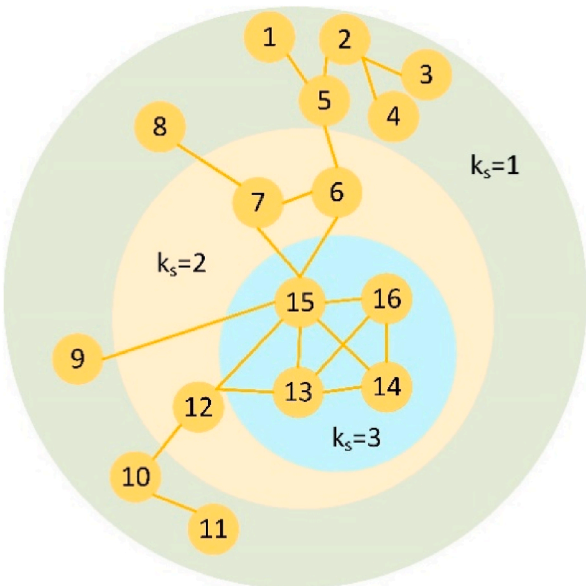


Fig. 4. K-shell decomposition example diagram.

$$\alpha = \frac{n}{n-1}\left[1 - \frac{\sum_{i=1}^{n}\sigma_Y^2}{\sigma_X^2}\right] \tag{7}$$

where V_j σ_j and $\overline{x}_j$ are the variable coefficient of the components, variances of the components, and average of the components. The bigger the V_j is, the more deviations the homologous datum has. α, σ_Y^2 and σ_X^2 are the Cronbach's coefficient Alpha, variances of the total scores, and the variance of the components respectively, and n is the number of components.

3.3.4. Determination of conditional probability table based on weighted degree

The conditional probability distribution of the intermediate nodes is derived by weighting the sum of the probabilities of their root nodes (similarly for the top nodes). The probabilities of intermediate nodes can be expressed by the weighted degree determined by MKS:

$$\chi(j) = \sum_{i \in j} \frac{WK(i)}{\sum WK(i)} \Lambda(i) \tag{8}$$

where Λ(i) denotes the prior probability of the ith root node pointing to the jth intermediate node.

4. Case study

4.1. Description of scaffold collapse emergency scenario

A scaffold collapse accident transpired at a construction site located on Binhe South Road, Minshan District of Benxi City, Liaoning Province on March 17, 2021, as reported by the China Emergency Information Network. The 15-m-high scaffold collapsed around noon, resulting in three workers trapped beneath the rubble. Most of the injured workers suffered traumatic injuries such as fractures, underlining the urgent need for immediate first aid measures like bandaging and bleeding control to avert potential fatalities.

Upon the collapse, the construction site workers quickly raised an alarm and informed the construction manager. At 12:18 p.m., the manager reported the incident to the local emergency management department. Simultaneously, he set up a cordon around the affected area to maintain order, evacuate vehicles, and direct rescue personnel to the specified location. An expert team was convened at 12:30 p.m. to offer recommendations and technical assistance for emergency management plans. At 12:38 p.m., an on-site emergency command was established to partake in the creation of emergency management plans and on-site intervention efforts. Rescuers arrived at the site at 2:00 p.m. and, after surveying the situation, executed a pre-established rescue plan to free the trapped workers. The rescue team was split into three groups: the first to maintain order on-site, the second to clear and cut the local collapse, and the third to rescue the trapped workers. The trapped workers were successfully rescued by 2:50 p.m., promptly given first aid by the medical team on site, and then transported to the hospital. An investigation team was formed at 3:10 p.m. to ascertain the cause of the accident and carry out the required clean-up efforts post-collapse.

4.2. Construction of the functional resonance analysis method model

4.2.1. Identification of functions and variabilities

This study undertakes an investigation of the emergency response process for a scaffold collapse at a construction site, employing the FRAM methodology as detailed in **Section 3.1**. Additional data was obtained through discussing with six experts in emergency management, whose profiles are summarized in Table 4.

Two rounds of expert discussions were held to finalize the list of 20 functions involved in the scaffold collapse emergency response

Table 4
Information for the experts.

Expert	Age	Occupation	Specialty Area	Job tenure	Project Experience
1	48	Professor in University	Engineering Management	20 years in academia	8 major emergency management projects and 4 research papers, focusing on risk assessment and mitigation strategies
2	50	Professor in University	Emergency Management	22 years in academia	Led a research team in 8 emergency management projects, with a focus on disaster preparedness and response planning
3	44	Professor in University	Emergency Management	18 years in academia,	Contributed to 6 safety-related projects and obtained 2 invention patents, emphasizing on structural safety and resilience planning
4	40	Professor in University	Management Science and Engineering	14 years in academia	Participated in 6 safety-related projects and published 2 research papers on community emergency safety
5	52	Senior Engineer	Disaster Prevention and Mitigation	26 years in construction industry	Obtained 51 software copyrights, 3 invention patents, and participated in the drafting of 2 local standards in the field of construction safety
6	41	Construction Project Manager	Construction Safety Management	16 years in construction site	Oversaw safety protocols in 8+ construction projects, ensuring compliance with emergency management standards

process, as presented in Table 5. During the first round, we identified these functions through a thorough analysis of the "Essentials of Emergency Management for Safety Production in 2018″ issued by China's Ministry of Emergency Management and the "Emergency Rescue Disposal of Building Construction Collapse Accidents" published by the China Emergency Information Network, in conjunction with the expert opinions gathered during the discussion. In the second expert discussion meeting, the emphasis was on recognizing the interconnections between the identified functions and their inherent variability. To ensure a comprehensive understanding, we listed six aspects of each function in Appendix A.

Building on the principles for identifying variabilities of functions discussed in Section 3.1, our study particularly emphasizes the coupling of upstream and downstream functions in this case study. This coupling is determined by performing a holistic analysis of the input, output, precondition, resource, and time, as summarized in Table 5. The emergency response process starts with Alarm of accident (coded as F1) and concludes with Resuming construction activities gradually (coded as F20), signaling the removal of hazards and hidden danger.

4.2.2. Functional resonance analysis method model of scaffold collapse scenario

By employing the principles of FRAM, the functional descriptions provided in Appendix A, and the identified couplings outlined in Table 5, we synthesized these elements using the FRAM Model Visualization (FMV) tool. This led to the creation of a customized FRAM model specifically tailored to our case study, as depicted in Fig. 5.

4.3. Development of the Bayesian Network model

According to the analysis in **Section 3.2**, the resilience of the emergency response to a scaffold collapse can be assessed in terms of four key aspects: robustness, redundancy, resourcefulness, and rapidity. To evaluate these aspects, the functions identified in Table 5 were classified accordingly, and the findings are summarized in Table 6. The resulting analysis was then visualized using AgenaRisk, as shown in Fig. 6.

4.4. Determination of node probability

4.4.1. Construction of complex network for topology analysis

The FRAM model can be utilized to portray the scaffold collapse emergency response process as a complex network. Fig. 5 demonstrates this model, where nodes symbolize functional equivalents, and directed links indicate coupling equivalents. This study aims to perform a quantitative analysis of the complex network's topological indicators. Using the MKS method, outlined in Section 3.3.2, we obtain the adjacency matrix of the complex network based on the FRAM model, as exhibited in Appendix B. Utilizing the node information from the adjacency matrix, we sequentially calculate the degree, k_s value, and weighted degree of each node in the complex network, as illustrated in Figs. 7 and 8.

This study presents an analysis of the comprehensive characteristics of the complex network associated with the emergency response process of a scaffold collapse. It can be seen from Fig. 7 (a) and Fig. 7 (b) that a majority of nodes have in and out degrees of 5 or less. To be precise, nodes with $K_{in} = 1$, $K_{out} = 2$, $K_{in} = 2$, $K_{out} = 3$ and $K_{in} = 1$, $K_{out} = 4$ account for approximately 40 % of the total nodes. This pattern suggests that the network demonstrates a high level of activity, which is of critical importance for the analysis of the emergency response process. The k_s values, as demonstrated in Fig. 8(a), reveal that nodes with a k_s value of 4 constitute 65 % of all nodes. This pattern suggests a relatively uniform distribution of influential nodes within the complex network, affirming the

Table 5
Analysis of functional variabilities and couplings.

Function	Description	The coupling of variability
F1	Alarm of accident	F1(O) → F2(I)
F2	Headcount of people worked on scaffolds	F1(O) → F2(O) → F3(I), F12(R)
F3	Emergency response at the accident site	F2(O) → F3(O) → F4(I), F5(I), F7(C), F9(I), F12(P)
F4	Scaffold collapse response plan	F3(O), F19(O) → F4(O) → F6(I), F9(C), F10(C)
F5	Government and emergency department response	F3(O) → F5(O) → F7(I), F9(I)
F6	Intersectoral coordination and linkage	F4(O) → F6(O) → F9(R), F10(R), F11(R), F13(R), F14(R), F15(R), F16(R), F17(R), F18(R)
F7	Establishment of expert group	F3(O), F5(O), F12(O) → F7(O) → F13(C), F14(C), F15(C), F16(C), F17(C)
F8	Collaboration with external forces	F5(O) → F8(O) → F16(R), F17(R)
F9	Establishment of on-site command	F3(O), F4(O), F6(O) → F9(O) → F10(I), F11(I)
F10	Setting up a cordon and evacuating the crowd	F4(O), F6(O), F9(O) → F10(O) → F12(I)
F11	Monitoring of the rescue environment	F6(O), F9(O) → F11(O) → F12(P), F13(P), F14(P), F15(P), F16(P), F17(P)
F12	Searching for trapped people	F2(O), F3(O), F10(O), F11(O) → F12(O) → F7(C), F13(I)
F13	Grid method for dividing accident area	F6(O), F7(O), F11(O), F12(O) → F13(O) → F14(I)
F14	Reinforcement or demolition of the non-collapsed part	F6(O), F7(O), F11(O), F13(O) → F14(O) → F15(I)
F15	The first action to rescue	F6(O), F7(O), F11(O), F14(O) → F15(O) → F16(I)
F16	The second action to rescue	F6(O), F7(O), F8(O), F11(O), F14(O) → F16(O) → F17(I)
F17	The third action to rescue	F6(O), F7(O), F8(O), F11(O), F16(O) → F17(O) → F18(I), F19(I)
F18	Medical assistance	F6(O), F17(O) → F18(O) → F19(C)
F19	Generation of information reports	F17(O), F18(O) → F19(O) → F20(I)
F20	Resuming construction activities gradually	F19(O) → F20(O)

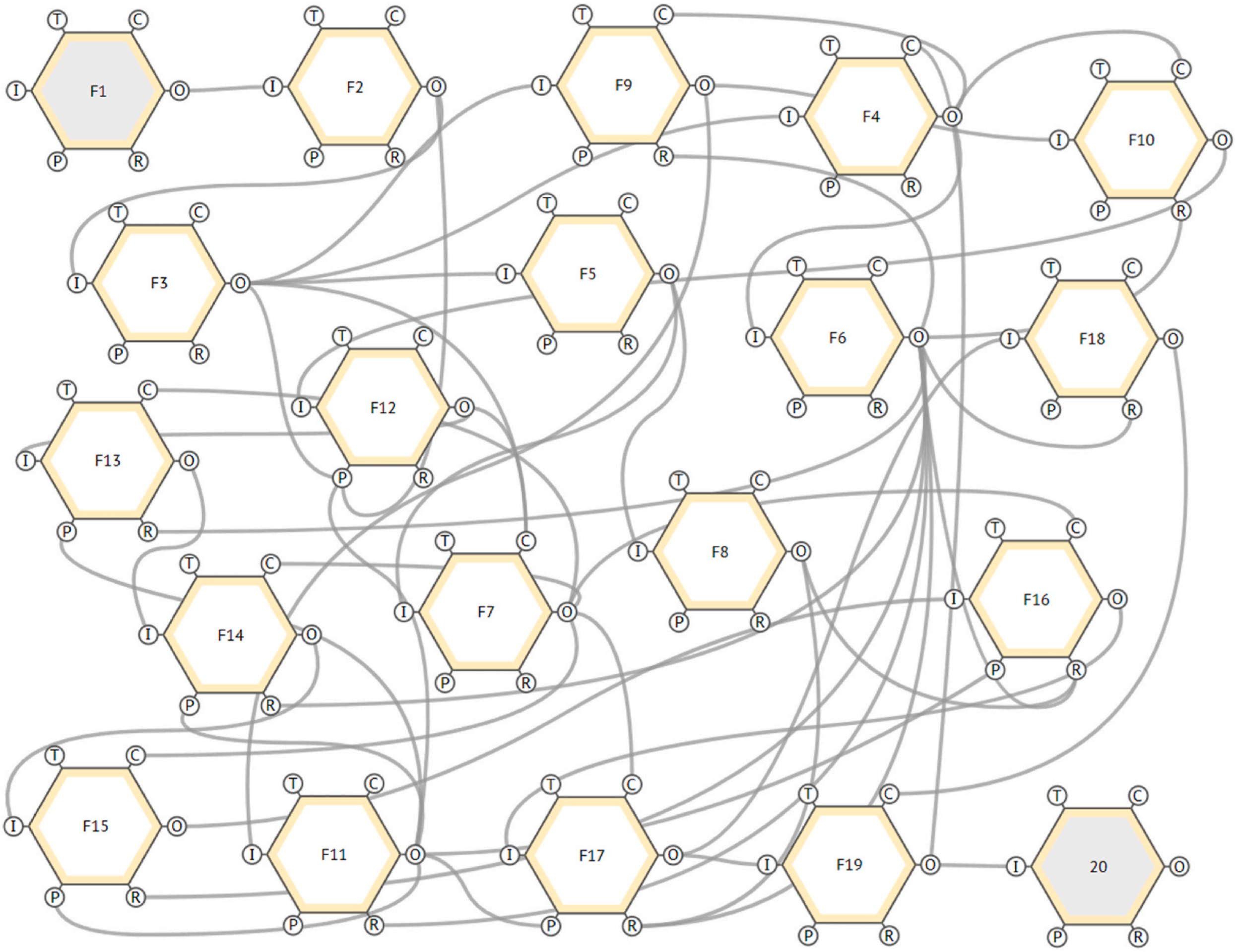


Fig. 5. Visual model of functional resonance analysis method.

Table 6
Categorization of functions.

Resilience aspect	Functions
Robustness	F2, F10, F11, F13, F14
Redundancy	F3, F5, F6, F9, F20
Resourcefulness	F4, F7, F8, F19
Rapidity	F1, F12, F15, F16, F17, F18

reasonable structure of the emergency response process functions distribution.

However, an exclusive macroscopic analysis of degree and k_s values does not sufficiently differentiate the influence of each node in the network. For instance, nodes F13 and F15 have identical degree and k_s values. To address this, we computed the weighted degree using the MKS algorithm (Fig. 8(b)), thereby effectively determining the varying magnitudes of influence for each node in the complex network. Specifically, node F6 (Intersectoral coordination and linkage) has the highest weighted degree (138.219) and displays a high out-degree and low in-degree. This underlines the crucial role of intersectoral coordination and linkage in the emergency response process of scaffold collapse, acting as a prerequisite for most of the subsequent actions. Consequently, enhancing sector coordination and linkage is vital for improving the emergency response process efficiency. Node F12 (Searching for trapped people), while having a higher out-degree and identical in-degree to node F15 (The first action to rescue), has a lower weighted degree (66.035) compared to node F15's 71.384. This indicates that node F15 is interconnected with more critical nodes than F12. Hence, the completion of the initial rescue action (node F15) is contingent upon the completion of various critical tasks, emphasizing its importance in the emergency response process for scaffold collapse. Nodes F7, F11, and F16 also present high weighted degrees, warranting particular attention in actual emergency response scenarios.

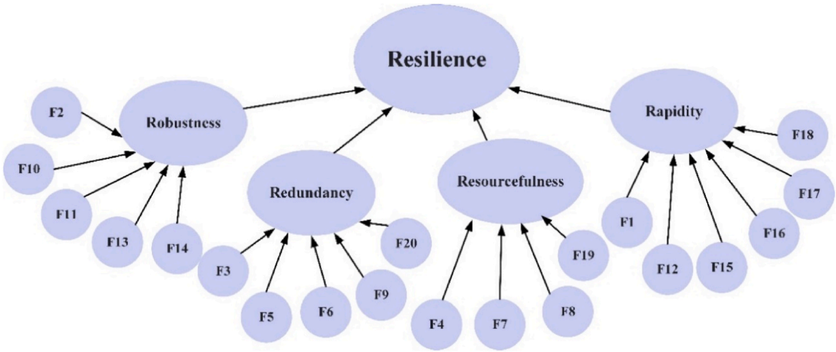
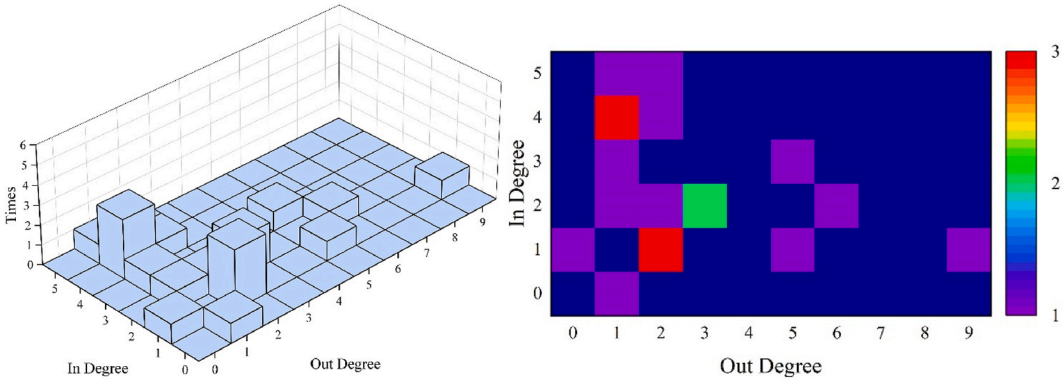
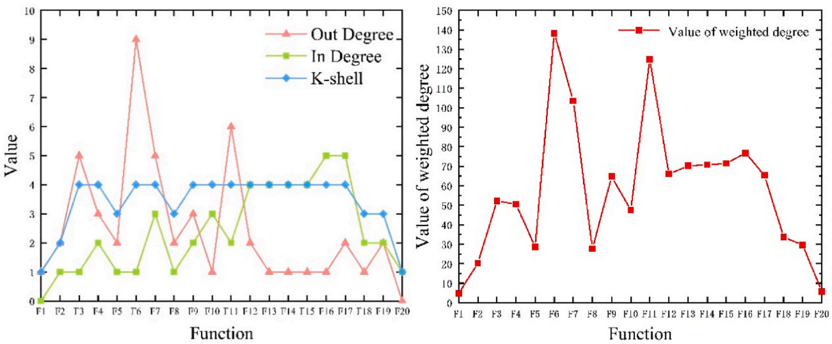


Fig. 6. BN developed for emergency response resilience evaluation.



(a) Degree distribution. **(b)** Phase diagram of degree distribution.

Fig. 7. Node degree of complex network.



(a) Node evaluation from degree and k-shell. **(b)** Node evaluation from MKS.

Fig. 8. Node evaluation from different perspectives.

4.4.2. Determination of prior probability and conditional probability of nodes

(1) Determination of probability distribution for root nodes

In line with the Delphi method detailed in Section 3.3.3, we invited the six emergency management experts, referenced in section 4.2, to complete the proposed Bayesian Network (BN) questionnaire. The prior probabilities for each root node were formulated based on the collective insights of the participating experts. We achieved final consensus through two rounds of expert consultation using the Delphi method.

To evaluate the consistency of the collected data, we employed Cronbach's coefficient alpha. The derived value, using Equation **(6)** and **(7)**, was 0.910, demonstrating a high level of reliability in the data. Table 7 showcases the final outcomes of this study.

Utilizing the root node probability distributions outlined in Table 7, we applied Equation **(8)** to derive the probability distributions for the four intermediate and top nodes. The resulting probability distributions are compiled in Table 8. Following this, the expressions of these probability distributions, as detailed in Table 8, were incorporated into AgenaRisk to facilitate BN simulations.

4.5. *Results and analysis of Bayesian Networks inference*

This section outlines the results of forward propagation, backward propagation, and sensitivity analysis conducted using AgenaRisk. It is worth noting that the resilience values derived from BN simulations have limited physically meaningful results. In this study, we use quantitative resilience to measure the quality of emergency response, with higher resilience values indicating a more effective emergency response performed. Utilizing AgenaRisk software, we developed a basic resilience model for the construction emergency response case study, specifically addressing a scaffold collapse scenario. The model's foundation was established by inputting the prior probabilities of 20 root nodes as delineated in Table 7. We then proceeded to calculate the posterior distribution probabilities for the intermediate and top nodes, employing the probability distribution expressions provided in Table 8. This computation culminated in a final resilience value of 82.872 for the emergency response process, which is graphically represented in Fig. 9.

Considering the innovative nature of the model and the paucity of quantitative analyses in the domain of construction emergency response, a one-sample *t*-test was conducted. This test aimed to determine if a statistically significant difference existed between the proposed model and the conventional expert scoring method, thereby evaluating the model's validity. A group of 30 experts and staff members was convened to assess the resilience of the emergency response process. The one-sample *t*-test was applied to compare these expert assessments with the model's output. According to the results, as shown in Table 9, with a p-value exceeding 0.05, we establish that there is no substantial statistical difference between the proposed modeling approach and the expert scoring method, validating the model's robustness.

4.5.1. *Forward propagation analysis*

BNs provide a notable capability for propagation analysis, allowing the transmission of evidence impact throughout the network. Forward propagation analysis, a type of causal investigation, involves performing predictive calculations by successively transferring the resulting marginal distribution from a node to its associated sub-node. Our study devised four scenarios for forward propagation analysis, assigning false states to four critical nodes with the highest influence in the emergency response process based on their weighted degrees: F6 (Intersectoral coordination and linkage), F7 (Establishment of expert group), F11 (Monitoring of the rescue environment), and F16 (The second action to rescue). Scenario 1 reflects the failure of F6, leading to increased redundancy and resilience loss. Scenario 2 depicts the concurrent failure of F6 and F7, causing a drop in resilience from 82.872 % to 66.908 %. Scenario 3 models the simultaneous failure of F6, F7, and F11, further reducing resilience to 57.676 %. Scenario 4, which represents the failure of all four critical nodes, has a profound negative impact on resilience, with the emergency response process's resilience decreasing to 51.826 %. The outcomes from these scenarios are presented in Table 10, and each case's forward propagation analysis is illustrated in Fig. 10. These analyses underscore the essential nature of sustaining the functionality of these four critical nodes for emergency response process resilience. The failure of any of these nodes can substantially diminish the system's emergency handling capacity, underscoring the need to identify vulnerabilities and reinforce the functionality of relevant nodes to preserve the highest level of resilience in emergency response scenarios.

4.5.2. *Backward propagation analysis*

Back propagation, a distinctive feature of BNs, facilitates hypothesis analysis by establishing an observed value for a specific target variable, then calculating the ancestral variable's marginal probability by reversing the successor variable's impact throughout the network. In this case study, assigning a resilience value of 100 % (as depicted in Fig. 11) triggers an elevation in redundancy, resourcefulness, robustness, and rapidity from 77.129 % to 82.530 %, 79.812 %–83.378 %, 86.179 %–90.340 %, and 82.872 %–

Table 7
The prior probabilities of root nodes.
(2)Determination of probability distribution for intermediate nodes and top node

Node	Prior probabilities		Node	Prior probabilities	
	Ture	False		Ture	False
F1	0.794	0.206	F11	0.852	0.148
F2	0.790	0.210	F12	0.866	0.134
F3	0.804	0.196	F13	0.824	0.176
F4	0.814	0.186	F14	0.898	0.102
F5	0.816	0.184	F15	0.896	0.104
F6	0.732	0.268	F16	0.878	0.122
F7	0.800	0.200	F17	0.798	0.202
F8	0.630	0.370	F18	0.918	0.082
F9	0.800	0.200	F19	0.922	0.078
F10	0.920	0.080	F20	0.904	0.096

Table 8
Probability distribution expression.

Node	Expression
Robustness	0.0608F2+0.1425F10 + 0.3743F11 + 0.2103F13 + 0.2121F14
Redundancy	0.1803F3+0.0988F5+0.4773F6+0.2237F9+0.0199F20
Resourcefulness	0.2392F4+0.4896F7+0.1312F8+0.1400F19
Rapidity	0.0147F1+0.2077F12 + 0.2246F15 + 0.2416F16 + 0.2056F17 + 0.1058F18
Resilience	0.2895 Robustness+0.2513 Redundancy+0.1834 Resourcefulness+0.2758 Rapidity

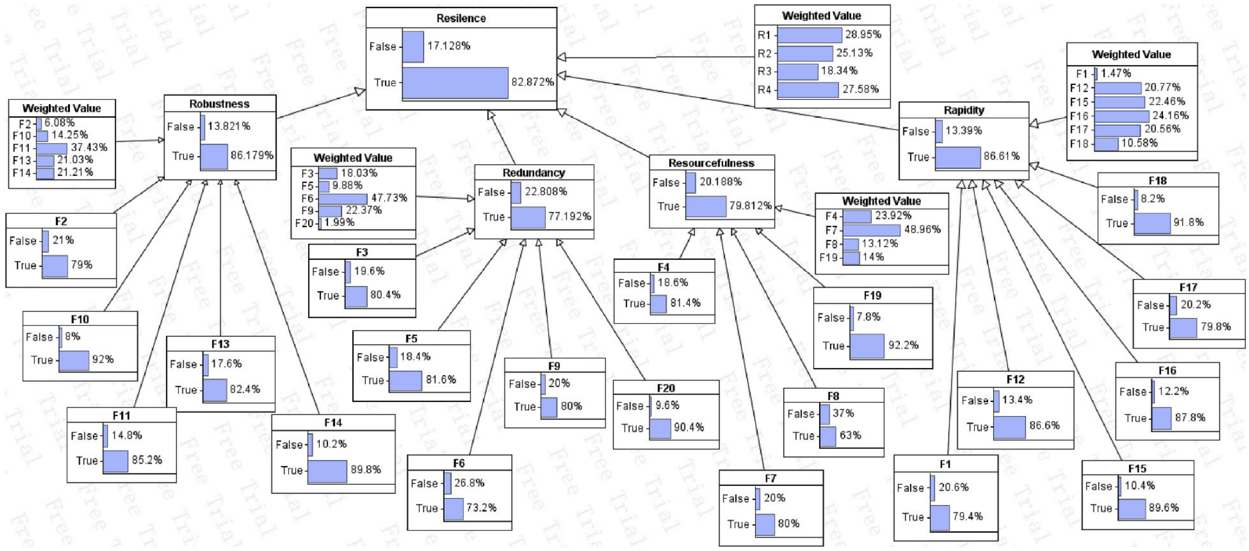


Fig. 9. Basic model of the BN.

Table 9
Results of one-sample *t*-test.

Name	Comparison	Mean	Min	Max	SD	95 % CI of Diff	t	p	Cohen's d
Resilience	82.872	81.11	68.7	96.4	6.697	−4.256~0.732	−1.445	0.159	0.264

Table 10
Different cases for forward propagation analysis.

Scenario	F6	F7	F11	F16	Redundancy (%)	Resourcefulness (%)	Robustness (%)	Rapidity (%)	Resilience (%)
Basic	–	–	–	–	77.192	79.812	86.179	86.610	82.872
1	false	–	–	–	42.253 (↓)	79.812	86.179	86.610	74.427 (↓)
2	false	false	–	–	42.253	40.644 (↓)	86.179	86.610	66.908 (↓)
3	false	false	false	–	42.253	40.644	54.289 (↓)	86.610	57.676 (↓)
4	false	false	false	false	42.253	40.644	54.289	65.397 (↓)	51.826 (↓)

90.470 %, respectively. Additionally, diverse analyses can be conducted for various intended outcomes. Notably, rapidity demonstrates the most significant sensitivity to alterations in system resilience within the emergency response process, as it exhibits the most substantial increase of 7.598 %. This observation underscores the priority to address rapidity-related functions when striving for rapid improvement in the emergency response process's resilience. Furthermore, this suggests a swift decline in the emergency response system's resilience when rapidity-associated functions fail.

4.5.3. Sensitivity analysis

Sensitivity analysis assesses the effectiveness of expert constructed models by providing visual depictions of nodes that exert significant influence on selected target nodes within the BN. In this study, 20 root nodes are selected as sensitive nodes to influence the target node of emergency response resilience. The sensitivity report, illustrated in a tornado graph (Fig. 12), reflects that the longer the blue bar in the graph, the more the node is susceptible to changes in resilience level. Nodes F6 (Intersectoral coordination and linkage)

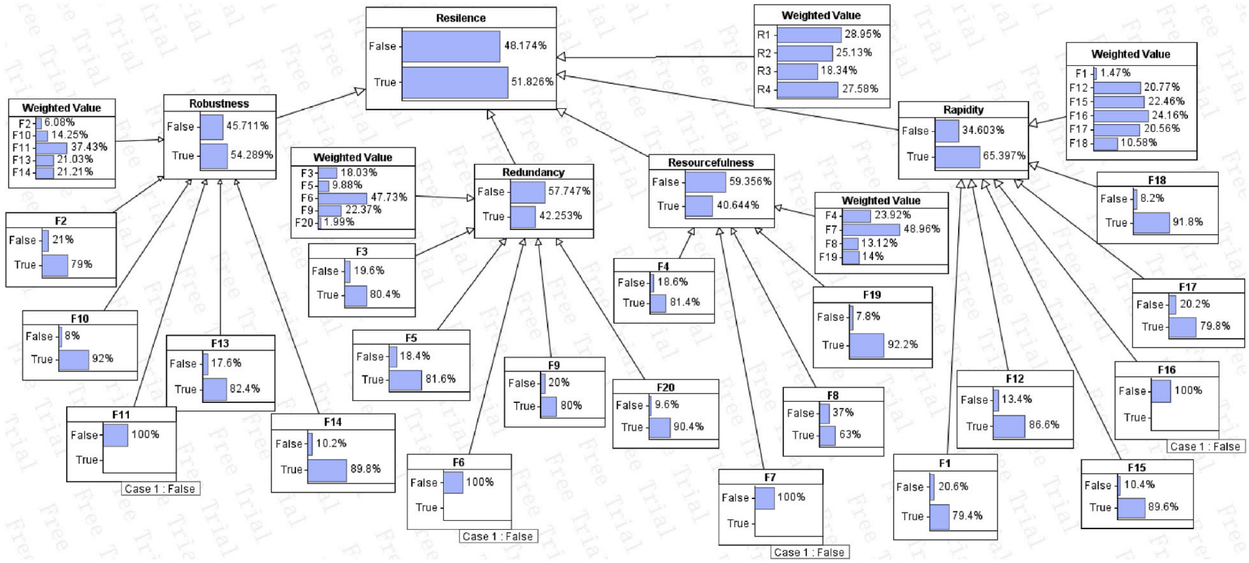


Fig. 10. Forward propagation analysis of the BN.

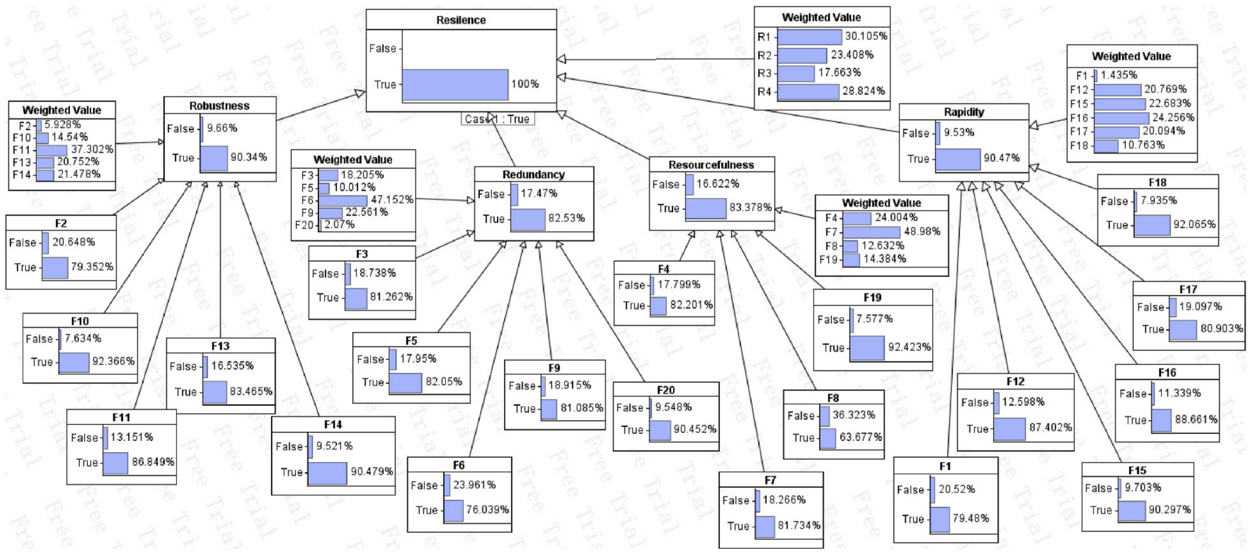


Fig. 11. Backward propagation analysis of the BN.

and F11 (Monitoring of the rescue environment) were observed to have the most substantial impact on emergency response process resilience. The probability of resilience fluctuated from 0.741 (when F6 is false) to 0.861 (when F6 is true) with a change rate of 16.2 %, and from 0.738 (when F11 is false) to 0.845 (when F11 is true) with a change rate of 14.5 %. Therefore, augmenting intersectoral coordination and linkage and enhancing monitoring of the rescue environment greatly affect the improvement of emergency response resilience. Fundamental rescue operations relating to people rescue in the emergency process, such as nodes F7, F9, F12, F13, F14, F15, F16, and F17, also played a significant role. Conversely, nodes F2, F5, F8, F18, and F19 exhibited limited sensitivity range and exerted a relatively low impact on resilience. Lastly, nodes F1 and F20, the beginning and end nodes of the emergency response process, though less sensitive, warrant considerable attention. A timely alarm for an accident is a prerequisite for all emergency response activities, and the resumption of construction activities is the ultimate objective of emergency response.

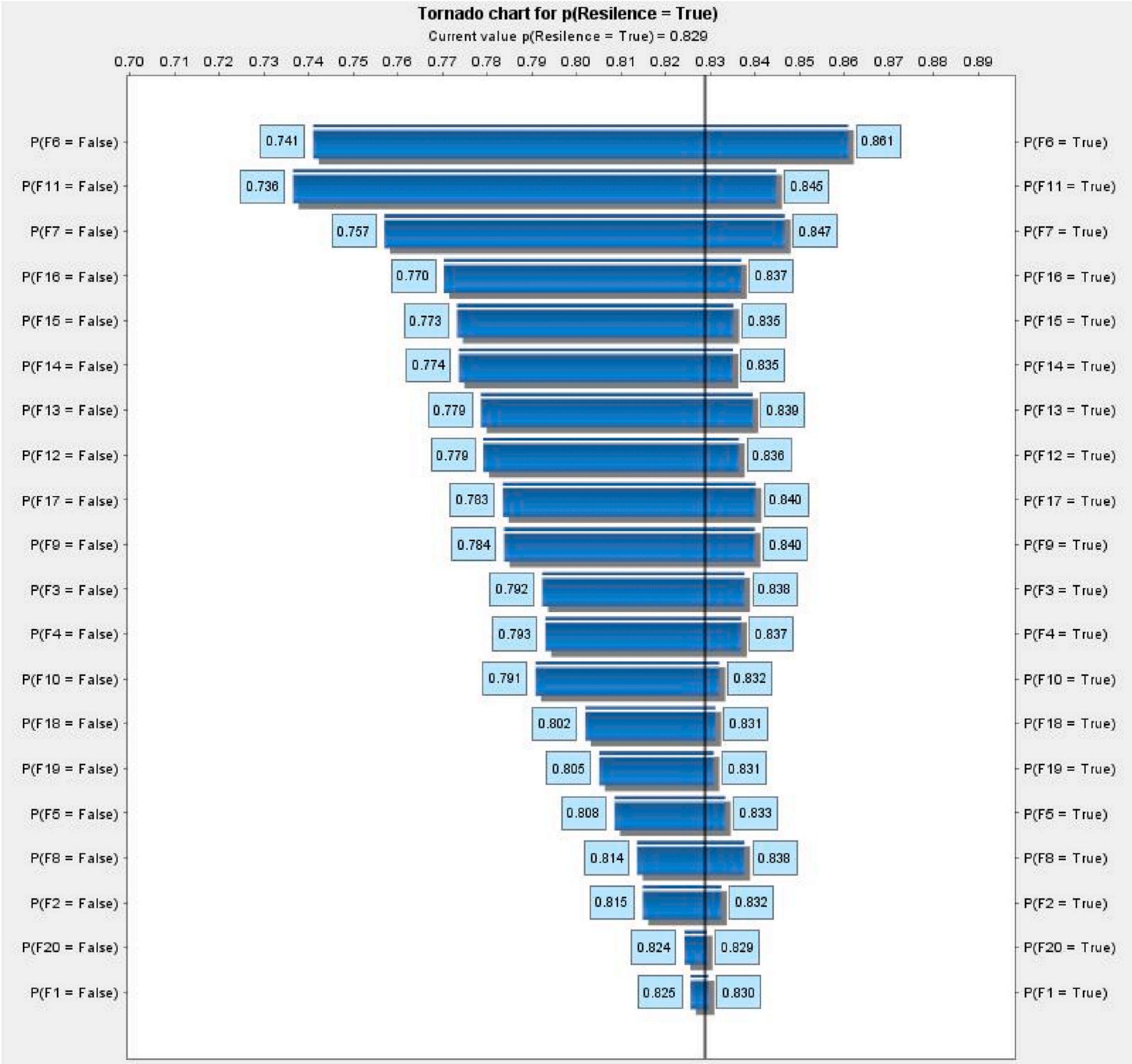


Fig. 12. Sensitivity analysis of BN.

5. Conclusion and future work

5.1. Conclusion

The inherent complexity of construction systems in emergency scenarios often leads to significant uncertainty. In response to this challenge, our study embraces the concept of resilience as a fresh perspective for emergency response, and develops an innovative and comprehensive model based on this idea. This model effectively integrates the Functional Resonance Analysis Method (FRAM), the Modified K-Shell (MKS) Decomposition Algorithm, and Bayesian Networks (BNs). Its primary aim is to fill the quantitative research gaps in emergency response, while also reducing the potential biases that may arise from traditional expert-driven methods. To demonstrate the practicality and effectiveness of our model, we applied it to a real-life emergency scenario—a scaffold collapse. This application not only demonstrates the model's effectiveness and utility but also provides a valuable tool for emergency management professionals. Through this case study, we can draw the following conclusions:

(1) The case study brings to light the paramount importance of F6 (Intersectoral coordination and linkage) within the emergency response process. Characterized by high out-degree and weighted degree values, F6 stands out as a critical prerequisite and foundational element for the execution of various emergency actions. Enhanced communication and coordination across

departments facilitate the identification of gaps, optimization of efforts, and strategic allocation of resources. This collective improvement culminates in an elevated efficacy of emergency operations. In addition to its integral role, F6 is identified as the most sensitive function in the emergency response process, playing a vital role in determining the resilience level of the system. Any shortcomings in intersectoral coordination and linkage can drastically reduce the redundancy of the emergency response process, ultimately resulting in a diminished resilience.

(2) The case studies demonstrate the critical importance of rapidity in emergency response resilience, elucidating how the resilience of the emergency response system can experience a precipitous decline when functions associated with rapidity are compromised. The capacity for rapid response is crucial, as it can be the determining factor in the extent of the consequences, which may vary from life-and-death situations to disparities between minor and major incidents. Given these stakes, it is essential to prioritize functions related to rapidity, thereby strengthening the resilience of the emergency response process.

(3) This case study elucidates that rescue operations demand substantial time investment, encompassing three distinct phases: F15 (The first action to rescue), F16 (The second action to rescue), and F17 (The third action to rescue). Additionally, it highlights that functions integral to rescue operations, such as F18 (Medical assistance), are intricately linked with rapidity. Given these insights, it becomes imperative to prioritize and enhance rescue operations at both operational and practical levels. By accelerating rescue efforts, we can significantly improve the overall resilience of the emergency response system.

5.2. Future work

This study serves as a valuable reference for emergency managers operating within the construction industry. However, there is room for further refinement and enhancement. A notable area for improvement is the representation of the emergency response process's dynamic nature, which is currently inadequately and insufficiently captured. To address this, we propose enriching the FRAM model by incorporating a temporal dimension, utilizing historical data to extend the timeline of the functions. The incorporation of this time aspect, followed by an analysis using dynamic Bayesian Networks (BNs), would enable a more comprehensive and nuanced exploration of the interactions between variables, as well as their evolution over time. Ultimately, this approach would facilitate a more complete understanding of the system's resilience, contributing significantly to the field.

Data availability statement

Data will be made available on request.

CRediT authorship contribution statement

Zihao Guo: Writing – review & editing. **Jianjun She:** Resources, Funding acquisition, Conceptualization. **Zhijian Li:** Methodology, Investigation, Data curation. **Jiewen Du:** Supervision, Investigation, Formal analysis. **Song Ye:** Software, Resources.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Description of the Six Aspects of Each Function

Item	Function	Input	Output	Precondition	Control	Resource	Time
F1	Alarm for scaffold collapse	Scaffold collapse occurs	Notification sent to construction manager	Monitoring equipment and capacity	Worker awareness and training	Alarm and communication infrastructure	Not applicable
F2	Headcount of people who worked on scaffolds	F1(O)	Determination of the number of trapped individuals	Personnel documentation and records	Not applicable	Communication devices	
F3	Emergency response at the accident site	F2(O)	1. Determination of the collapse location and potential impact area 2. Reporting of accidents	Emergency training and preparedness	Not applicable	Personal protective equipment	

(*continued on next page*)

(*continued*)

Item	Function	Input	Output	Precondition	Control	Resource	Time
F4	Scaffold collapse response plan	F3(O2)	Determination of appropriate emergency plans	Prepared emergency plan	F19(O1)	National or regional regulations	
F5	Government and emergency department response	F3(O2)	Convening of an emergency meeting	Considerable hazards exist due to the collapse	Not applicable	Communication devices	
F6	Intersectoral coordination and linkage	F4(O)	Mobilization of personnel and resource	Coordination mechanism	Not applicable	Transportation and logistics	
F7	Establishment of an expert group	F5(O)	Development of a professional rescue plan	Coordination mechanism	F3(O1) F12(O)	Professionals	
F8	Collaboration with external forces	F5(O)	Increase in rescue resources	Not applicable	Not applicable	Engagement of stakeholder	
F9	Establishment of on-site command	F3(O1)	On-site command and decision-making	Emergency training and preparedness	F4(O)	F6(O)	
F10	Setting up a cordon and evacuating the crowd	F9(O)	Reduction of potential risk and hazard	Emergency training and preparedness	F4(O)	F6(O)	
F11	Monitoring of the rescue environment	F9(O)	Potential hazards are monitored at safe levels for emergency operation	Monitoring equipment and capacity	Not applicable	F5(O)	
F12	Searching for trapped individuals	F10(O)	Determination of the location of trapped individuals	F3(O1) F2(O) F11(O)	F7(O)	Professional equipment	
F13	Grid method for dividing accident area	F12(O)	Rescue operations in divided sections	F10(O)	F7(O)	F6(O)	
F14	Reinforcement or demolition of the non-collapsed part	F13(O)	Prevention of secondary collapse	F10(O)	F7(O)	F6(O)	
F15	The first action to rescue	F14(O)	Cleaning up partial collapse objects	F10(O)	F7(O)	F6(O)	
F16	The second action to rescue	F15(O)	Cleaning up larger collapse objects by crane	F10(O)	F7(O)	F6(O) F8(O)	
F17	The third action to rescue	F17(O)	1. All trapped individuals were rescued 2. Site inspection and clean-up	F10(O)	F7(O)	F6(O) F8(O)	
F18	Medical assistance	F17(O1)	Generation of casualty reports	Not applicable	Not applicable	F6(O)	
F19	Generation of information reports	F17(O2)	1. Summary of the accident 2. Responding to society	Not applicable	F18(O)	Data and information of accident	
F20	Resuming construction activities gradually	F19(O)	Elimination of risk and potential hazard	Work resumption permit	Not applicable	Not applicable	

Appendix B. Adjacency Matrix of the Complex Network Based on the FRAM Model

	F1	F2	F3	F4	F5	F6	F7	F8	F9	F10	F11	F12	F13	F14	F15	F16	F17	F18	F19	F20
F1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
F2	1	0	1	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0
F3	0	1	0	1	1	0	1	0	1	0	0	1	0	0	0	0	0	0	0	0
F4	0	0	1	0	0	1	0	0	1	1	0	0	0	0	0	0	0	0	1	0
F5	0	0	1	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0
F6	0	0	0	1	0	0	0	0	1	1	1	0	1	1	1	1	1	1	0	0
F7	0	0	1	0	1	0	0	0	0	0	0	1	1	1	1	1	1	0	0	0
F8	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0
F9	0	0	1	1	0	1	0	0	0	1	1	0	0	0	0	0	0	0	0	0
F10	0	0	0	1	0	1	0	0	1	0	0	1	0	0	0	0	0	0	0	0
F11	0	0	0	0	0	1	0	0	1	0	0	1	1	1	1	1	1	0	0	0
F12	0	1	1	0	0	0	1	0	0	1	1	0	1	0	0	0	0	0	0	0
F13	0	0	0	0	0	1	1	0	0	0	1	1	0	1	0	0	0	0	0	0
F14	0	0	0	0	0	1	1	0	0	0	1	0	1	0	1	0	0	0	0	0
F15	0	0	0	0	0	1	1	0	0	0	1	0	0	1	0	1	0	0	0	0
F16	0	0	0	0	0	1	1	1	0	0	1	0	0	0	1	0	1	0	0	0
F17	0	0	0	0	0	1	1	1	0	0	1	0	0	0	0	1	0	1	1	0
F18	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	1	0	1	0
F19	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	1
F20	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0

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