Early Warning of Safety Risks in Prefabricated High-Rise Construction

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Abstract. As intelligent construction technology advances in the field of high-rise prefabricated construction, there has been a notable improvement in the level of construction safety management. However, construction safety incidents, especially those related to unsafe behaviors of construction personnel, still occur and are a key factor affecting the overall safety level. In response to this situation, this study collected 100 cases of safety incidents in high-rise prefabricated construction in China and refined them through an improved Human Factors Analysis and Classification System (HFACS) framework. This framework was used to deeply analyze the root causes of unsafe behaviors in high-rise prefabricated construction, constructing a structural system that includes multiple levels of influencing factors. By employing expert interviews and qualitative analysis methods using the Interpretive Structural Modeling (ISM), the intrinsic connections between influencing factors at different levels were revealed, further refining the interaction mechanisms of risk factors. The study developed a Bayesian Network (BN) model that reflects the factors influencing unsafe behaviors of construction personnel. The study shows that the probabilities of operator misjudgment, poor workspace planning, and machine-related threats are 29%, 30%, and 26%, respectively. Particularly noteworthy is that among the top-level influencing factors, government regulation and policy enforcement have the most significant effect on standardizing the behaviors of construction enterprises. Sensitivity analysis shows that these have the highest impact, highlighting the central role of policy orientation and legal enforcement in preventing unsafe construction behaviors.

Keywords: Safety Engineering; Prefabricated Construction; Risk Analysis and Prediction; Bayesian Network

1 INTRODUCTION

Assembly building is an emerging trend with advantages such as energy conservation, environmental protection, short construction cycles, and high degree of mechanization.

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Scientific evaluation of the installation risks of prefabricated components and the implementation of preventive measures are crucial to ensuring construction safety, improving the quality of construction projects, and safeguarding the safety of workers.

In recent years, although research on assembly building has primarily focused on construction safety and quality, exploration of specific risks in high-rise construction has also been increasing[1]. Research has shown that by improving traditional Bayesian networks and integrating cloud models[2], can significantly improve the accuracy of risk assessment and has been successfully applied to safety evaluations in high-rise construction. Other studies have covered the identification of risk factors affecting safety in high-rise construction through the entire modular system[3], constructing a comprehensive evaluation index system. These studies utilize advanced mathematical tools such as C-OWA operators and ABC analysis for risk grading, further refining the granularity of risk management[4]. There are also studies that combine structural entropy weight theory with credibility measurement, created new models for scientifically assessing construction risks[5]. Furthermore, some research leverages dynamic fuzzy theory to visually demonstrate the changing trends of risks over time, which strongly advances both the theoretical and practical development of high-rise construction risk assessment. However, given the multitude of factors and complex interrelationships involved in high-rise construction, current assessment methods mostly rely on qualitative analysis, facing issues such as uncertainty, fuzziness, and strong subjective judgment dependence. This limits their comprehensive adaptability to the characteristics of high-rise construction in assembly buildings. Building upon this foundation, the integration of British assembly building with climate aims to address these challenges and achieve the goal of risk assessment[6]. The integration of interdisciplinary theories and technologies is gradually optimizing the method system of high-rise construction risk assessment, with the aim of constructing a safety risk prevention and control framework that is more accurate and closely aligned with practical operational needs.

Given this, the paper constructs an analytical model based on HFACS theory and fuzzy Bayesian networks. It applies an explanatory structural model to identify the causal relationships of installation construction risk factors in assembly buildings and transforms it into a Bayesian network model. Additionally, it improves subjective evaluation by introducing an enhanced similarity aggregation method. The rationality and superiority of this model are verified to reduce the likelihood of high-rise construction risks occurring in assembly buildings.

2 FUZZY BAYESIAN-BASED RISK WARNING METHOD

2.1 Risk Identification

Data from the last decade was collected from websites of administrative bodies such as the State Administration of Work Safety, the Ministry of Housing and Urban-Rural Development, and various provincial and municipal authorities, encompassing 100 reports on construction accidents Important factors were extracted from summaries of causes of accidents in prefabricated construction and are summarized into four main points as shown in Table 1:

Table 1. Causes of Modular Construction Accidents

Level	Integrative Factors	Specific Manifestations
Deficiencies in Government Regulation and Policy Enforcement A1	Compliance IsuesA11	The design schemes, production of prefabricated components, transportation, hoisting, and other processes do not comply with relevant national regulations and standards, nor do the construction processes meet regulations.
	Lack of Supervisory Mechanism A12	The construction site lacks effective quality control and safety inspection systems, resulting in potential risks not being identified and corrected in a timely manner.
Organizational Level Influencing Factors A2	Improper Installation Setup A21	There may be irregularities in the operation during the assembly, connection, and fixing of prefabricated components, such as inaccurate positioning of embedded parts, substandard welding quality, and improper sealing and waterproofing treatments.
	Insufficient Trust in Workers A22	Construction workers may lack a thorough understanding of the new prefabricated construction technology and safety regulations, leading to insufficient confidence in its safety, which could affect the precision and accuracy of operations.
	Insufficient Emergency Plans and Drills A23	In the event of emergencies, the lack of targeted emergency plans or irregular emergency drills may exacerbate the consequences of accidents.
Prerequisites for Unsafe Behavior A3	Human Operational Error A31	Operational errors resulting from inadequate worker training, fatigue, lack of concentration, etc., such as improper securing of safety ropes during high-altitude edge operations and incorrect tool usage.
	Lack of Safety Awareness A32	The generally low safety culture among construction teams, coupled with a lack of essential knowledge in safety production and self-protection awareness, increases the likelihood of accidents.
	Diverse Environmental Influences A33	Uncontrollable environmental factors such as weather changes, site constraints, and interference from cross operations affect construction safety.
Unsafe Behavior of Construction Personnel A4	Operator Error Judgment A41	In complex construction environments, operators may encounter safety hazards due to lack of experience or incorrect judgment, particularly when operating heavy machinery or adjusting component positions.
	The workspace planning is unreasonable (A42).	Chaotic construction site layout and unreasonable placement of high-altitude work platforms result in construction workers operating in cramped or unsafe conditions, increasing the risk of falls and other safety incidents.
	The threat of machine-added forces (A43).	Large lifting equipment or other machinery may exert additional forces on prefabricated components during operation, potentially leading to structural damage or personnel injuries if not properly controlled.

2.2 Establishing an Improved HFACS Framework for High-Rise Construction Risks in Prefabricated Buildings.

Within construction enterprises, there are various manifestations of managerial oversight, making decisions and actions by enterprise managers crucial. For example, managers intervene directly in production activities by issuing construction instructions; however, any decision-making errors could lead to significant safety risks. The established improved HFACS framework model is shown in Figure 1：

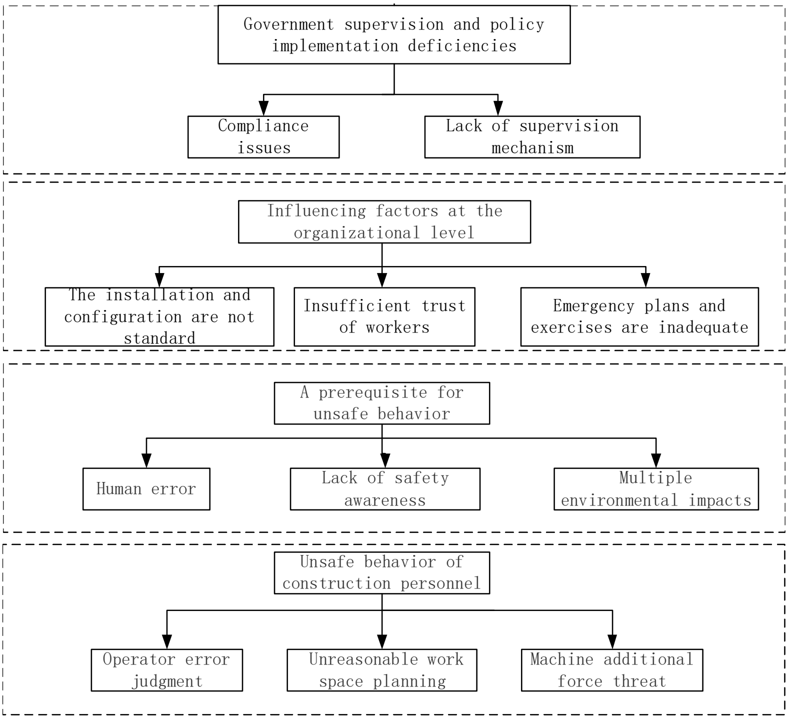

Fig. 1. HFACS Framework Model for Risks in High-rise Modular Construction

2.3 Constructing a Hierarchical Structure of Prefabricated Building High-Rise Construction Risks Based on ISM.

The explanatory structural model ISM (Interactive Safety Management) [13] is an advanced safety management approach that emphasizes implementing dynamic, real-time, and all-staff participation safety management strategies in the workplace. ISM can analyze not only the relationships between adjacent factors but also the relationships between factors on a horizontal level. Let the adjacency matrix be F, a_{ij} is an element in F, where:

$$a_{ij} = \begin{cases} 0 - \mathit{Factor}\ \text{i does not have}\ \mathit{a\ direct\ impact\ on\ factor}\ \text{j} \\ 1 - \mathit{Factor}\ \text{i does not have}\ \mathit{a\ direct\ impact\ on\ factor}\ \text{j.} \end{cases}$$

Let the identity matrix be E, the reachability matrix be m, and construct the ISM adjacency matrix F and Herein, F_{n-1} is the reachability matrix M, and M are defined as follows:

$$F=\begin{vmatrix}0&0&1&1&0&1&0&0&1&1&0\\0&0&0&0&0&1&0&0&1&0&0\\0&0&0&0&0&0&0&0&1&0&0\\0&0&0&0&0&0&0&1&0&0&1\\0&0&0&0&0&0&1&0&0&0&1\\0&0&0&0&0&0&0&0&0&1&0\\0&0&0&0&0&0&0&0&0&1&1\\0&0&0&0&0&0&0&0&0&1&0\\0&0&0&0&0&0&0&0&0&0&0\\0&0&0&0&0&0&0&0&0&0&0\\0&0&0&0&0&0&0&0&0&0&0\end{vmatrix} \tag{1}$$

$$M=\begin{vmatrix}1&0&1&1&0&1&0&0&1&1&1\\0&1&0&0&1&1&0&0&1&1&0\\0&0&1&0&0&0&0&0&1&0&0\\0&0&0&1&0&0&1&0&0&1&1\\0&0&0&0&1&0&0&0&0&0&1\\0&0&0&0&0&1&0&0&0&1&0\\0&0&0&0&0&0&1&0&0&1&1\\0&0&0&0&0&0&0&1&0&1&0\\0&0&0&0&0&0&0&0&1&0&0\\0&0&0&0&0&0&0&0&0&1&0\\0&0&0&0&0&0&0&0&0&0&1\end{vmatrix} \tag{2}$$

Calculate according to Boolean algebra rules M ， as shown below：

$$F_1=(F+E),F_n=(F+E)^n \tag{3}$$

$$F_1=(F+E)\neq F_2\neq\cdots\neq F_{n-1}=F_n \tag{4}$$

2.4 Build a Bayesian Network Model

After determining the logical relationships between events and clarifying their paths through the explanatory structural model (ISM), map each event in the model to the nodes of the Bayesian network one by one, and respectively map the basic events, intermediate events, and top events to the child nodes, intermediate nodes, and parent nodes of the Bayesian network, thus constructing a hierarchical and logically rigorous network structure. Use the professional software tool GeNIe to construct a risk model suitable for prefabricated high-rise construction. The final Bayesian network structure diagram of safety risks is shown in Figure 2 below:

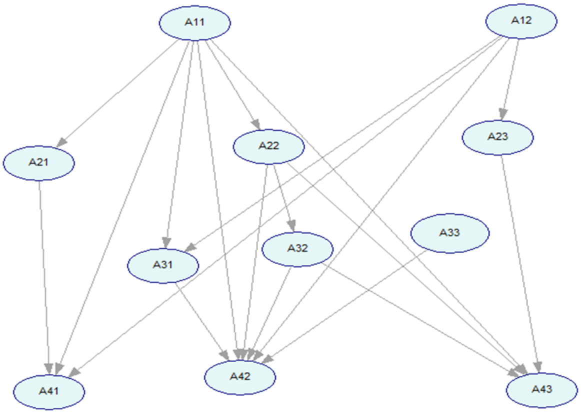

Fig. 2. DBN Network Structure Diagram

2.5 Parameter Learning.

Expert Evaluation of Linguistic Fuzzy Transformation. This paper employs a combined method of fuzzy theory, expert scoring, and actual case data to determine exponential probabilities[7]. This method can eliminate serious biases caused by excessive reliance on historical statistical data, while incorporating practical engineering and expert knowledge, thus improving the accuracy of the final analysis results. This paper references a 7-level linguistic scale to provide experts with scoring standards for risk factors in prefabricated installation construction. The fuzzy intervals corresponding to the 7-level linguistic scale are shown in Table 2.

Table 2. Language variables and corresponding trapezoidal fuzzy numbers

Linguistic Value	Fuzzy Interval			
	a	b	c	d
Very Low （VL）	0	0	0.1	0.2
Low （L）	0.1	0.2	0.2	0.3
Slightly Low （ML）	0.2	0.3	0.4	0.5
Medium （M）	0.4	0.5	0.5	0.6
Slightly High （MH）	0.5	0.6	0.7	0.8
High （H）	0.7	0.8	0.8	0.9
Very High （VH）	0.8	0.9	1	1

Expert Opinions Aggregation. In order to integrate expert opinions and ensure closer proximity to the likelihood of events occurring, this paper adopts an improved Similarity Aggregation Method (SAM). This method fully considers the impact of experts with different weights on the consistency between every two experts, thereby reducing the likelihood of ignoring the opinions of lower-weighted experts and increasing their subjectivity, leading to an increase in error rates.

（1） Determining expert weights

By understanding the professional titles, work experience and education of the experts, the scoring criteria for experts are established as shown in Table 5. Based on the scoring levels in Table 3, the weight scores for each expert are calculated. The method for calculating weights is the ratio of individual expert scores to the total scores of all experts.

Table 3. Expert classification and scoring standard

Standard	Category	Score
Professional Title Levels	Project Manager/Professor	10
	Engineer/Associate Professor	8
	Technician	6
Working Hours	≥20 Years	10
	15-19 Years	8
	10-14 Years	6
Education	PhD	10
	Master's Degree	8
	Bachelor's Degree	6

（2）Determining the consistency between opinions of every two experts.

$$H\left(\tilde{R}_i,\tilde{R}_j\right)=1-\frac{1}{4}\sum_{i=1}^{4}\left|a_m-b_n\right| \tag{5}$$

In equation (5), $\tilde{R}_i$ and $\tilde{R}_j$ are the trapezoidal fuzzy numbers of experts E_i and E_j， $\tilde{R}_i=\left(a_1,a_2,a_3,a_4\right)$， $\tilde{R}_j=\left(b_1,b_2,b_3,b_4\right)$， $H\left(\tilde{R}_i,\tilde{R}_j\right)\in[0,1]$， by comparing the sizes of $H\left(\tilde{R}_i,\tilde{R}_j\right)$, the similarity of opinions between two experts can be determined.

(3) Determining the weighted consistency of expert opinions

$$A_{\mathrm{W}}\left(E_i\right)=\frac{\sum_{j=1}^{n}W\left(E_j\right)\cdot H\left(\tilde{R}_i,\tilde{R}_j\right)}{\sum_{j=1}^{n}W\left(E_j\right)},i\neq j \tag{6}$$

In Equation (6), $W\left(E_i\right)$ and $W\left(E_j\right)$ represent the weights of experts E_i and E_j, respectively. This revised method considers the importance of expert weights and incorporates them into the calculation of weighted consistency, thus enhancing the accuracy of estimates.

(4) Determine the relative consensus of expert opinions

$$A_{\mathrm{R}}\left(E_i\right)=\frac{A_{\mathrm{W}}\left(E_j\right)}{\sum_{i=1}^{n}A_{\mathrm{W}}\left(E_i\right)} \tag{7}$$

(5) Determine the consistency coefficient of expert opinions

$$C_{\mathrm{C}}\left(E_i\right)=\beta\cdot W\left(E_i\right)+(1-\beta)\cdot A_{\mathrm{R}}\left(E_i\right) \tag{8}$$

Equation (8) introduces β（$0\leq\beta\leq1$） as a relaxation factor, critical for balancing relative consistency and expert weights, with an assumed value of β =0.5.

(6) Determine the results of expert opinions

$$\tilde{R} = C_C\left(E_1\right)\cdot\tilde{R}_1 + C_C\left(E_2\right)\cdot\tilde{R}_2 + \cdots + C_C\left(E_n\right)\cdot\tilde{R}_n \tag{9}$$

Determine Node Parameters. After the above processing, the overall fuzzy numbers from all expert opinions can be obtained. Defuzzification is the process of transforming these overall fuzzy numbers into a definite Fuzzy Possibility Score (FPS). In situations of insufficient information, the FPS serves as a prior input along with conditional probabilities to measure the relative risk levels of each node. This paper uses the centroid method for defuzzification, as illustrated in Equation (10).

$$\begin{aligned} S_{\mathrm{FP}} &= \frac{\int_a^b \frac{x-a}{b-a} x dx + \int_b^c x dx + \int_c^d \frac{d-x}{d-c} x dx}{\int_a^b \frac{x-a}{b-a} dx + \int_b^c dx + \int_c^d \frac{d-x}{d-c} dx} \\ &= \frac{1}{3}\frac{(c+d)^2 - cd - (a+b)^2 + ab}{c+d-a-b} \end{aligned} \tag{10}$$

In equation (10), S_{FP} represents the resolved FPS, that is, the Fuzzy Possibility Score.

3 CASE STUDY

3.1 Project Overview

A landmark high-rise residential project, located at the center of a modern urban area, employs advanced prefabricated construction techniques. The building stands approximately 100 meters tall, with a total floor area of about 150,000 square meters, comprising 30 floors designed to house nearly 500 residences. The entire structural body uses prefabricated concrete (PC) components, which are mass-produced in factories to precise design specifications and quality standards, before being transported to the construction site for efficient and organized assembly.

3.2 Determine Model Parameters

Initially, four experts from relevant fields were invited to assess the project, ensuring their evaluations remained uninfluenced by one another to preserve their subjective integrity. The collected data yielded information on expert weights as shown in Table 4：

Table 4. Expert information and weights

Expert	Professional Title Levels	Working Hours	Education	Weight
1	Professor	≥20 Years	PhD	0.283
2	Professor	15-19	PhD	0.253
3	Associate Professor	10-14	PhD	0.211
4	Project Manager	≥20 Years	Master's Degree	0.253

It is assumed that each node can be in one of two states: occurring (State = 1) or not occurring (State = 0). For non-root nodes, given the values of parent nodes, the frequency of states appearing serves as conditional probabilities, with the probabilities for root nodes shown in Table 5：

Table 5. Evaluation opinions and prior probabilities of sub nodes

Nodes	Influencing Factors	State0	State1
A11	Compliance Issues	0.848	0.152
A12	Lack of Supervision Mechanisms	0.677	0.323
A33	Influence of Diverse Environment	0.864	0.136

3.3 Risk Analysis

Forward Reasoning. The calculated probabilities for each node are input into the established Dynamic Bayesian Network (DBN) model (Fig 3.), resulting in a Faulty DBN (FDBN) model without evidence input. The analysis indicates that insufficient emergency plans and drills (A23), improper installation setups (A23), unreasonable workspace planning (A42), and operator error judgments (A41) have higher probabilities of occurrence, posing significant risks during operations, necessitating enhanced preventative measures.

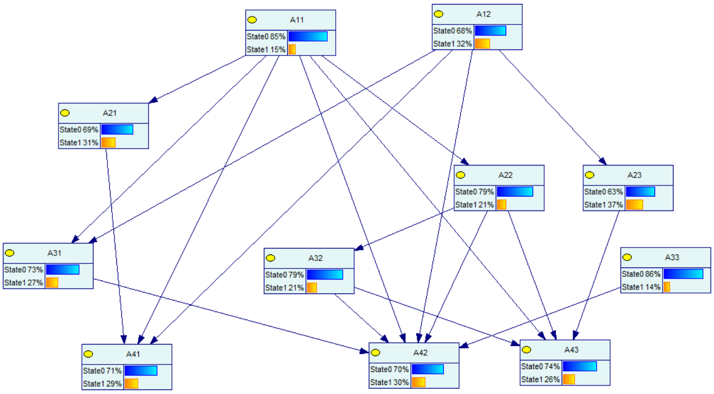

Fig. 3. FDBN model without evidence input

Path Analysis. The Bayesian network model established in GeNIe software can be used to analyze and infer how various factors affect unsafe behavior during the construction of high-rise prefabricated buildings. A41, A42, and A43 serve as two decisive nodes in the model; their states are directly linked to the occurrence of unsafe behavior. When the states of these two nodes are set to "state1 = 100%", the model predicts the occurrence of unsafe behavior, indicating that A41, A42, and A43 might be key factors or starting points of pathways triggering unsafe behavior. Induced pathways are statistically shown in Table 6.

Table 6. Statistical Induction Pathways

Factors	Inducing Pathways
A41	A11(31%)—A21(54%)—A41(100%)
	A11(31%)—A41(100%)
	A12(54%)—A41(100%)
A42	A11(22%)—A31(40%)—A42(100%)
	A11(22%)—A22(28%)—A32(26%)—A42(100%)
	A11(22%)—A42(100%)
	A12(63%)—A42(100%)
	A11(22%)—A42(100%)
	A33(19%)-- A42(100%)
A43	A11(28%)—A22(40%)—A32(38%)—A43(100%)
	A11(28%)—A43(100%)
	A11(22%)—A22(28%)—A43(100%)
	A12(37%)—A23(57%)—A43(100%)

The main risk pathways leading to safety risks in prefabricated high-rise construction are identified as: A11 Compliance Issues (31%) leading to A21 Improper Installation Setup (54%) leading to A41 Operator Error Judgment (100%); A11 Compliance Issues (22%) leading to A31 Human Operational Error (40%) leading to A42 Poor Workspace Planning (100%); A12 Lack of Supervisory Mechanism (37%) leading to A23 Insufficient Emergency Plans and Drills (57%) leading to A43 Machine-related Threats (100%).

Sensitivity Analysis. The values of sensitivity coefficients indicate the impact of each node on the target node. Nodes A41, A42, and A43 are sequentially set as target nodes, and the sensitivity coefficients for related nodes are derived. The calculated sensitivity coefficients are shown in Table 7.

Table 7. Sensitivity Coefficient

	Nodes	Sensitivity Coefficients	Ranking		Nodes	Sensitivity Coefficients	Ranking		Nodes	Sensitivity Coefficients	Ranking
A41	A11	0.177	1	A42	A11	0.082	2	A43	A11	0.135	1
	A12	0.144	2		A12	0.212	1		A12	0.026	5
	A21	0.072	3		A22	0.026	4		A22	0.064	2
					A31	0.023	5		A23	0.054	3
					A32	0.01	6		A32	0.053	4
					A33	0.064	3				

From the table, it can be seen that the sensitivity values for operator error judgment are generally higher than those for machine-related threats, which are higher than those for poor workspace planning. Compliance issues are the most sensitive points for operator error judgment. The lack of supervisory mechanisms is the most sensitive area for poor workspace planning. In summary, whether it is erroneous behavior or environmental factor behavior, the most sensitive points are concentrated in the realm of government supervision. Therefore, the government should pay more attention to the risk of accidents in the construction of prefabricated high-rise buildings, strengthen the supervision of construction safety, enhance legal regulations, and eliminate unsafe behaviors.

4 CONCLUSION

This study focuses on prefabricated construction accidents in China over the past decade or so. Initially, through preliminary research and case analysis, the HFACS framework was improved. The improved HFACS framework was used to identify an indicator system from four aspects: government negligence, organizational influence, prerequisites for unsafe behavior, and the unsafe behavior of construction workers, while the reliability of the revised HFACS framework was validated through evaluator reliability. This indirectly demonstrates the reliability of the system of influencing factors. Subsequently, experts were invited to use the ISM method to construct a hierarchy of influencing factors and establish a BN structure. Finally, the conditional probabilities for each node were calculated based on the statistical frequency of the root nodes, and a Bayesian network diagram was drawn using GeNIe software.

The analysis structure indicates that the probabilities of operator error judgment, poor workspace planning, and machine-related threats are 29%, 30%, and 26% respectively. The main pathways are: Compliance issues leading to improper installation setup leading to operator error judgment; Compliance issues leading to human operational errors leading to poor workspace planning; Lack of supervisory mechanisms leading to insufficient emergency plans and drills leading to machine-related threats. This reveals that issues such as compliance problems, human operational errors, lack of supervisory mechanisms, and insufficient emergency plans and drills require that government departments and organizations strengthen safety supervision.

This study not only provides a reference for establishing and analyzing the framework for research on the probability of risks in prefabricated high-rise construction but also serves as a tool for investigating and analyzing risks in such constructions, which is of significant importance for the safety of prefabricated buildings.

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