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Research on Quantitative Assessment and Dynamic Reasoning Method for Emergency Response Capability in Prefabricated Construction Safety

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Abstract: In response to the common issues of lacking a comprehensive quantitative assessment system and insufficient dynamic understanding of emergency response capability in prefabricated construction safety, this study proposes a research methodology based on decision-making trial and evaluation laboratory (DEMATEL) and fuzzy cognitive maps (FCM) to promote the construction of emergency response capacity. Firstly, a quantitative evaluation indicator system comprising 4 core categories of organizational management, personnel quality, technical measures, and emergency resources, along with 16 main categories, is established using grounded theory and three levels of coding approach. Subsequently, through a combination of expert surveys and quantitative analysis, DEMATEL is employed to unveil the causal relationships and key indicators of the evaluation criteria. Next, the DEMATEL and FCM models are integrated to conduct predictive and diagnostic reasoning analysis based on key indicators. Finally, a case study is conducted to validate the usability and effectiveness of the proposed model and methodology. The results demonstrate that indicators related to organizational management and personnel quality belong to the cause group, while technical measures and emergency resources fall into the effect group. The "completeness of emergency plans" exhibits the most significant influence on other indicators and is also the most influenced indicator by others. Predictive reasoning analysis reveals that well-controlled "emergency organizational structure and procedures" are crucial for enhancing emergency response capacity. Diagnostic reasoning analysis indicates that the improvement of emergency response capability should focus on enhancing the "completeness of emergency plans". The synergistic effect between "emergency organizational structure and procedures" and "completeness of emergency plans" contributes to the enhancement of emergency response capability in prefabricated construction safety. The study holds both theoretical and practical significance for advancing safety management in prefabricated construction. Considering the dynamic coupling of multiple factors will be the primary direction of research in the field of safety management in the future.

Keywords: prefabricated construction; emergency capability; quantitative assessment; dynamic reasoning; DEMATEL; FCM

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1. Introduction

Compared to traditional construction methods, prefabricated construction involves complex and overlapping processes, resulting in frequent safety accidents [1]. Insufficient emergency response capability often leads to escalated risks and amplified losses [2], making the advancement of emergency response capacity a crucial foundation for engineering project management and its systems [3]. Despite this significance, an effective support system for evaluating emergency response capability in prefabricated construction safety is currently lacking, requiring further research into systematically identifying evaluation indicators, quantifying causal relationships, and conducting dynamic predictive and diagnostic reasoning analyses. Therefore, this study holds paramount importance as it investigates the quantitative assessment and dynamic reasoning of emergency response capability in prefabricated construction safety.

In recent years, numerous scholars have explored construction safety emergency management from various perspectives. Ni et al. (2020) [4] integrated the "capability-time-effectiveness" model to comprehensively evaluate the emergency response effectiveness of construction task scheduling and resource allocation. Cheng et al. (2022) [5] employed DEMATEL and entropy weighting methods to study the emergency response capability in subway tunnel construction. However, these studies often focus on static assessments, overlooking the dynamic nature of construction safety emergency response capabilities. Chen et al. (2017) [6] proposed a dynamic evaluation method for emergency response to rainstorm construction accidents based on system dynamics, but the approach has limitations in handling fuzzy information. Additionally, other studies have explored strategies to enhance construction emergency capabilities from risk identification [7], emergency resource allocation [8], and emergency organizational management [9] perspectives. Overall, these studies provide theoretical support and methodological foundations for improving emergency response capability in prefabricated construction safety, which is crucial for preventing accidents and reducing losses. However, the current research mainly concentrates on static quantitative analysis, overlooking the fuzzy representation of emergency capabilities and the dynamic nature of quantitative assessment. Particularly in the theoretical research and management practices of emergency response capability in prefabricated construction safety, there is a lack of research combining dynamic and static quantitative assessment with dynamic reasoning.

Multicriteria methods are used to address multidimensional decision problems, such as AHP (analytic hierarchy process), TOPSIS (technique for order of preference by similarity to ideal solution), and ELECTRE (elimination and choice translating reality). DEMATEL is chosen because it can help analyze causal relationships between factors, contributing to a more comprehensive understanding of decision problems beyond just weighting and ranking.

With the integration of research methodologies and expanding application scenarios, DEMATEL and FCM have been widely used in quantitative assessment and dynamic reasoning [10]. FCM, as a knowledge and data-driven reasoning method, can describe causal relationships and weights among fuzzy concepts, possessing strong dynamic reasoning capabilities [11]. Kosko (1986) [12] first proposed the FCM model, and since then, it has been extensively applied in fields such as social management [13], energy planning [14], and safety assessment [15]. However, accurately identifying the interrelationships between concepts in FCM poses challenges [16]. DEMATEL, on the other hand, can quantify the interrelationships among complex concepts and has the static assessment capability to accurately identify causal relationships [17]. Fontela et al. (1974) [18] first proposed the DEMATEL method, and since then, it has been widely applied in supply chain management [19], product development [20], innovation evaluation [21], and other fields. These studies have demonstrated the feasibility and rationality of DEMATEL and FCM in static causal assessment and dynamic reasoning of concept relationships, providing theoretical foundations and methodological support for the quantitative assessment and dynamic reasoning research of emergency response capability in prefabricated construction safety.

In essence, this paper explores emergency response capability development in prefabricated construction safety, presenting it as a complex system. We propose a quantitative assessment and dynamic reasoning methodology using DEMATEL-FCM. Grounded theory aids in constructing an emergency capability evaluation system. DEMATEL then uncovers causal relationships within this system. The correlation matrix from DEMATEL evolves into the interaction matrix of the FCM model, enabling dynamic predictive and diagnostic reasoning for key indicators. This reveals emergency capability patterns, offering decision-making insights for enhancing prefabricated construction safety.

The rest of this study is organized as follows: In Section 2, research methods such as DEMATEL and FCM are introduced. In Section 3, the study variables are summarized. In Section 4, an improved model of the DEMATEL-FCM is developed. In Section 5, an empirical analysis is described. In Section 6, a research discussion is initiated. In Section 7, the conclusions, innovations, and limitations of this study are summarized.

2. Methodology

2.1. DEMATEL

DEMATEL is a sophisticated tool developed in the 1970s by the Science and Human Affairs Program of the Battelle Memorial Institute [18]. It aids organizations in comprehending and tackling complex, interconnected issues by revealing the relationships and hierarchies among diverse factors [22].

DEMATEL employs graph theory principles to depict and analyze causality and correlations among these elements [23,24]. This methodology unfolds through four key phases: (1) Factor identification—in the first stage, all potentially influential factors are identified, often through brainstorming or other creative techniques. (2) Direct influence matrix construction—this stage involves developing a matrix to assess and numerically represent the direct influence of each factor on all others. (3) Total influence matrix construction—a subsequent step uses an algorithm based on graph theory to calculate the combined effect of each factor, encompassing both direct and indirect influences. (4) Analysis and interpretation the final phase uses the total influence matrix to determine the relative importance of each factor and their interrelationships.

The advantage of DEMATEL lies in its ability to deal with complex interactions between factors and its use of graphical representation for easy result interpretation. Its limitation, however, is the potential introduction of bias due to reliance on expert subjective evaluations.

2.2. FCM

FCMs offer an advanced methodology for understanding and modeling intricate systems [25]. FCMs center around concepts (or nodes, variables) and relationships (edges, connections). Concepts depict system elements, ranging from tangible to abstract, while relationships illustrate causal links between these concepts, with weights assigned to signify their strength and direction [15].

The FCM process includes the following: (1) Concept identification—the initial stage involves defining and identifying system components. (2) Relationship definition—outlining the causal relationship between concepts. (3) Weight assignment—post relationship definition, weights are assigned to these connections, reflecting their strength and direction; weights, typically subjective, can be derived from expert consultation, literature review, or data analysis. (4) Map construction—constructing a map that encapsulates all concepts and their interconnections. (5) Analysis execution—utilizing the map to analyze the system, which may include evaluating the impact of concept modifications, identifying feedback loops, or predicting future system states.

FCMs provide a robust approach when dealing with systems harboring imprecise or uncertain relationships. They are particularly useful when lacking quantitative data as they rely on subjective judgments or expert opinions. Although FCMs are utilized across numerous fields, like any model, they have limitations, including potential oversimplification of complex systems and a dependency on subjective expert opinion.

2.3. The Research Framework of the DEMATEL and FCM

The advantages and disadvantages of DEMATEL and FCM are compared, as shown in Table 1. It can be observed that the DEMATEL method provides an accurate base model and initial parameters for the FCM model, reducing errors in the empirical tuning of the

FCM model. The dynamic inference of the FCM model, capable of handling uncertain information, compensates for the limitations of DEMATEL in accurately reflecting real-world situations. The combination of DEMATEL and FCM offers advantages such as leveraging the strengths of both methods, mitigating the shortcomings of a single approach, and improving decision accuracy and efficiency.

Table 1. Comparison Analysis of DEMATEL and FCM.

Method	Advantages	Disadvantages	Similarities	Combining
DEMATEL	1. Reduced the composition of system elements and simplified the relationships between elements. 2. Quantified causal relationships, providing high credibility and reliability in decision-making and assessment. 3. Graphically intuitive and easy to understand, assisting analysts in better comprehending causal relationships and making decisions.	1. Relies on experts' experience and knowledge to address complex issues. 2. May not accurately reflect real-world situations when dealing with uncertain problems. 3. Overlapping causal relationships can occur, leading to less precise outcomes.	1. Both can be used to deal with complex systems and uncertain information. 2. Both have graphical features, allowing for an intuitive representation of causal relationships and decision processes. 3. Both exhibit high flexibility and strong adaptability, making them applicable in various domains and scenarios	1. The DEMATEL method provides accurate basic models and initial parameters for the FCM model, reducing the error of empirical parameter tuning in the FCM model. 2. The dynamic reasoning of the FCM model can handle uncertain information, making up for the shortcomings of the DEMATEL method in accurately reflecting the actual situation.
FCM	1. Representing and analyzing causal relationships in complex systems. 2. Handling uncertainty and incomplete information. 3. Quantifying different scenarios and requirements by adjusting model weights.	1. The FCM algorithm has a slow convergence rate and requires significant computational resources. 2. Parameter selection and adjustment in the FCM model often rely on trial and error and empirical knowledge. 3. FCM results may be influenced by various fuzzy logic operation methods, thus requiring improvement in result stability and repeatability.		

To address the common issues of the lack of a quantitative assessment system and insufficient dynamic interpretation of emergency preparedness in modular construction safety, a comprehensive assessment method combining DEMATEL and FCM is proposed, as illustrated in Figure 1. Firstly, a safety emergency preparedness assessment index system for modular construction is established through a three-tiered coding analysis using grounded theory. Then, DEMATEL is utilized to quantify the centrality and causality of the assessment indicators, thereby examining the static relationships among them. Finally, the comprehensive association matrix from DEMATEL is transformed into an interaction matrix for the FCM model. This enables dynamic analysis, prediction, and diagnostic reasoning of key indicators, leading to management recommendations for emergency preparedness based on the integrated assessment results.

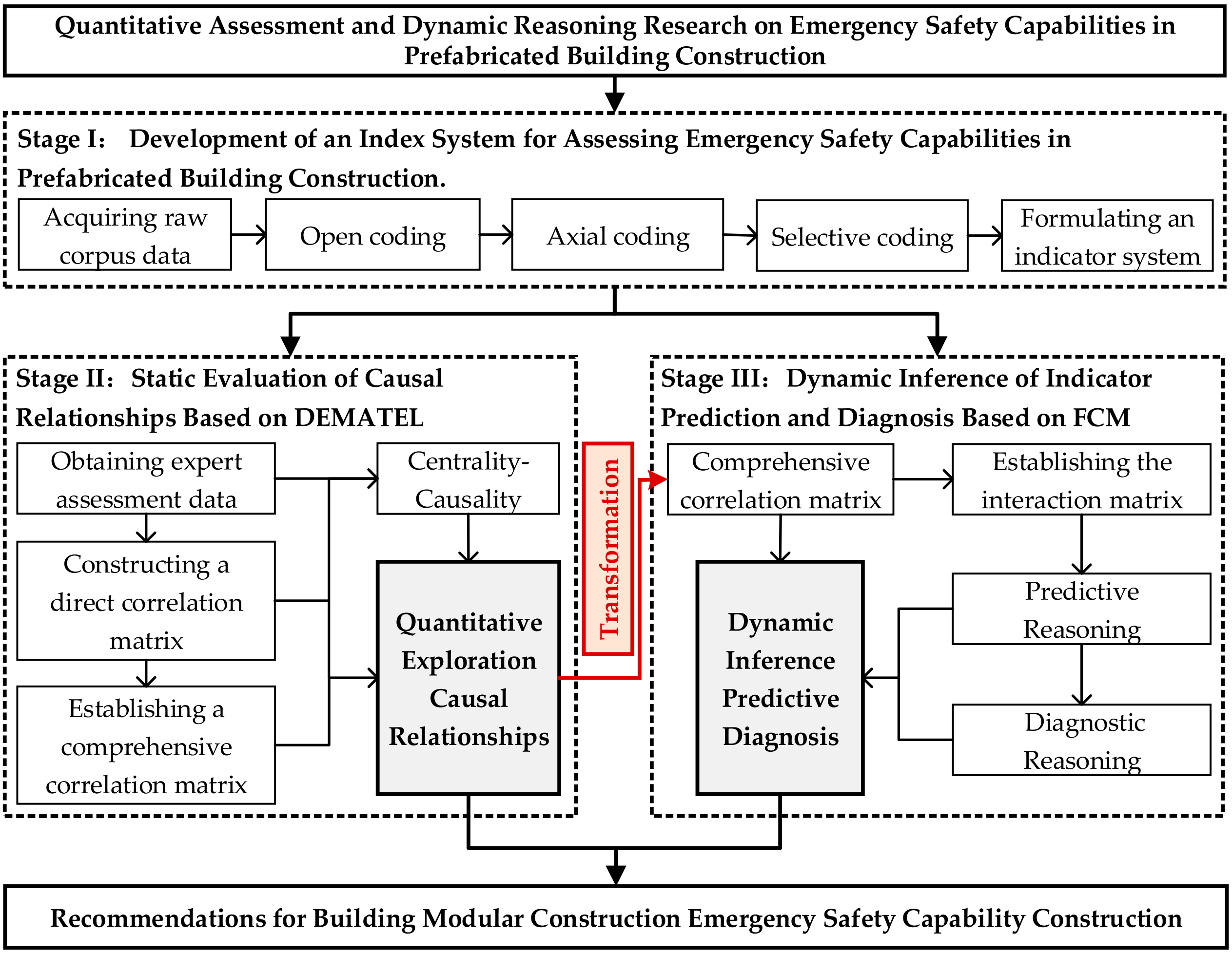

Figure 1. Research framework based on DEMATEL and FCM.

3. Research Variables

To establish a comprehensive indicator system for evaluating emergency response capability in prefabricated construction safety, this study collected a total of 295 pieces of primary data through literature analysis, policy compilation, and research interviews. In the literature analysis phase, the advanced search method was employed using the following query: ((TI=(prefabricated building OR off-site construction buildings OR PB) AND TS=(construction safety* OR construction risk* OR safety assessment* OR risk assessment* OR risk control* OR safety control*) AND TS=(emergency response capability* OR emergency assessment*)) AND Language:(English)) for a search conducted up to 5 April 2023, with a time span from 2013 to 2023. Among the search results, 100 articles and 7 reviews were retrieved, totaling 107 relevant documents. A selection of 9 highly cited articles was made. Nine relevant articles on emergency management in prefabricated construction safety were compiled from databases such as the Web of Science, resulting in 50 pieces of primary data (these 9 articles are from the reference list of this paper). The policy compilation phase focused on gathering materials, including the "Construction Law of the People's Republic of China", "Work Safety Law of the People's Republic of China", "Regulations on Safety Production of Construction Projects in the People's Republic of China", and "Technical Code for Construction Safety of Assembled Building", resulting in 72 pieces of primary data from 12 sources. During the research interviews, conducted from October 2022 to May 2023, a total of 20 experts and scholars from various fields were interviewed, including government safety supervision and management departments, China Construction Third Engineering Bureau Co., Ltd., China Construction Third Engineering Bureau

Group Co., Ltd., Hainan Branch, China Merchants Sanya Deep Sea Science and Technology City Development Co., Ltd., Hubei Green Intelligent Building Engineering Technology Research Center, Wuhan University of Technology. These interviews yielded 173 pieces of primary data.

3.1. Open Coding

The 295 pieces of primary data were subjected to open coding analysis, and initial concepts were formed through the process of "Primary Data—Open Coding—Labeling". After categorization and comparison, initial concepts with frequencies lower than four were excluded. The coding process of the 93 resulting labels from open coding is shown in Table 2. The labels from literature analysis, policy compilation, and research interviews are prefixed with *K*I (e.g., KI_{111}, KI_{112}, etc.), *K*II (e.g., KII_{111}, KII_{112}, etc.), and *K*III (e.g., $KIII_{111}$, $KIII_{112}$, etc.), respectively. For instance, " KI_{111}" indicates that the data source is from literature analysis, and it represents the first labeled concept derived from the primary data of the first literature source.

Table 2. Process of open coding in the original corpus.

Data Source		Excerpts from Original Statements	Open Coding—Labeling
Literature Review	Literature 1	. . .qualifications, skills, and experience, safety awareness and responsibilities, supervision plans and allocation of responsibilities, safety supervision inspections and records, safety education, training, and assessment, participation in safety plans, reasonableness of construction schemes, safety management systems and regulations. . .	KI_{111}: Qualifications, skills, and experience KI_{112}: Safety awareness and responsibility KI_{113}: Safety education KI_{114}: Reasonableness of construction schemes KI_{115}: Safety management system
	Literature 2	. . .analyze the basic pattern of emergency response. . . action objectives, action modules, emergency resources. . . utilizing time-effectiveness assessment, broad priority relationships, organizational structure. . . combining to form an integrated "capability-time-effectiveness-decision" emergency response effectiveness pre-assessment model. . .	KI_{211}: Basic modes of emergency response KI_{212}: Action objectives KI_{213}: Action modules KI_{214}: Emergency resources KI_{215}: Pre-evaluation model for emergency response effectiveness
	. . .. . .	. . .. . .	. . .. . .
Policy Compilation	Policy 1	The People's Republic of China Building Law: . . .prepare safety technical measures plan. . . it is necessary to strengthen safety production publicity, education, and training, and enhance the safety skills and emergency response capabilities of employees. . .	KII_{111}: Safety technical measures KII_{112}: Safety production publicity, education, and training KII_{113}: Safety skills and emergency response capabilities
	Policy 2	The People's Republic of China Regulation on Safety Production in Construction Projects: . . .safety production measures and emergency rescue plans. . . taking into account the characteristics of different projects and the influence of different construction environments. . . adopting different safety production measures and emergency rescue measures. . .	KII_{211}: Safety production measures KII_{212}: Emergency rescue plans KII_{213}: Engineering characteristics and different environments KII_{214}: Emergency rescue measures
	. . .. . .	. . .. . .	. . .. . .

Table 2. *Cont.*

Data Source		Excerpts from Original Statements	Open Coding—Labeling
Expert Interviews	Expert 1	. . .establishing an effective inter-departmental coordination mechanism is crucial for enhancing emergency response capabilities. . . actively introducing modern technological means to promptly identify safety hazards and violations. . . the psychological state of personnel is equally important when responding to safety accidents. . . raising public awareness of safety and self-protection abilities. . . formulating relevant emergency measures tailored to the construction environment. . .	$KIII_{111}$: Coordinating mechanism $KIII_{112}$: Modern technological means $KIII_{113}$: Psychological state of personnel $KIII_{114}$: Public safety awareness and self-protection ability $KIII_{115}$: Formulating relevant emergency measures for the construction environment
	Expert 2	. . .including safety training for all participants. . . emergency plans are essential. . . high-quality safety equipment and facilities are crucial for preventing and responding to safety accidents. . . regular safety drills and assessments are also highly important. . . a sound safety management system. . .	$KIII_{211}$: Safety training $KIII_{212}$: Emergency plan $KIII_{213}$: Safety equipment and facilities $KIII_{214}$: Safety drills and evaluations $KIII_{215}$: Safety management system
	. . .. . .	. . .. . .	. . .. . .

3.2. Axial Coding

The process of "Open Coding—Axial Coding" was used to achieve the "Labeling—Conceptualization—Categorization" of the primary data. Firstly, based on the frequency of label occurrence, a further refinement of the initial attributes of the 93 labels was carried out to achieve conceptualization through open coding. Next, the conceptualized labels from open coding were synthesized and organized. Based on the inherent logic of "Labeling—Conceptualization" in open coding, 20 initial categories for the emergency response capability in prefabricated construction safety were formed through axial coding. An illustrative example of the axial coding process is presented in Table 3.

Table 3. Process of implementing axial coding from open coding labels.

Open Coding—Labeling	Open Coding—Conceptualization	Axial Coding—Categorization
KI_{113} Safety Education KI_{114} Rationality of Construction Plan KI_{115} Safety Management System	H_1 Emergency Plan System	X_1 (Degree of Emergency Plan Adequacy)
KI_{211} Basic Model of Emergency Response KI_{215} Pre-Evaluation Model for Emergency Response Effectiveness	H_2 Emergency Plan Procedures	
KII_{111} Safety Technical Measures KII_{211} Safety Production Measures KII_{214} Emergency Rescue Measures	H_3 Emergency Plan Measures	
. . .. . .	. . .. . .	. . .. . .

3.3. Selective Coding

The process of selective coding was applied to the 20 initial categories, resulting in the identification of 16 main categories (X_1 to X_{16}). Similar expressions within conceptually related categories were summarized and merged to refine the evaluation indicators' core categories. This led to the formation of four core categories, namely, organizational management (Z_1), personnel quality (Z_2), technical measures (Z_3), and emergency resources (Z_4). Based on this foundation, a saturation test was conducted on the indicator system, ultimately resulting in the establishment of the assessment indicator system for emergency response capability in prefabricated construction safety, as shown in Table 4.

Table 4. Assessment index system for emergency response capability in prefabricated building construction safety.

Core Category	Main Category	Abbreviation
Organizational Management (Z_1)	Emergency Plan Completeness	X_1
	Emergency Organizational Structure and Procedures	X_2
	Emergency Coordination Capability	X_3
	Frequency of Emergency Drills	X_4
Personnel Quality (Z_2)	Level of Emergency Training	X_5
	Safety Awareness and Occupational Skills	X_6
	Emergency Response Experience	X_7
	Team Collaboration Ability	X_8
Technical Measures (Z_3)	Adequacy of Emergency Facilities	X_9
	Emergency Technological Level	X_{10}
	Emergency Response Efficiency	X_{11}
	Completeness of Information Systems	X_{12}
Emergency Resources (Z_4)	Emergency Equipment and Material Reserves	X_{13}
	Emergency Communication System	X_{14}
	Emergency Rescue Capability	X_{15}
	External Support and Collaboration Ability	X_{16}

4. Model Development

To address the common issues of lacking a comprehensive quantitative assessment system and insufficient dynamic understanding of emergency response capability in prefabricated construction safety, a research framework for integrated quantitative assessment and dynamic reasoning based on DEMATEL and FCM is proposed. Firstly, using grounded theory and three levels of coding approach, the assessment indicator system for emergency response capability in prefabricated construction safety is established. Next, DEMATEL is utilized to quantify the centrality and causality of the assessment indicators, thus analyzing the static relationships of causal interactions among the indicators. Finally, the comprehensive correlation matrix derived from DEMATEL is transformed into the interaction matrix of the FCM model, enabling dynamic simulations for predictive and diagnostic reasoning of key indicators. Based on the results of the integrated assessment, management strategies and recommendations for enhancing emergency response capability can be formulated.

4.1. Quantifying Interrelationships Using DEMATEL Method

Experts from the relevant field were invited to assess the indicator system, and the DEMATEL method was employed to quantify the direct association matrix, indirect association matrix, and comprehensive association matrix of the evaluation indicators. The causality between emergency response capability assessment indicators in prefabricated construction safety was analyzed through centrality and causality measures involving the following five steps:

(1) M experts were invited to assess the direct positive relationships between evaluation indicators X_i and X_j (i, j = 1, 2,. . . , 16) using a Likert 5-point scale (0 = *not important at all*, 1 = *not important*, 2 = *no impact*, 3 = *important*, and 4 = *very important*). The assessment results of the m expert were represented as $F_m = \left[f_{ij}\right]_{16\times16}$, and the direct association matrix of the emergency response capability assessment indicators was synthesized using the arithmetic mean method, resulting in matrix $\boldsymbol{T} = \left[t_{ij}\right]_{16\times16}$. The calculation formula for t_{ij} was as follows:

$$t_{ij} = \frac{1}{M}\sum_{m=1}^{M} f_{ij} i, j\{1, 2, \ldots, 16\}; m \in \{1, 2, \ldots, M\} \quad (1)$$

(2) Normalize the direct association matrix $\boldsymbol{T} = \left[t_{ij}\right]_{16\times16}$ to obtain the normalized direct association matrix $\boldsymbol{G} = \left[g_{ij}\right]_{16\times16}$. Based on the absorbing principle of Markov chains, establish the indirect association matrix $\boldsymbol{Y} = \left[y_{ij}\right]_{16\times16}$ for the evaluation indicators. The formulas for calculating g_{ij} and $\boldsymbol{Y}$ are shown in Equations (2) and (3), respectively:

$$g_{ij} = \boldsymbol{T}min\left[\frac{1}{maxi\sum_{i=1}^{16} t_{ij}}, \frac{1}{maxj\sum_{j=1}^{16} t_{ij}}\right] i,j \in \{1,2,\ldots,16\} \tag{2}$$

$$\boldsymbol{Y} = \left[y_{ij}\right]_{16\times16} = \lim_{t\to\infty}\left[\boldsymbol{G} + \boldsymbol{G}^2 + \ldots + \boldsymbol{G}^t\right] = \lim_{t\to\infty}\left[\frac{\boldsymbol{I} - \boldsymbol{G}^t}{\boldsymbol{I} - \boldsymbol{G}}\right] = \boldsymbol{G}(\boldsymbol{I} - \boldsymbol{G})^{-1}\ i,j \in \{1,2,\ldots,16\} \tag{3}$$

(3) Create the comprehensive association matrix $\boldsymbol{Q} = \left[q_{ij}\right]_{16\times16}$. By summing Equations (2) and (3), calculate the values of q_{ij} for the emergency response capability assessment indicators. The formula for q_{ij} is given by the following:

$$q_{ij} = g_{ij} + y_{ij}\ i,j \in \{1,2,\ldots,16\} \tag{4}$$

(4) Calculate the influence value ($\boldsymbol{O}_i$) and the affected value ($\boldsymbol{P}_i$) for each emergency response capability assessment indicator X_i. By summing the row elements and column elements in the comprehensive association matrix $\boldsymbol{Q} = \left[q_{ij}\right]_{16\times16}$, obtain $\boldsymbol{O}_i$ and $\boldsymbol{P}_i$, respectively. The formulas for calculating $\boldsymbol{O}_i$ and $\boldsymbol{P}_i$ are shown in Equations (5) and (6):

$$\boldsymbol{O}_i = \left[\sum_{i=1}^{16} q_{ij}\right]_{16\times1} \quad i \in \{1,2,\ldots,16\} \tag{5}$$

$$\boldsymbol{P}_i = \left[\sum_{i=1}^{16} q_{ij}\right]_{1\times16} \quad i \in \{1,2,\ldots,16\} \tag{6}$$

(5) Compute the centrality value (W_i) and the causality value (R_i) for each emergency response capability assessment indicator X_i. According to the DEMATEL principle, W_i indicates the position and importance of indicator X_i in the evaluation indicator system X_1~X_{16}. A larger W_i value for X_i implies greater importance. R_i distinguishes the assessment indicators into causal factors and result factors, with $R_i \geq 0$ indicating a causal factor and $R_i < 0$ indicating a result factor. The formulas for calculating W_i and R_i are given by Equations (7) and (8), respectively:

$$W_i = \boldsymbol{O}_i + \boldsymbol{P}_i\ i \in \{1,2,\ldots,16\} \tag{7}$$

$$R_i = \boldsymbol{O}_i - \boldsymbol{P}_i\ i \in \{1,2,\ldots,16\} \tag{8}$$

4.2. Predictive and Diagnostic Reasoning Using the FCM Model

Integrating the DEMATEL method with the FCM model, predictive and diagnostic reasoning analysis of key indicators and emergency response capability is conducted. This process involves the following five steps:

(1) Set the maximum percentage of centrality ω ($0 < \omega \leq 1$) to calculate the centrality threshold ξ for selecting key indicators. A larger value of ω indicates a higher centrality threshold, resulting in fewer selected key indicators. If S key indicators are obtained, retain the rows and columns corresponding to the key indicators X_i (i = 1, 2,. . ., S) from the comprehensive association matrix $\boldsymbol{Q} = \left[q_{ij}\right]_{16\times16}$ generated by DEMATEL, and resequence the S key indicators as C_i (i = 1, 2,. . ., S, $S \leq 16$). This will yield a comprehensive association matrix of key indicators $\boldsymbol{C} = \left[c_{ij}\right]_{S\times S}$. The formula for calculating the centrality threshold ξ is given by the following:

$$\xi = \omega max W_i\ i \in \{1,2,\ldots,16\} \tag{9}$$

(2) To investigate the interaction between key indicators and emergency response capability, the key indicators C_i (i = 1, 2,. . ., S) and their comprehensive association matrix $\boldsymbol{C} = \left[c_{ij}\right]_{S\times S}$ are used as the basis. The quantified factor C_T is introduced to establish the interaction matrix $\boldsymbol{C}' = \left[c_{ij}\right]_{(S+1)\times(S+1)}$ for the FCM model. Concept node definition based on the FCM model, C_i is referred to as the cause node, and C_T is referred to as the result node. The correlation weights when C_i affects C_T, C_T affects C_i, and C_T affects C_T are represented by $c_{i,S+1}$, $c_{S+1,j}$, and $c_{S+1,S+1}$, respectively. The formulas for calculating $c_{i,S+1}$, $c_{S+1,j}$, and $c_{S+1,S+1}$ are given by Equations (10)–(12), respectively:

$$c_{i,S+1} = \frac{\sum_{j=1}^{S} c_{i,j}}{\sum_{i,j=1}^{S} c_{i,j}} = \frac{[c_{i.}]_{i\times 1}}{\sum_{i,j=1}^{S} c_{i,j}}\ i,j \in \{1,2,\ldots,S\} \tag{10}$$

$$c_{S+1,j} = \frac{\sum_{i=1}^{S} c_{i,j}}{\sum_{i,j=1}^{S} c_{i,j}} = \frac{\left[c_{.j}\right]_{1\times j}}{\sum_{i,j=1}^{S} c_{i,j}}\ i,j \in \{1,2,\ldots,S\} \tag{11}$$

$$c_{S+1,S+1} = \frac{1}{S\times S}\sum_{i,j=1}^{S} c_{i,j}\ i,j \in \{1,2,\ldots,S\} \tag{12}$$

(3) In the FCM model, the initial state matrix for cause nodes C_i (i = 1, 2,. . ., S) and the result node C_T is denoted as $\boldsymbol{A}_i(0) = (\boldsymbol{A}_1(0), \boldsymbol{A}_2(0), \ldots, \boldsymbol{A}_S(0), \boldsymbol{A}_{S+1}(0))$. Through iterative transformation using the threshold function, when $\boldsymbol{A}_i(t+1) = \boldsymbol{A}_i(t)$, it indicates that the model has reached a stable state. The expression for the inference transformation function is given by the following:

$$\boldsymbol{A}_i(t+1) = f\left\{\boldsymbol{A}_i(t) + \sum_{j=1, j\neq i}^{S+1} c_{j,i}\boldsymbol{A}_j(t)\right\}\ i,j \in \{1,2,\ldots,S\} \tag{13}$$

where $\boldsymbol{A}_i(t+1)$ represents the value of indicator C_i at time $(t+1)$; t is the iteration count; $\boldsymbol{A}_i(t)$ and $\boldsymbol{A}_j(t)$ represent the status values of concept nodes C_i and C_j, respectively, at the t iteration; $c_{j,i}$ denotes the correlation weight of concept node C_j affecting C_i; and $f(\cdot)$ represents the threshold function.

(4) The FCM model ensures that the concept node values are within an interval during the iterative process using the threshold function $f(x)$ to maintain simulation randomness. The threshold function $f(\cdot)$ is represented as follows:

$$f(x) = \tanh(x) = \frac{e^x - e^{-x}}{e^x + e^{-x}} \tag{14}$$

(5) The reasoning analysis of the FCM model includes predictive reasoning and diagnostic reasoning. Predictive reasoning is conducted from cause nodes to the result node, aiming to predict future results of the result node C_T based on current evidence from cause nodes C_i (i = 1, 2,. . ., S). Diagnostic reasoning is conducted from the result node to cause nodes, aiming to explore possible causes of cause nodes C_i (i = 1, 2,. . ., S) based on the known status of the result node C_T.

5. Case Study

5.1. Empirical Cases

In Wuhan City, a prefabricated construction project with a total floor area of 112,500 square meters is being undertaken. The residential building area is 97,500 square meters, and the commercial area is 15,000 square meters, with a plot ratio of 2.58. The project has an overall assembly rate of 85%, and the construction schedule is tight with complex and overlapping processes. During the construction process, the project team faces various safety risks, including the construction risks associated with high-rise buildings, the quality of prefabricated components, and on-site coordination.

To address these challenges and mitigate unforeseen accidents, a plan is implemented to collect on-site engineering data and focus on the construction safety emergency response capability. A practical and optimized construction safety emergency response system will be developed to enhance the emergency management level at the construction site, ensuring the smooth progress of the project.

5.2. Data Collection and Preprocessing

Twenty domain experts with at least 10 years of experience in management and research related to prefabricated construction were invited, including four government officials, eleven industry professionals, and five experts from academic institutions. The experts used a uniform Likert 5-point scale to rate the questionnaire. The data collection process took nearly 3 months, resulting in a total of 15 valid questionnaires with an effective response rate of 75%. The statistical results of the years of service and unit distribution of domain experts are shown in Table 5.

Table 5. Distribution of field experts by years of work experience and unit type.

Years of Service (Years)	Owner Unit (Person)	Design Unit (Person)	Supervision Unit (Person)	Construction Unit (Person)	Government Department (Person)	University (Person)
$10 \leq$ Years < 15	1	1	1	1	2	1
$15 \leq$ Years < 20	1	1	1	1	1	2
$20 \leq$ Years	1	0	1	1	1	2
Total	3	2	3	3	4	5

Using IBM SPSS Statistics 26.0 software for consistency testing, the Cronbach reliability coefficient was 0.923 > 0.8. The single measurement in the intraclass correlation coefficient is 0.918 > 0.75, and the average measurement is 0.902 > 0.75, both of which are significant levels, indicating that the survey data can provide data support for the model construction and empirical analysis of this research. Due to space constraints, we present an example of the rating results for X_1 with respect to X_1~X_{16} in Table 6.

Table 6. Scoring results of emergency response capability assessment index X_1 for X_1~X_{16}.

Experts	X_1	X_2	X_3	X_4	X_5	X_6	X_7	X_8	X_9	X_{10}	X_{11}	X_{12}	X_{13}	X_{14}	X_{15}	X_{16}
1	0	4	3	2	4	2	3	3	4	4	4	4	4	4	4	4
2	0	4	4	2	2	3	3	3	4	4	4	4	3	3	4	4
3	0	4	4	2	2	3	3	3	4	4	4	4	3	3	4	4
4	0	4	3	2	3	3	3	4	3	3	4	3	4	4	3	4
5	0	3	3	2	3	3	4	4	3	3	4	3	4	4	3	4
6	0	3	3	2	3	3	4	4	3	4	4	3	4	4	3	4
7	0	4	3	2	3	3	4	4	3	4	3	3	3	3	4	4
8	0	4	3	2	3	3	4	4	3	4	3	4	3	3	4	4
9	0	3	2	2	4	3	4	3	3	4	4	4	3	4	4	4
10	0	3	2	2	4	3	4	3	4	4	4	4	3	4	4	4
11	0	3	2	2	4	3	4	3	4	3	4	4	4	4	4	4
12	0	4	3	2	4	3	4	3	4	3	4	3	4	4	4	3
13	0	4	3	2	4	3	3	3	4	3	4	3	4	4	4	3
14	0	4	3	2	4	2	3	3	4	3	4	2	4	4	4	4
15	0	4	3	2	4	2	3	3	4	4	4	2	4	4	4	4

6. Results and Discussion

6.1. Static Evaluation of Causal Relationships

Using Equation (1), the average values of the correlation strength between indicator X_i and X_j ($i, j = 1, 2, \ldots, 16$) were calculated based on the 15 valid questionnaires, resulting in the direct correlation matrix $\boldsymbol{T} = \left[t_{ij}\right]_{16\times16}$. The normalization process was performed on $\boldsymbol{T} = \left[t_{ij}\right]_{16\times16}$ using Equation (2), resulting in the normalized matrix $\boldsymbol{G} = \left[g_{ij}\right]_{16\times16}$. Then, according to Equation (3), the indirect correlation matrix $\boldsymbol{Y} = \left[y_{ij}\right]_{16\times16}$ was constructed.

By applying the computation rule q_{ij} from Equation (4), the comprehensive correlation matrix $\boldsymbol{Q} = \left[q_{ij}\right]_{16\times16}$ for the evaluation indicators was established, as shown in Table 7.

Table 7. Comprehensive correlation matrix of emergency response capability assessment indices.

$Q_{16\times16}$	X_1	X_2	X_3	X_4	X_5	X_6	X_7	X_8	X_9	X_{10}	X_{11}	X_{12}	X_{13}	X_{14}	X_{15}	X_{16}
X_1	0.1331	0.2420	0.1950	0.1492	0.2091	0.1795	0.2116	0.1909	0.2010	0.2602	0.2509	0.1831	0.1995	0.2469	0.2600	0.2102
X_2	0.2819	0.1016	0.1965	0.1106	0.2295	0.1483	0.2278	0.1406	0.1783	0.2725	0.2536	0.1706	0.1765	0.2546	0.2650	0.1774
X_3	0.2013	0.2193	0.0558	0.0861	0.1316	0.0870	0.1299	0.0830	0.0839	0.1572	0.2229	0.0397	0.0825	0.1851	0.1525	0.0828
X_4	0.2036	0.1843	0.0963	0.0492	0.1719	0.1274	0.1705	0.0853	0.0456	0.1589	0.2254	0.0389	0.1214	0.1484	0.1542	0.0825
X_5	0.2609	0.2004	0.1468	0.1364	0.0695	0.1756	0.2192	0.1330	0.0937	0.2155	0.2039	0.0860	0.1680	0.2016	0.2096	0.0924
X_6	0.1596	0.1416	0.1304	0.0843	0.1668	0.0465	0.1654	0.1194	0.0804	0.1527	0.1826	0.0356	0.0405	0.1815	0.1478	0.0784
X_7	0.2640	0.2412	0.2241	0.1744	0.1877	0.1411	0.0718	0.1728	0.1339	0.2539	0.2107	0.0504	0.0578	0.1698	0.2117	0.0572
X_8	0.1404	0.0879	0.0784	0.0736	0.1163	0.1128	0.0774	0.0323	0.0705	0.1348	0.1662	0.0667	0.0699	0.1278	0.1319	0.0316
X_9	0.1113	0.0662	0.0607	0.0568	0.0218	0.0195	0.0215	0.0174	0.0184	0.1088	0.0293	0.0181	0.0189	0.1051	0.1071	0.0204
X_{10}	0.2489	0.1906	0.1388	0.1298	0.1008	0.1688	0.1358	0.1258	0.0880	0.0909	0.1938	0.1202	0.1243	0.1930	0.1999	0.1262
X_{11}	0.2429	0.1486	0.1341	0.1638	0.1342	0.1283	0.0955	0.1226	0.1225	0.1984	0.0755	0.0798	0.0851	0.1886	0.1940	0.0856
X_{12}	0.1046	0.0613	0.0187	0.0535	0.0193	0.0556	0.0191	0.0154	0.0152	0.1027	0.0248	0.0150	0.0153	0.0240	0.1019	0.0171
X_{13}	0.1023	0.0593	0.0169	0.0522	0.0172	0.0155	0.0170	0.0138	0.0140	0.1005	0.0223	0.0143	0.0145	0.0216	0.0997	0.0160
X_{14}	0.2368	0.1439	0.1299	0.1230	0.0904	0.0864	0.0894	0.0805	0.1190	0.2308	0.1447	0.1158	0.1193	0.0682	0.1892	0.1210
X_{15}	0.1925	0.1381	0.1258	0.0817	0.1228	0.0826	0.0849	0.0765	0.1148	0.1873	0.1378	0.1497	0.0768	0.1395	0.0687	0.1542
X_{16}	0.1266	0.1171	0.1089	0.1030	0.0325	0.0669	0.0324	0.0252	0.0254	0.1604	0.0435	0.0241	0.0265	0.1182	0.1201	0.0281

Based on the comprehensive correlation matrix $\boldsymbol{Q} = \left[q_{ij}\right]_{16\times16}$ from Table 7, the impact degree values ($\boldsymbol{O}_i$), affected degree values ($\boldsymbol{P}_i$), centrality values (W_i), and causality values (R_i) of the evaluation indicators X_1~X_{16} for the safety emergency response capability in modular construction were computed using Equations (5)–(8). The results are presented in Table 8.

Table 8. DEMATEL calculation results of emergency response capability assessment indices.

Index	O_i	O_i Rank	P_i	P_i Rank	W_i	W_i Rank	R_i	Factor Types
X_1	3.3222	1	3.0107	1	6.3329	1	0.3115	Causal Factors
X_2	3.1854	2	2.3435	6	5.5289	2	0.8419	Causal Factors
X_3	2.0007	9	1.8570	7	3.8576	9	0.1437	Causal Factors
X_4	2.0640	8	1.6278	11	3.6918	10	0.4362	Causal Factors
X_5	2.6125	4	1.8215	8	4.4341	7	0.7910	Causal Factors
X_6	1.9135	11	1.6416	10	3.5551	11	0.2719	Causal Factors
X_7	2.6224	3	1.7694	9	4.3918	8	0.8530	Causal Factors
X_8	1.5186	12	1.4344	12	2.9530	12	0.0842	Causal Factors
X_9	0.8012	14	1.4044	13	2.2056	14	−0.6033	Resultant Factors
X_{10}	2.3755	5	2.7855	2	5.1609	3	−0.4100	Resultant Factors
X_{11}	2.1993	6	2.3878	4	4.5871	4	−0.1886	Resultant Factors
X_{12}	0.6635	15	1.2081	16	1.8716	16	−0.5446	Resultant Factors
X_{13}	0.5972	16	1.3971	14	1.9943	15	−0.7998	Resultant Factors
X_{14}	2.0882	7	2.3740	5	4.4622	6	−0.2858	Resultant Factors
X_{15}	1.9338	10	2.6132	3	4.5470	5	−0.6794	Resultant Factors
X_{16}	1.1589	13	1.3810	15	2.5399	13	−0.2221	Resultant Factors

Based on the analysis from Table 8, it is evident that in terms of impact degree, indicator X_1 (completeness of emergency plans) exhibits the highest impact, indicating that X_1 is more likely to trigger and influence other construction safety emergency response evaluation indicators. Following that, indicators X_2 (emergency organizational structure and procedures) and X_7 (emergency response experience) rank next in impact degree. Regarding the affected degree, X_1 (completeness of emergency plans), X_{10} (emergency technical level), and X_{15} (emergency rescue capacity) rank as the top three, indicating that they are more susceptible to the influence of other construction safety emergency response evaluation indicators.

Based on this, a four-quadrant causality diagram was plotted using the central line of centrality (average of the maximum and minimum centrality values $W_i = 4.10$) and the differentiation boundary of causality ($R_i = 0.00$), as shown in Figure 2.

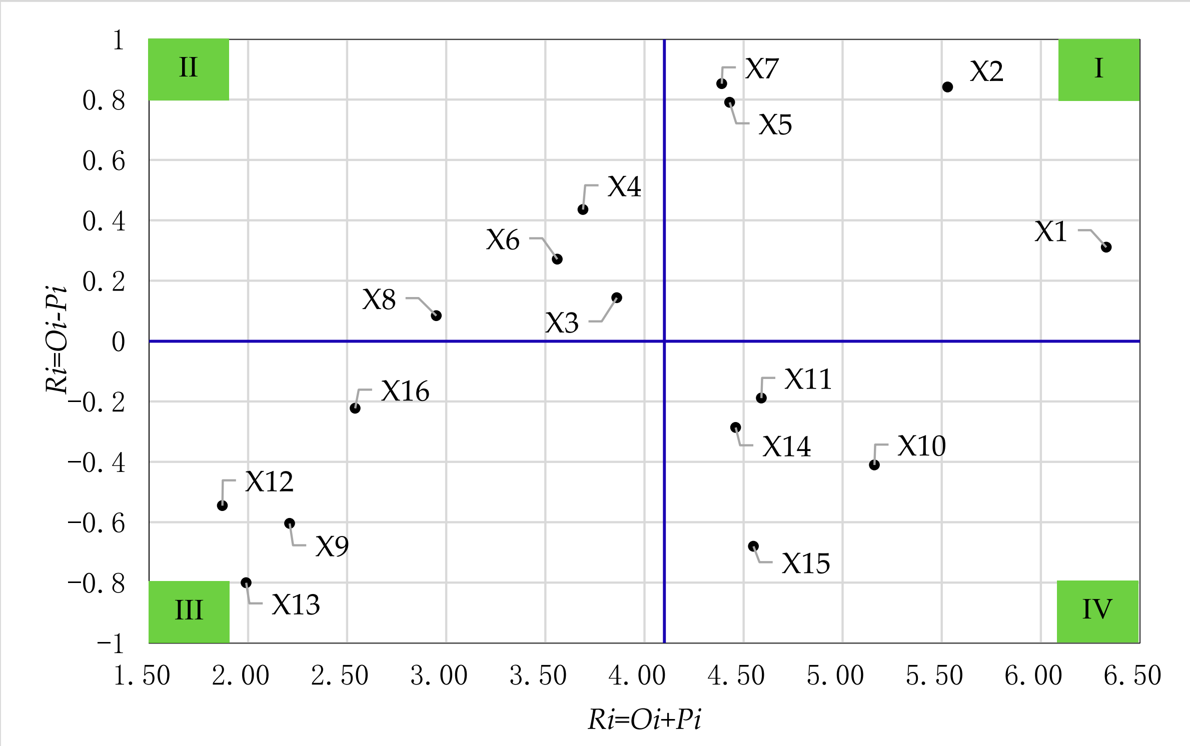

Figure 2. Causal relationship diagram of emergency response capability assessment indices.

Based on the analysis from Figure 2, it is evident that quadrants I and II belong to the cause factor group, while quadrants III and IV belong to the result factor group. In the cause factor group, X_1 to X_4 of Z_1 (organizational management) and X_5 to X_8 of Z_2 (personnel qualification) are classified into quadrants I and II. In the result factor group, X_9 to X_{12} of Z_3 (technical measures) and X_{13} to X_{16} of Z_4 (emergency resources) are classified into quadrants III and IV. Within quadrants I and II, X_1 (completeness of emergency plans) has the highest centrality value of 6.3329, followed by X_2 (emergency organizational structure and procedures), X_5 (emergency training level), and X_7 (emergency response experience). Within quadrants III and IV, X_{10} (emergency technical level) has the highest centrality value of 5.1609, followed by X_{11} (emergency response efficiency), X_{15} (emergency rescue capacity), and X_{14} (emergency communication system).

Considering the static analysis of the causality relationship in both Figure 2 and Table 8, the indicators X_1, X_2, X_{10}, X_{11}, X_{15}, X_{14}, X_5, and X_7 rank as the top eight in centrality. These indicators should be given priority attention in the construction of the emergency response capacity for prefabricated building construction safety. Among them, X_1, X_2, X_5, and X_7 are located in quadrant I, belonging to cause factors with "high centrality and high causality" characteristics. They not only have a significant impact on other indicators but are also strongly influenced by other indicators, making them highly important. On the other hand, X_{10}, X_{11}, X_{15}, and X_{14} are in quadrant IV, belonging to result factors with "high centrality and low causality" characteristics. Although they have a low impact on other indicators, they are greatly influenced by other indicators, making them important in the construction of the emergency response capacity for prefabricated building construction safety as well.

6.2. Dynamic Inference of Indicator Prediction and Diagnosis

Based on expert consultation, we set $\omega = 0.65$. Using Equation (9), we calculate $\xi = 4.1164$ and identify the top eight $\boldsymbol{W}_i$ rankings from Table 7 as the key indicators, resequenced as C_1 (completeness of emergency plans), C_2 (emergency organizational structure and procedures), C_3 (emergency training level), C_4 (emergency response experience), C_5

(emergency technical level), C_6 (emergency response efficiency), C_7 (emergency communication system), and C_8 (emergency rescue capacity). Retaining the rows and columns corresponding to the key indicators from Table 7, we obtain the comprehensive association matrix of key indicators as $\boldsymbol{C} = [c_{ij}]_{8\times 8}$. We introduce the emergency capacity quantification factor C_T and establish the interaction matrix of FCM model $\boldsymbol{C}' = [c_{ij}]_{9\times 9}$ f according to Equations (10)–(12), as shown in Table 9.

Table 9. Comprehensive correlation matrix of key indices for emergency response capability assessment.

$C'_{9\times 9}$	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_T
C_1	0.1331	0.2420	0.1950	0.2091	0.2116	0.2509	0.2469	0.2600	0.1552
C_2	0.2819	0.1016	0.1965	0.2295	0.2278	0.2536	0.2546	0.2650	0.1607
C_3	0.2013	0.2193	0.0558	0.1316	0.1299	0.2229	0.1851	0.1525	0.1153
C_4	0.2609	0.2004	0.1468	0.0695	0.2192	0.2039	0.2016	0.2096	0.1342
C_5	0.2640	0.2412	0.2241	0.1877	0.0718	0.2107	0.1698	0.2117	0.1403
C_6	0.2429	0.1486	0.1341	0.1342	0.0955	0.0755	0.1886	0.1940	0.1077
C_7	0.2368	0.1439	0.1299	0.0904	0.0894	0.1447	0.0682	0.1892	0.0970
C_8	0.1925	0.1381	0.1258	0.1228	0.0849	0.1378	0.1395	0.0687	0.0897
C_T	0.1610	0.1274	0.1072	0.1043	0.1003	0.1331	0.1291	0.1376	0.1760

Taking C_1 and C_T from Table 9 as an example, we calculate the value of C_1 acting on C_T using Equation (10) as $c_{1,9} = [c_{1.}]/\sum c_{i.} = 1.7486/11.2666 = 0.1552$. Here, $[c_{1.}] = c_{1,1} + c_{1,2} + \ldots + c_{1,8} = 1.7486$, $\sum c_{i.} = [c_{1.}] + [c_{2.}] + \ldots + [c_{8.}] = 11.2666$. Using Equation (11), we calculate the value of C_T acting on C_1 as $c_{9,1} = [c_{.1}]/\sum c_{.j} = 1.8135/11.2666 = 0.1610$. Additionally, utilizing Equation (12), we calculate the value of C_T acting on itself as $c_{9,9} = \sum c_{ij}/64 = 0.1760$. Similarly, we can perform similar calculations for other cases.

(1) Predictive Reasoning Analysis

In FCM predictive reasoning analysis, the cause nodes are denoted as C_i (i = 1, 2,. . ., 8), and the result node is C_T. Equation (14) for the threshold function is applied to Equation (13) to perform iterations and transformations, quantitatively predicting the impact of each key indicator C_i on the quantified factor C_T. To simplify the study, C_i is taken as a 5-point linguistic variable (−1 = very unfavorable, −0.5 = unfavorable, 0 = neutral, 0.5 = favorable, and 1 = very favorable). Taking C_1 (emergency organization structure) as an example, in the predictive reasoning of C_1 and C_T, the initial state of the cause node C_1 takes values of "−1, −0.5, 0, 0.5, 1", while the initial state values of other cause nodes C_i (i = 1, 2,. . ., 8) and the result node C_T are all set to 0, resulting in an initial state matrix $\boldsymbol{A}_i(0) = (\pm 1/\pm 0.5,0,0,0,0,0,0,0,0)$. When the FCM model runs to the t iteration, if $\boldsymbol{A}_i(t) = \boldsymbol{A}_i(t-1)$, it indicates that the model has reached a stable state. The results of the predictive reasoning analysis for C_i (i = 1, 2,. . ., 8) and C_T are shown in Table 10.

Table 10. Stable prediction inference values based on cause nodes.

State	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8
$P(C_T\|C_i = -1)$	−0.6869	−0.6930	−0.6357	−0.6618	−0.6695	−0.6243	−0.6067	−0.5937
$P(C_T\|C_i = -0.5)$	−0.5701	−0.5758	−0.5232	−0.5469	−0.5540	−0.5127	−0.4968	−0.4850
$P(C_T\|C_i = 0.5)$	0.5701	0.5758	0.5232	0.5469	0.5540	0.5127	0.4968	0.4850
$P(C_T\|C_i = 1)$	0.6869	0.6930	0.6357	0.6618	0.6695	0.6243	0.6067	0.5937

In the FCM predictive reasoning analysis, the iteration trend curves under different scenarios are simulated 30 times, as shown in Figure 3.

Combining Table 10 with Figure 3a analysis, taking the cause node C_1 as an example, when C_1 takes a value of −1 (or −0.5), the stable value of C_T is −0.6869 (or −0.5701); when C_1 takes a value of 1 (or 0.5), the stable value of C_T is 0.6869 (or 0.5701). This indicates a positive correlation between C_1 and C_T. Similarly, there is a positive correlation between other cause nodes C_i (i = 2, 3,. . ., 8) and C_T. Additionally, by comparing the stable values and slope of the curves of C_T under different scenarios, it is found that the correlation between C_2 and C_T is the strongest. In descending order of strength, the correlations are as follows: C_2 (emergency organization and procedures), C_1 (emergency plan completeness), C_5 (emergency technical level), C_4 (emergency response experience), C_3 (emergency training level), C_6 (emergency response efficiency), C_7 (emergency communication system), and C_8 (emergency rescue force). The dynamic analysis of predictive reasoning shows that effective control and continuous optimization of C_2 is crucial for emergency capability construction.

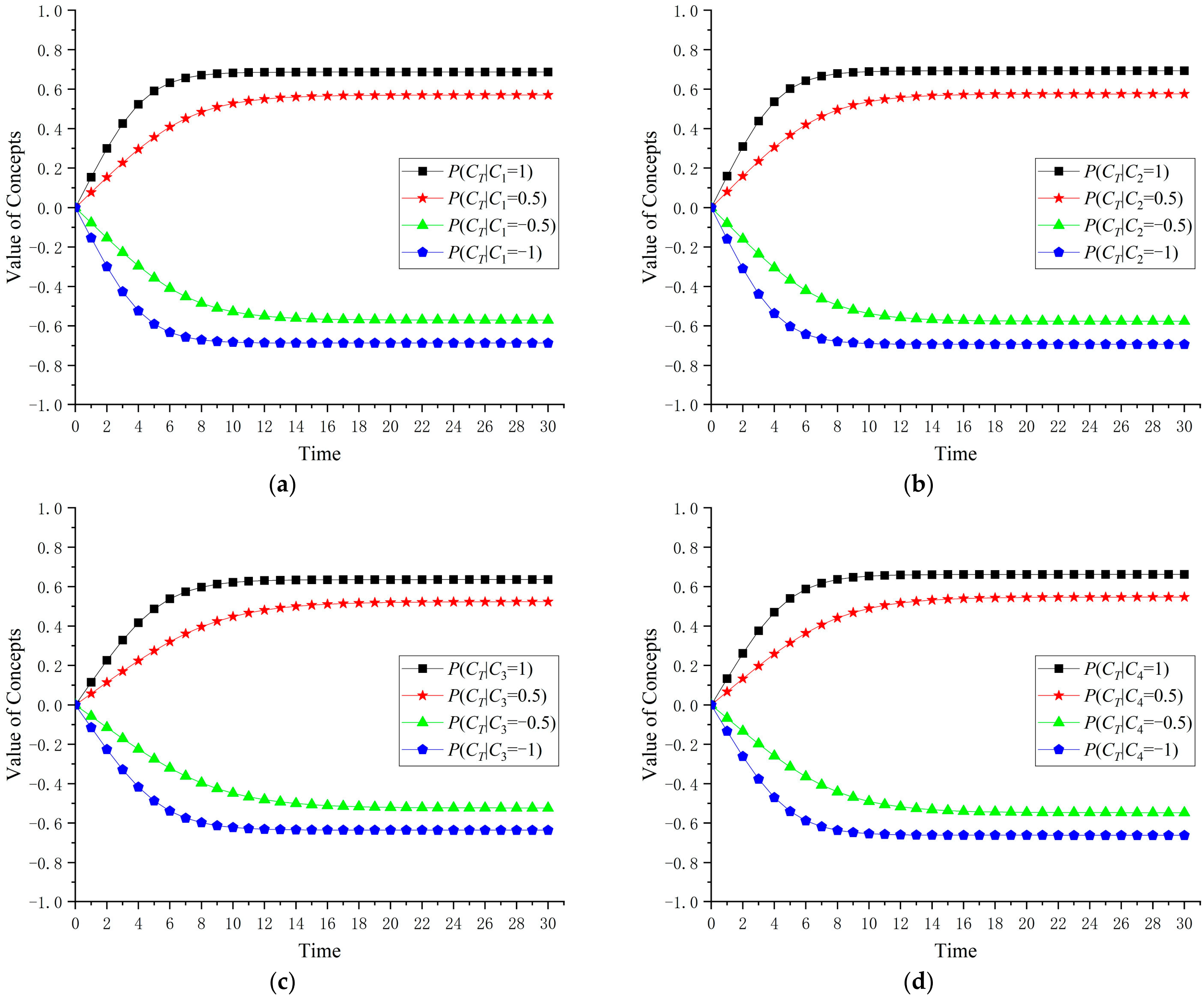

Figure 3. *Cont.*

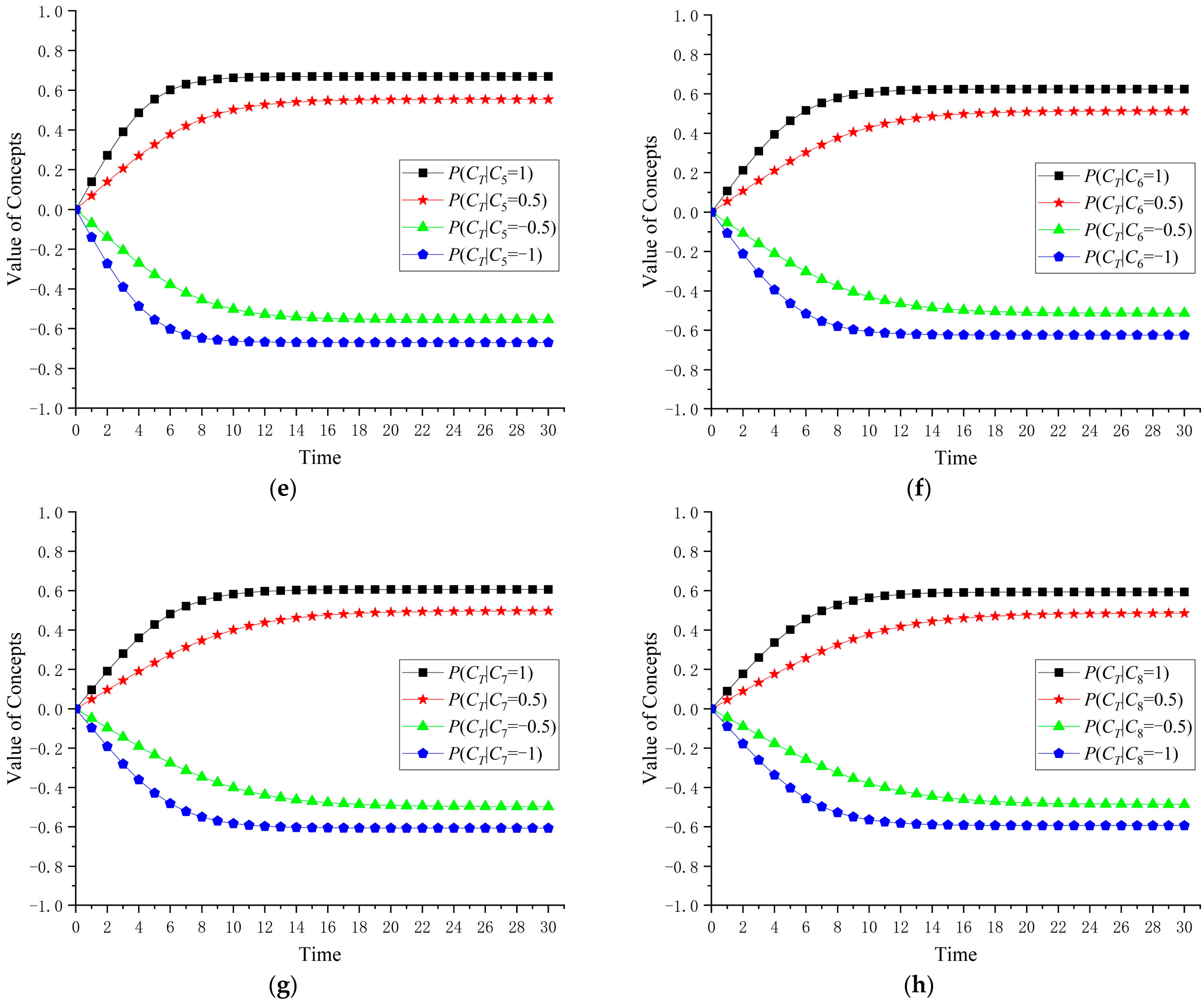

Figure 3. Iteration curve of predictive inference based on cause nodes. (**a**) Predictive inference based on C_1. (**b**) Predictive inference based on C_2. (**c**) Predictive inference based on C_3. (**d**) Predictive inference based on C_4. (**e**) Predictive inference based on C_5. (**f**) Predictive inference based on C_6. (**g**) Predictive inference based on C_7. (**h**) Predictive inference based on C_8.

(2) Diagnostic Reasoning Analysis

In the FCM diagnostic reasoning analysis, the cause nodes are C_i (i = 2, 3,. . ., 8), and the result node is C_T. The threshold function (Equation (14)) is applied to the iteration and transformation process (Equation (13)) to quantitatively diagnose the most likely key indicators C_i causing changes in the quantitative factor C_T. To simplify the study, C_T is represented using five linguistic variables (−1 = *very unfavorable*, −0.5 = *unfavorable*, 0 = *neutral*, 0.5 = *favorable*, and 1 = *very favorable*). When conducting the diagnostic reasoning for C_T and C_i, the initial states of the result node C_T are set to "−1, −0.5, 0, 0.5, 1", and the initial states of the cause nodes C_i (i = 2, 3,. . ., 8) are all set to 0. The initial state matrix is $\boldsymbol{A}_i(0) = (0, 0{,}0{,}0{,}0{,}0{,}0{,}0{,}\pm 1/\pm 0.5)$. When the FCM model runs to the t iteration, if $\boldsymbol{A}_i(t) = \boldsymbol{A}_i(t-1)$, it indicates that the model has reached a stable state. The results of C_T and C_i (i = 1, 2,. . ., 8) diagnostic reasoning analysis are shown in Table 11.

Table 11. Stable diagnostic inference values based on result nodes.

State	$P(C_i \mid C_T{=}-1)$	$P(C_i \mid C_T{=}-0.5)$	$P(C_i \mid C_T{=}0.5)$	$P(C_i \mid C_T{=}1)$
C_1	−0.6933	−0.5760	0.5760	0.6933
C_2	−0.6528	−0.5387	0.5387	0.6528
C_3	−0.6235	−0.5121	0.5121	0.6235
C_4	−0.6188	−0.5078	0.5078	0.6188
C_5	−0.6123	−0.5019	0.5019	0.6123
C_6	−0.6604	−0.5457	0.5457	0.6604
C_7	−0.6551	−0.5408	0.5408	0.6551
C_8	−0.6661	−0.5509	0.5509	0.6661

In the FCM diagnostic reasoning analysis, the iterative trend curves under different scenarios are simulated 30 times, as shown in Figure 4.

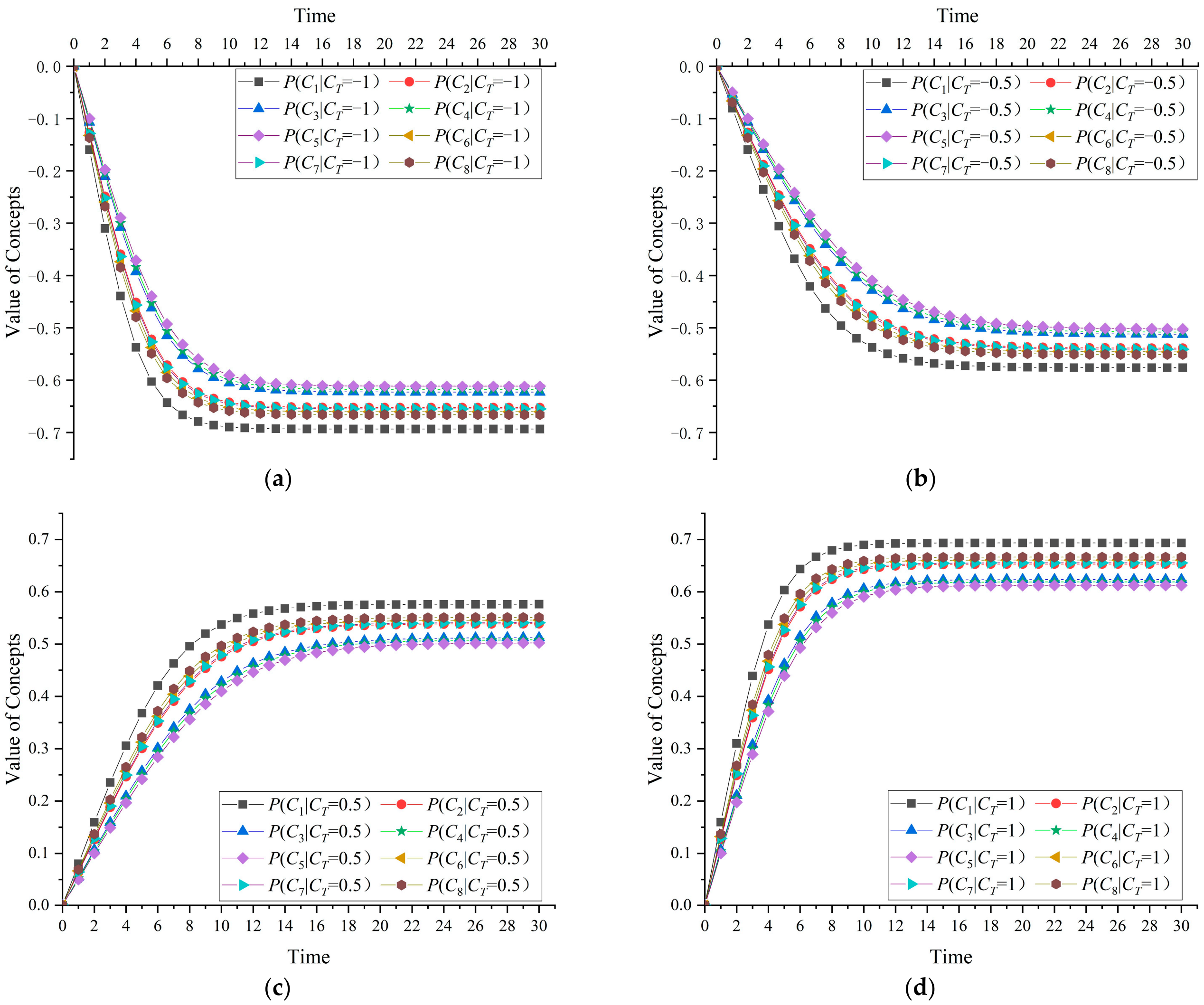

Figure 4. Iteration curve of diagnostic inference based on result nodes. (**a**) Diagnostic inference based on $C_T = -1$. (**b**) Diagnostic inference based on $C_T = -0.5$. (**c**) Diagnostic inference based on $C_T = 0.5$. (**d**) Diagnostic inference based on $C_T = 1$.

Based on the analysis of Table 11 and Figure 4a, considering the result node $C_T = -1$ as an example, the stable values of $P(C_i|C_T = -1)$ (i = 1, 2,. . . , 8) are −0.6933, −0.6528, −0.6235, −0.6188, −0.6123, −0.6604, −0.6551, and −0.6661. This indicates a positive correlation between C_T and C_i, which aligns with the results of the predictive reasoning analysis. Additionally, by combining Table 11 with Figure 4b–d and comparing the stable values and slope of the curves for the reason nodes C_i (i = 1, 2,. . ., 8) under different scenarios (C_T = −0.5, 0.5, 1), it is observed that C_T exhibits the strongest correlation with C_1. In descending order, the correlation strength is observed as follows: C_1 (completeness of emergency plans), C_8 (emergency rescue capability), C_6 (emergency response efficiency), C_7 (emergency communication system), C_2 (emergency organizational structure and procedures), C_3 (emergency training level), C_4 (emergency handling experience), and C_5 (emergency technical level). The dynamic analysis of diagnostic reasoning indicates the need to focus on "the completeness of emergency plans" during the development of safety emergency capabilities in prefabricated construction projects.

6.3. Management Strategies and Recommendations

(1) Organizational management: Establish a dedicated emergency management department and enhance communication and collaboration among various departments. Develop comprehensive emergency plans based on the challenges and safety risks of prefabricated projects. Clearly define emergency response procedures and establish a robust emergency management oversight mechanism.

(2) Personnel qualifications: Conduct regular emergency training and educational activities to enhance the emergency awareness and skills of construction site personnel. Strengthen team collaboration capabilities and clarify emergency positions and responsibilities. Through training and practical exercises, improve the emergency response and crisis management abilities of dedicated personnel.

(3) Technical measures: Establish a robust emergency communication system to ensure rapid and accurate information dissemination during emergencies. Utilize advanced monitoring and warning technologies to build emergency resource management systems, warning systems, and emergency decision support systems. These systems will enable real-time monitoring and early warning of safety conditions and risks on the construction site.

(4) Emergency resources: Establish and strengthen emergency rescue forces to enhance response speed and capabilities. Adequately allocate emergency equipment and tools to effectively respond to various unexpected incidents on the construction site. Set up emergency resource reserves and support mechanisms to share and enhance comprehensive emergency capabilities.

7. Conclusions

Through literature analysis, policy compilation, and research interviews, a total of 295 pieces of original data were obtained. Using the three levels of coding procedure of grounded theory, a comprehensive set of 16 main categories (X_1 to X_{16}) and 4 core categories (Z_1 to Z_4) was developed for the assessment of emergency response capabilities in prefabricated construction.

Static causal analysis based on DEMATEL, the indicator X_1 (completeness of emergency plans) has the highest impact on other indicators and is also most influenced by them. The top eight indicators in terms of centrality are X_1 (completeness of emergency plans), X_2 (emergency organization and procedures), X_{10} (emergency technological level), X_{11} (emergency response efficiency), X_{15} (emergency rescue force), X_{14} (emergency communication system), X_5 (emergency training level), and X_7 (emergency handling experience). These indicators fall into quadrants I and IV, suggesting that they should be prioritized in the construction of emergency response capabilities for prefabricated construction.

Prediction and diagnosis of dynamic inference index based on FCM, the prediction analysis indicates that controlling C_2 (emergency organization and procedures) is crucial for enhancing emergency response capabilities. The diagnosis analysis highlights the importance of focusing on C_1 (completeness of emergency plans) in the construction of emergency response capabilities for prefabricated construction. By combining the results of prediction and diagnosis analyses, it is recommended to fully utilize the organizational management role of C_1 and C_2, thereby synergistically improving the emergency response capabilities of prefabricated construction.

DEMATEL-FCM combines causal relationship analysis and fuzzy logic, enabling decision-makers to have a more comprehensive understanding of causal relationships within systems and make wiser decisions. This helps improve the quality and efficiency of decision-making, thereby positively impacting decision-making in various fields such as prefabricated construction safety, supply chain management, financial risk analysis, and more.

It should be noted that in the prediction analysis of the FCM model, this study only considers the interaction between individual key indicators and the quantified emergency response factor. It does not explore the combined effects of multiple key indicators or fully reflect the integrated application of emergency response capacity development strategies. Future research will attempt to investigate the synergistic changes in multiple key indicators in prediction inference and introduce cost management mechanisms for implementing combined strategies to achieve the optimal enhancement of emergency response capabilities in prefabricated construction under rational resource allocation.

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