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Critical Success Factors for Safety Program Implementation of Regeneration of Abandoned Industrial Building Projects in China: A Fuzzy DEMATEL Approach

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Abstract: The regeneration of abandoned industrial buildings (RAIBs) has received extensive attention in urban renewal efforts to achieve urban sustainable development goals. Meanwhile, the construction safety performance of RAIBs is a major challenge with increasing RAIB projects in China. Safety programs have been considered as one of the proactive methods to effectively reduce accidents and injuries in the construction industry. Various studies have conducted critical success factors (CSFs) that influence the effective implementation of safety programs in new buildings. However, the CSFs affecting the construction safety program implementation of RAIBs were ignored. The aim of this study is to determine CSFs that affect the safety program implementation of RAIB projects. First, sixteen factors were identified combining characteristics of RAIBs with literature reviews and experts' opinion. Second, the fuzzy set theory and decision-making trial and evaluation laboratory (DEMATEL) approach are proposed to identify the influencing degree of the factors and categorize these factors into cause-and-effect groups. Then, according to the causal diagram, management support (C1), allocation of authority and responsibility (C3), control of subcontractor (C5), personal attitude (C9), and safety inspections and hazard assessment (C14) are identified as the CSFs for the safety program implementation of RAIBs' construction. This study guides the managers and stakeholders to especially concentrate on these CSFs in order to improve the efficiency of the safety program implementation of RAIB projects with limited resources. This study also will contribute to the improvement of safety performance and to the sustainable development goal of RAIB projects.

Keywords: abandoned industrial buildings; regeneration; safety program; fuzzy DEMATEL; urban renewal; sustainable; safety performance; CSFs

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1. Introduction

The regeneration of abandoned industrial buildings (RAIBs), rather than their demolition or rebuilding, has received extensive attention in urban renewal efforts to achieve urban sustainable development goals [1–3]. The sustainable development goals (SDGs) are seventeen global development goals proposed by the United Nations, which continue to guide global development efforts from 2015 to 2030 after the expiry of the millennium development goals (MDGs) from 2000 to 2015 [4]. The eleventh goal is directly related to cities and urban sustainable development [5]. The regeneration of abandoned industrial buildings is the refurbishment and reuse of abandoned industrial buildings to meet the needs of new functions on the premise that the original buildings are not completely dismantled [6]. RAIBs not only extend the physical life of buildings, reduce the creation of demolition waste, preserve the historical and cultural context, but also contribute to significant social, economic, cultural, and environmental benefits to sustainable urbanization [7–11].

However, the rapid growth of RAIB projects, resulting in the safety performance of refurbishment, is a major challenge. The refurbishment of the RAIB project needs to comply with the preservation laws of abandoned industrial buildings (AIBs) and current occupational health and safety (OHS) standards, and also involve partial structural demolition, structural renovation, facade retentions, modern plumbing, electrical, heating, ventilation and air conditioning (HVAC) and communications systems' retrofit and building pollutants treatments [12]. Compared with new buildings, the refurbishment of RAIB projects have more complexity, uncertainty and are potentially dangerous [13]. Neglecting the refurbishment safety of RAIB projects can lead to accidents and injury. For example, On 19 March 2016, two workers fell from a height while removing the roof of a steel structure factory at a machinery factory in Liuzhou city, Guangxi Province, China, causing the death of one and injury of the other. In May 2019, a tractor factory under renovation collapsed during partial demolition located in No.148 Zhaohua Road, Changning District, Shanghai, China, causing 10 deaths, 15 injuries and direct economic losses of 34.3 million yuan. Accidents will lead to cost increases, schedule delays and other adverse effects [14,15]. Accordingly, in order to improve the safety performance of RAIB projects and realize sustainable urbanization, the safety problem of the RAIBs must be considered.

A safety program as a proactive approach is considered to be one of the most effective tools to reduce accidents and injury on construction projects [16,17]. A reasonable safety program can not only prevent personal injury, but also minimize the loss of machinery and equipment [18]. In order to develop an effective safety program, factors affecting safety program implementation need to be identified. Especially with limited resources, identifying critical success factors (CSFs) is essential to improve safety performance. CSFs affecting the implementation of safety programs have been extensively studied in new buildings. Management support, personal safety awareness, communication, and the establishment of safety committees have been identified as CSFs for safety program implementation in new buildings [19–22]. However, no research has been done in the RAIB projects, which is increasingly vital not only in China, but also in other developing countries.

RAIB projects have different characteristics from new construction projects and general refurbishment projects. For example, The AIBs were built earlier and the data preservation technology was backward, so the complete basic design information could not be provided. Therefore, designers and construction personnel cannot obtain comprehensive structural information of AIBs. Moreover, the RAIB projects need to operate on the original building structure and space, resulting in a limited workspace. Besides, the transformation technology of RAIB projects is more complex under the background of the preservation of building features, green regeneration, and low carbon concept. More importantly, for the AIBs with pollution in the process of original function use, industrial buildings, equipment pipe networks, and the surrounding environment are polluted to varying degrees due to the erosion of various hazard sources such as acid, alkali, heavy metal, organic matter, and even microorganism. During the RAIBs construction, a large number of toxic and harmful industrial residues will enter the human body through breathing, skin, and even mouth with construction dust, threatening human health. Therefore, the previous related studies on new construction projects may not be applicable to RAIB projects. The CSFs for safety program implementation of RAIB projects require further investigation.

The main aim of this study is to determine the CSFs for safety program implementation of RAIB projects based on the fuzzy-DEMATEL method to ensure the effective implementation of the safety program, improve the safety performance of RAIB projects, and achieve sustainable RAIB projects. Firstly, combining background information of RAIBs with literature reviews and experts' opinions, the factors affecting safety program implementation of RAIB projects are identified. Then fuzzy and decision-making trial and evaluation laboratory (DEMATEL) approach is used to examine the importance of the influencing factors and the causal relationship between them. Finally, according to the causal diagram of these influencing factors obtained from the study, the CSFs for safety program implementation of RAIB projects can be determined. This study fills the research gap of limited safety program research of RAIB projects. It would be useful for managers and stakeholders to prioritize CSFs for the safety program of RAIB projects and make an effective safety program for RAIB projects.

The remainder of the paper is structured as follows. Section 2 introduces the background information of RAIBs in China; Section 3 reviews the literature related to CSFs, occupational safety and health of RAIB projects, safety program implementation. Section 4 describes the research method of triangular fuzzy number and DEMATEL in detail, as well as the data collection; Section 5 reports the corresponding results; Discussion for this paper is shown in Section 6; Section 7 states the theoretical and managerial implications of this study. Section 8 describes the conclusion and limitation of this paper.

2. Background Information

The regeneration mode refers to the new function of AIBs after being regenerated [23]. The research team conducted an in-depth investigation on 148 completed RAIB projects in China's 30 cities during 2015–2018. We found eight regeneration modes for AIBs, including (i) creative/cultural spaces, (ii) museums, (iii) parks, (iv) venue buildings, (v) offices, (vi) housing, (vii) shopping malls, and (viii) schools (several representative RAIB projects are shown in Figure 1.

Figure 1. Representative RAIB (regeneration of abandoned industrial building) projects in China.

It is necessary to refurbish the AIBs in order to meet the requirements of new functions. According to Li et al. (2018), the main refurbishment aspects of RAIB projects involve demolition work, ground and foundation, main structure, envelope structure, mechanical and electrical installation, and green retrofit [24]. The main contents of each aspect are shown in Figure 2. In general, these contents can be briefly explained as the following six aspects. (1) In order to meet the needs of new functions and take economic factors into consideration, the buildings (part of main structure and envelope structure) and mechanical and electrical systems (such as water supply, drainage, HVAC, electrical, fire protection, etc.) that are seriously damaged and have no great historical value will be demolished or partially demolished. In addition, the original working equipment in the AIBs that is no longer in use needs to be removed to make room for the interior. (2) For retained AIBs, especially those with high story height and large column spacing, designers often divide the space vertically into two floors to meet the needs of new functions, which will require the addition of indoor stairs and floors, and will also be divided into multiple spaces horizontally. Because these additions will lead to load changes, existing structures generally need to be strengthened to ensure that the bearing capacity meets the requirements. Similarly, the change of ground load will also lead to the insufficient bearing capacity of the base and foundation, so it is necessary to reinforce the base and foundation. (3) In order to retain the historical characteristics of AIBs, the envelope structure generally needs to be retained. However, due to its poor thermal insulation effect and high energy consumption, it does not meet the current requirements. As a result, energy-saving renovation of envelope structure (especially the original doors and windows, external walls, and roofs) need to be carried out and the use of new energy technology is recommended. (4) As for the reserved existing resources (such as original building materials and equipment), many of them will be recycled into works of art or landscape pieces for exhibition to reflect the historical and cultural sense of AIBs. (5) Some of the retained electromechanical systems may need to be repaired, and new electromechanical systems (such as air conditioning systems, fire protection systems) may also be required. (6) For the AIBs that are polluted during the use of their original functions, the soil, buildings, equipment pipe network and the surrounding environment need to be polluted.

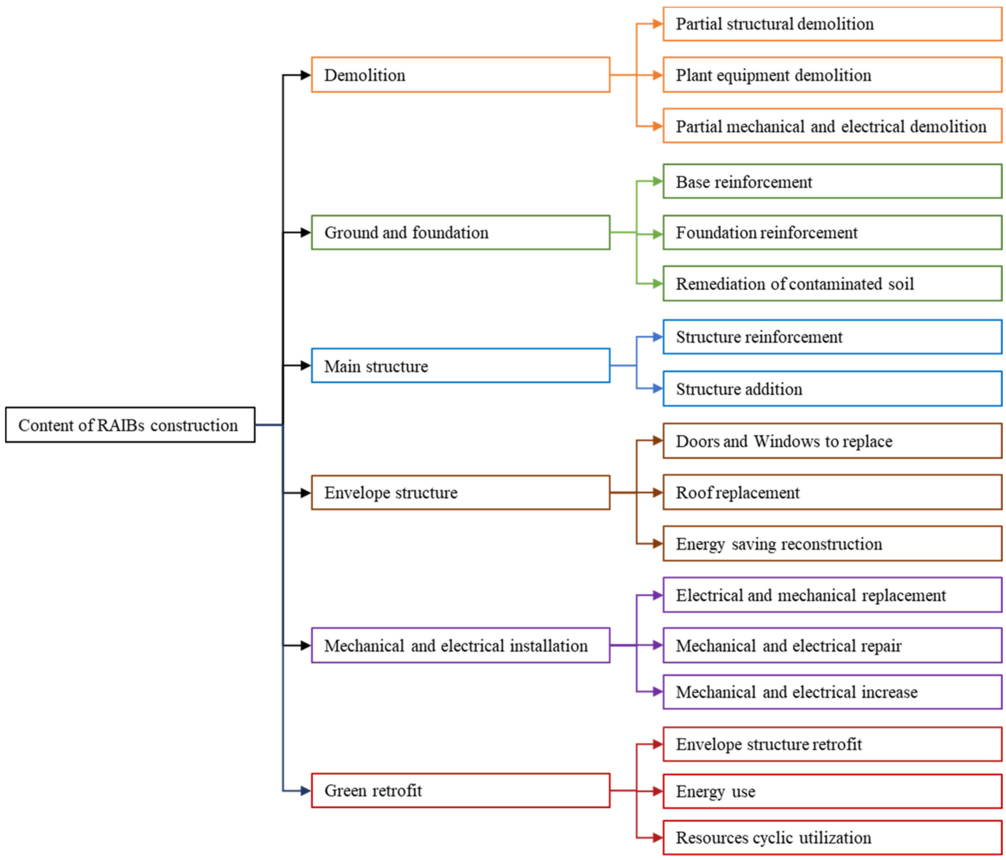

Figure 2. Content of RAIB projects.

3. Literature Review

3.1. Critical Success Factors

In 1961, Daniel [25] first proposed the concept of CSFs in the context of information systems development planning. In 1979, Rockart [26] defined the CSFs as "the limited number of areas in which results, if they are satisfactory, will ensure successful competitive performance for the organization". CSFs are those factors that play a key role in the success of projects. There are a large number of factors that affect the success of projects. However, there are generally three to six factors that determine the difference between the success and failure of projects. The CSFs are to find out the key factors for the success of the project through multi-dimensional analyses, then determine the requirements of the system based on these CSFs, and decide to achieve good performance and the objectives of the project. Currently, CSFs research has been widely used in various fields in different countries [27–34], which provides valuable guidance for the success of projects. In the context of the construction industry, Chen et al. [35] determined the CSFs of construction projects and examined the interrelationships among CSFs, which help project managers focus on the control of key factors and allow them to make reasonable resource allocations. Gudienė et al. [36] investigated the CSFs affecting the implementation of projects in construction enterprises in Lithuania using the analytic hierarchy process (AHP) approach. Ghanbaripour et al. [37] identified and prioritized CSFs for subway construction projects from a main contractors' perspective. Tan et al. [1] examined CSFs affecting the adaptive reuse of industrial buildings according to the current situation of adaptive reuse of industrial buildings in Hong Kong. Sarvari et al. [38] identified the CSFs for managing construction small and medium-sized enterprises (SMEs) in the developing countries of the Middle East.

3.2. Occupational Safety and Health of RAIB Projects

At present, there have been a few numbers of research focused on the issues related to occupational health and safety of RAIB projects. Li et al. [39] analyzed the interrelationship between safety factors of RAIBs by means of the interpretive structural model and analytic hierarchy process. Guo et al. [40] established a safety evaluation model for RAIBs based on structural entropy weight method and unascertained measure theory and proposed improvement strategies for construction safety management. Li et al. [41] constructed a risk emergency management model for RAIBs by combining a case-based reasoning method and a rule-based reasoning method to deal with unexpected accidents during the RAIBs construction. According to the refurbishment content of the RAIB projects mentioned in Section 2, reviewing the previous occupational safety and health research related to the repair, maintenance, alteration, and addition (RMAA) work and refurbishment projects may provide valuable information for tackling safety problems of the RAIB projects. In the context of RMAA work, Hon et al. studied the causes of accidents in RMAA work [42], safety climate factors [43], the relationship between safety climate and safety performance [44], the relationship between safety climate and injury occurrence, and safety management from knowledge management perspective [45]. Hon et al. [46] identified and evaluated the various strategies for improving the safety performance of RMAA works. Chan et al. [47] developed a Bayesian network (BN) model that encapsulates the interrelationships between safety factors and safety performance of electrical and mechanical works in RMAA projects, the results indicated that alcohol consumption and smoking habits of works exert a considerable influence on the safety performance of workers. As for demolition construction, Hughes and Ferrett [48] indicated that demolition works can be considered as one of the most hazardous construction operations and is responsible for more deaths and major injuries than any other activity. Alipour-Bashary et al. [49] developed a framework for the determination of building demolition safety index to evaluate the safety level of a building being demolished. The safety and health risks in demolition activities are mostly related to an unplanned collapse of the structure, this includes the incorrect use of demolition tools and unsafe sites which can cause injuries. Health Safety and Executive (HSE) [50] suggested some measures to reduce accidents in demolition works, including communication of safety information at different stages, appropriate demolition tools and equipment selection, and safety supervision. Most RAIB projects involved partial demolition. In comparison to complete demolition, partial demolition has more risks because of the amount of manual work that requires a large number of workers. Rakhshanifar et al. [51] proposed a safety and health checklist for reducing noncompliance with health and safety regulations and contributing to communication improvement between different participants in refurbishment projects including partial demolition.

3.3. Safety Program Implementation

Anton [52] defined a safety program as "the monitor and control of the environment, equipment, workplace, practices, and employees to reduce accidents, injuries, and losses in the workplace." Rowlinson [53] identified the objectives of safety program implementation in the construction industry are to prevent improper behavior that may result in accidents, to ensure safety problems are detected and reported, and to make sure that accidents are reported and resolved properly. That is, safety programs can reduce the gap between actual safety and target safety [54]. Chen and Jin [55] developed a multilevel survey of safety culture and climate to assess the effectiveness of a newly launched safety program. The results indicated that the proposed method can help managers to assess safety programs holistically. Buniya et al. [56] identified barriers to the implementation of safety programs in the construction industry and found out the barriers were grouped into four dimensions: non-conductive work climate, poor governance, poor safety awareness, and unsupportive industry norms.

Previous studies have studied the factors affecting safety program implementation in the construction industry. For example, The Construction Industry Institute identified key components of an effective safety program [57], including management commitment, staffing for safety, pre-project and pre-task planning, safety education and training, employee involvement, safety recognition and rewards, accident/incident investigations, substance abuse programs, subcontractor management. Hallowell1 and Gambatese [58] quantified the frequency and severity reduction of defined construction safety risk resulting from the independent implementation of each essential safety program element, and concluded upper management support and commitment and subcontractor selection and management are the most effective safety program elements. Pinto et al. [59] indicated that occupational risk assessment on workplace sites is the first and key step to support decision-making in safety programs. Further, Hallowell et al. [60] explored the interrelationships between highly effective safety program elements by using a Delphi panel of experts, and found out site safety manager, worker participation and involvement, a site-specific safety plan, and upper management support and commitment play a critical role in a highly effective safety program. Bavafa et al. [61] identified and assessed the causal relationships of safety program factors in the construction projects in Kuala Lumpur, the capital of Malaysia, and prioritized five important factors as safety commitment and responsibilities, sub-contractors and personnel's selection, safety supervisor and professionals, plan for safety, and employee involvement and safety evaluation.

Further, various scholars also have researched the CSFs for safety program implementation in the construction industry. Aksorn and Hadikusumo [19] examined CFSs influencing safety program performance in Thai construction projects and found out that the most influential factor is management support. Omran et al. [62] identified the CFSs that influence safety program performance in Malaysian construction projects, the results revealed that good communication is considered as the most important factor, followed by clear and realistic goals, safety committee/safety officer, sufficient resource allocation, and continuous participation of employee. Haadir and Panuwatwanich [21] studied the CFSs affecting the successful implementation of safety programs among construction companies in Saudi Arabia. The results concluded that seven critical safety factors that positively affect safety programs implementation include management support, clear and reasonable objectives, personal attitude, teamwork, effective enforcement, safety training, and suitable supervision. Buniya et al. [22] discussed the CSFs of safety program implementation in the Iraqi construction industry. The identified 21 CSFs are classified into four dimensions, namely worker involvement, safety prevention and control system, safety arrangement, and management commitment. Based on the results of previous studies concerning safety program implementation, 16 factors for safety program implementation of RAIB projects have been listed in Table 1.

Table 1. Factors affecting safety program implementation.

Number	Factor	Description	References
C1	Management support	Management support should allocate sufficient resources for safety management, formulate safety policies, and coordinate with employees to ensure the implementation of safety management activities. Management support also can help enterprises form a good safety climate and safety culture.	[19,22,61,63,64]
C2	Clear safety objectives	Reasonable safety objectives provide employees with a clear working direction and can be used as an indicator to measure safety performance. Safety objectives should be focused and prioritized, and also be integrated with the actual situation of the project.	[19,22,61]
C3	Allocation of authority and responsibility	Everyone is responsible for safety. Appropriate safety authorities and responsibilities should be clearly assigned to individuals. It can increase the safety motivation of people to take corresponding actions in safety activities.	[22,61,63–65]
C4	Program evaluation	A safety program should be monitored and reviewed regularly to determine whether it is successfully meeting the safety objectives.	[3,19,22]
C5	Control of Subcontractor	Subcontractor management entails ensuring subcontractor qualification and performance to ensure safe work practices at all levels.	[64–66]
C6	Participation of employees	The implementation of the safety program requires the participation of all employees, such as attending safety meetings and safety operations.	[64–66]
C7	Communication	The communication between managers and employees strengthens the transmission of information. Employees report the site situation to managers, and in turn, managers respond to the unsafe situation in time.	[55,64,65,67]
C8	Personal competency	Personal competency refers to people being able to identify and evaluate risks properly and also make the right decision at the right time based on their own knowledge, experience, and skills.	[55,65,66]
C9	Personal attitude	People with a positive safety attitude will pay attention to protecting their own safety and take correct emergency measures in time when accidents happen. On the contrary, when a person has a negative attitude, he or she may ignore potential hazard sources and conduct unsafe operations.	[42,64,66,68]
C10	Safety education and training of workers	Through regular safety education and training, all employees are given safety knowledge and skills to improve their safety attitude and behavior to prevent accidents.	[64–66,69]
C11	safety meeting	Safety meetings should be held regularly and safety records should be established to improve safety performance.	[64–66,69]
C12	Safety supervision	Safety personnel supervise workers' operations, assess hazardous conditions and communicate with workers on site, ensuring workers follow safety rules.	[65,66]
C13	Sufficient resources	Sufficient resources are the premise of realizing the short-term and long-term goals of safety management, including the input of human, material, and financial resources in safety activities.	[65,66]

Table 1. *Cont.*

Number	Factor	Description	References
C14	Safety inspections and hazard assessment	Check the safety problems and hidden dangers in the construction process regularly, so as to take appropriate corrective measures to solve the problems immediately and prevent the occurrence of accidents.	[65–67]
C15	Safety incentive	Safety incentives can motivate workers to maintain the enthusiasm and initiative towards safe behavior. Safety incentives can be economic or non-economic awards.	[66,70–73]
C16	Safety equipment acquisition and maintenance	Proper selection and regular maintenance of safety equipment must focus on creating a safe working environment	[65,66]

4. Methods

There have been lots of techniques to explore the critical factors of a project by researchers, such as the Analytic Hierarchy Process (AHP) approach [33,74], the Technique for Order Preference by Similarity to an Ideal Solution (TOPSIS) approach [75], and the structural equation model (SEM) [35]. However, AHP and TOPSIS approaches could not examine the interrelationship between factors, and the structural equation model requires a certain number of samples. To avoid these disadvantages, the Decision-making Trial and Evaluation Laboratory (DEMATEL) technique is considered as the best technique to identify critical factors. The DEMATEL approach was proposed in the Geneva Research Center of the Battelle Memorial Institute in 1972 by Gabus and Fontela [76]. It is a system analysis method that uses graph theory and matrix tools to explain complicated problems. It obtains the mutual influence and causality among factors in complex problems based on the experience and knowledge of experts, and then reveals the driving factors through comprehensive analysis. To solve the fuzziness caused by experts' subjective judgment, the triangle fuzzy number method is introduced to process the initial direct relation matrix to improve the accuracy of the DEMATEL method by Wu and Lee [77]. The Fuzzy DEMATEL technique also can be used with a small sample size [78]. At present, fuzzy DEMATEL method has been widely used in the research of CSFs in the field of supply chain management [79–81] and the construction industry [82–85]. Therefore, the fuzzy DEMATEL method (Figure 3) was used to identify the CSFs for safety program implementation of RAIB projects in this study. The flow diagram of the fuzzy DEMATEL approach is shown in Figure 3.

4.1. Triangular Fuzzy Numbers

The language judgment of decision makers always has an ambiguous characteristic. Fuzzy numbers become more meaningful to convert a subjective judgement into a range rather than a crisp value. Two types of fuzzy numbers, namely triangular and trapezoidal fuzzy numbers, are commonly used. In this study, triangular fuzzy numbers (TFNs) are used because they have simple forms that are easy to calculate [86]. Triangular fuzzy number is a concept of fuzzy set proposed by Zadeh in 1965 to address the problem under the situation of insufficient information [87]. We define a fuzzy number $\widetilde{Z} = (l, m, u)$ on R to be a triangular fuzzy number if its membership function $\mu_{\widetilde{Z}}(x)$ is equal to:

$$\mu_{\widetilde{Z}}(x) = \begin{cases} \frac{x-l}{m-l} & x \in [l, m] \\ \frac{x-u}{m-u} & x \in [m, u] \\ 0 & \text{otherwise} \end{cases}, \tag{1}$$

where $0 \leq l \leq m \leq u \leq 1$. And where $\mu_{\widetilde{Z}}(x) \in [0, 1]$, $\mu_{\widetilde{Z}}(x)$ repents the degree of x attributed to $\widetilde{Z}$, l, m, u refer to the smallest value, the most likely value, and the largest value of the support of $\widetilde{Z}$ respectively. When $l = m = u$, $\widetilde{Z}$ is an exact value. Figure 4 shows the distribution of a triangular fuzzy number.

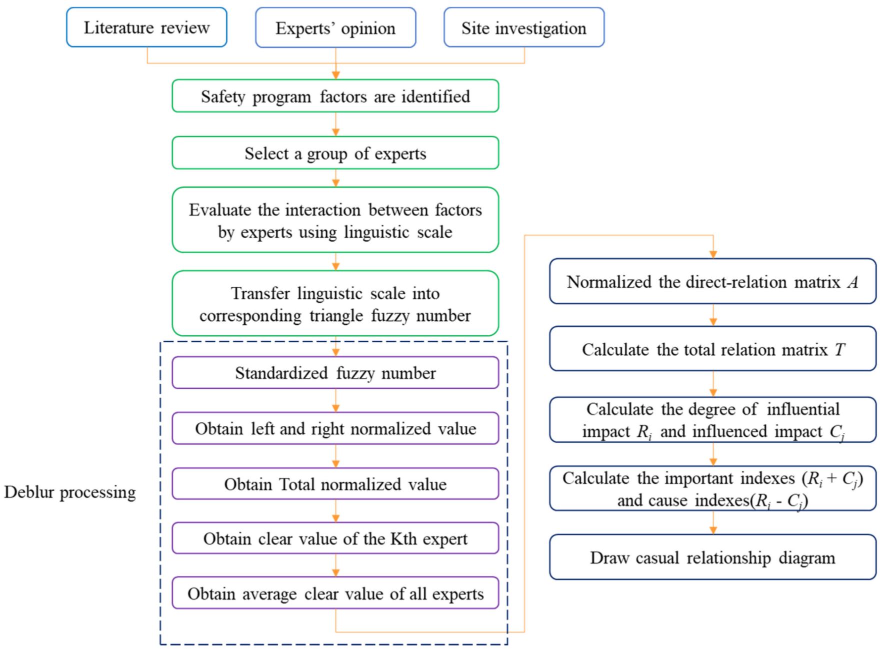

Figure 3. Flow diagram of the fuzzy DEMATEL approach.

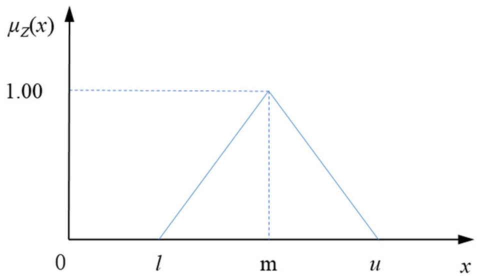

Figure 4. Triangular fuzzy number.

The membership function of triangular fuzzy numbers is shown in Figure 5. Based on the principle proposed by Zadeh [87], consider two different triangular fuzzy numbers, $M_1 = (l_1, m_1, u_1)$ and $M_2 = (l_2, m_2, u_2)$, with (l_1 and $l_2 \geq 0$), then the basic operation rules of triangular fuzzy numbers are defined as Formulas (2)–(6). Therefore, fuzzy ratings and their membership function are presented in Figure 5. The conversion method between the linguistic variable and the corresponding triangular fuzzy number is shown in Table 2 [80,83,88,89].

$$\widetilde{M}_1 = (\widetilde{l}_1, \widetilde{m}_1, \widetilde{u}_1);\ \widetilde{M}_2 = (\widetilde{l}_2, \widetilde{m}_2, \widetilde{u}_2), \tag{2}$$

$$\widetilde{M}_1 \oplus \widetilde{M}_2 = (\widetilde{l}_1 + \widetilde{l}_2, \widetilde{m}_1 + \widetilde{m}_2, \widetilde{u}_1 + \widetilde{u}_2), \tag{3}$$

$$\widetilde{M}_1 \otimes \widetilde{M}_2 \approx (\widetilde{l}_1\widetilde{l}_2, \widetilde{m}_1\widetilde{m}_2, \widetilde{u}_1\widetilde{u}_2), \tag{4}$$

$$\lambda \otimes \widetilde{M}_1 \approx (\lambda\widetilde{l}_1, \lambda\widetilde{m}_1, \lambda\widetilde{u}_1), \tag{5}$$

$$\frac{1}{\widetilde{M}_1} \approx (\frac{1}{\widetilde{l}_1}, \frac{1}{\widetilde{m}_1}, \frac{1}{\widetilde{u}_1}), \tag{6}$$

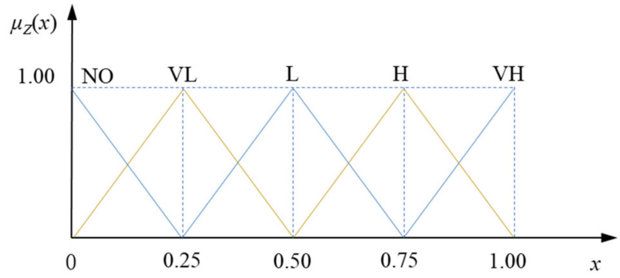

Figure 5. Fuzzy ratings and their membership function.

Table 2. Conversion relation between linguistic variables and triangular fuzzy numbers.

Linguistic Variable	Triangular Fuzzy Number
No influence	(0, 0, 0.25)
Very low influence	(0, 0.25, 0.5)
low influence	(0.25, 0.5, 0.75)
High influence	(0.5, 0.75, 1)
Very high influence	(0.75, 1, 1)

4.2. Fuzzy DEMATEL Method

The steps of the fuzzy DEMATEL approach are illustrated as follows:

Step 1: Choose a group of experts in a related field.

In this step, a panel of experts who have sufficient knowledge and experience in the relevant field was invited to evaluate the interaction between the factors.

Step 2: Evaluate the interactions among factors by experts with linguistic scale.

All experts were required to assess the degree of influence among factors using a linguistic variable, which includes "No influence (N)", "Very low influence (VL)", "Low influence (L)", "High influence (H)" and "Very high influence (VH)". By doing so, initial evaluation results were obtained.

Step 3: Transfer the linguistic variable into triangular fuzzy number.

According to Table 2, the linguistic assessment of experts can be converted into corresponding triangular fuzzy numbers. Then an initial direct relation fuzzy matrix is established. The initial direct relation fuzzy matrix $\widetilde{Z}_{ij}^k$ of each expert can be defined as follows:

$$\widetilde{Z}_{ij}^k = \begin{bmatrix} 0 & \widetilde{z}_{12}^k & \cdots & \widetilde{z}_{1n}^k \\ \vdots & \vdots & & \vdots \\ \widetilde{z}_{n1}^k & \widetilde{z}_{n2}^k & \cdots & 0 \end{bmatrix}_{n\times n}, \quad (7)$$

where $\widetilde{Z}_{ij}^k = [\widetilde{z}_{ij}^k]_{n\times n}$ and $\widetilde{z}_{ij}^k = (\widetilde{l}_{ij}^k, \widetilde{m}_{ij}^k, \widetilde{u}_{ij}^k)$. $\widetilde{z}_{ij}$ represents the direct influence of factor i on factor j. Where k represents the evaluation result of kth expert. When $i = j$, $\widetilde{z}_{ij}^k = (0, 0, 0)$.

Step 4: De-fuzzy the triangular fuzzy numbers into crisp values.

Converting the fuzzy data into crisp scores (CFCS) method proposed by Opricovic and Tzeng (2003) [90] was used to transfer triangular fuzzy numbers into crisp values. The specific steps are shown as follows:

(1) Standardize the fuzzy numbers with the Formulas (8)–(10).

$$xl_{ij}^k = (l_{ij}^k - \min_{1\le k\le K} l_{ij}^k)/(\max_{1\le k\le K} u_{ij}^k - \min_{1\le k\le K} l_{ij}^k), \quad (8)$$

$$xm_{ij}^k = (m_{ij}^k - \min_{1\le k\le K} l_{ij}^k)/(\max_{1\le k\le K} u_{ij}^k - \min_{1\le k\le K} l_{ij}^k), \quad (9)$$

$$xu_{ij}^k = (u_{ij}^k - \min_{1\le k\le K} l_{ij}^k)/(\max_{1\le k\le K} u_{ij}^k - \min_{1\le k\le K} l_{ij}^k), \quad (10)$$

(2) Then the left and right normalized values are calculated as follows:

$$xls_{ij}^k = xm_{ij}^k / (1 + xm_{ij}^k - xl_{ij}^k), \tag{11}$$

$$xus_{ij}^k = xu_{ij}^k / (1 + xu_{ij}^k - xm_{ij}^k), \tag{12}$$

(3) Total normalized values are calculated as follows:

$$x_{ij}^k = [xls_{ij}^k(1 - xls_{ij}^k) + xus_{ij}^k xus_{ij}^k] / (1 + xus_{ij}^k - xls_{ij}^k), \tag{13}$$

(4) Crisp value of evaluation results of the Kth expert is shown as follows:

$$z_{ij}^k = \min_{1 \le k \le K} l_{ij}^k + x_{ij}^k (\max_{1 \le k \le K} u_{ij}^k - \min_{1 \le k \le K} l_{ij}^k), \tag{14}$$

Step 5: Calculate initial direct relation matrix as follows:

$$W = \frac{1}{K} \sum_{1 \le k \le K} Z_{ij}^k, \tag{15}$$

where $Z_{ij}^k = \left[z_{ij}^k\right]_{n \times n}$, Then initial direct-relation matrix $W = \left[w_{ij}\right]_{n \times n}$ is obtained. w_{ij} is a crisp value reflecting the direct influence of factor i on factor j.

Step 6: Normalize the direct-relation matrix

The normalized direct-relation matrix A is calculated as follows:

$$A = S \times W, \tag{16}$$

where $S = \frac{1}{\max\limits_{1 \le i \le n} \sum_{j=1}^n w_{ij}}$.

Step 7: Calculate the total relation matrix.

The total relation matrix T is defined as $T = A + A^2 + \cdots + A^n$. When n is large enough, the matrix T can be calculated as follows:

$$T = A \times (I - A)^{-1}, \tag{17}$$

where I denote identity matrix. Where T represent the matrix $T_{ij} = [t_{ij}]_{n \times n}$. t_{ij} is not only include the direct interactions of factor i on factor j. but also include the indirect interactions of factor i on factor j.

Step 8: Calculate the degree of influential impact R_i and influenced impact C_i.

According to the total relation matrix T, the sum of rows and the sum of columns is the degree of influential impact R_i and influenced impact C_i, respectively. R_i and C_i are calculated as follows:

$$R_i = \sum_{j=1}^{n} t_{ij}, \tag{18}$$

$$C_i = \sum_{i=1}^{n} t_{ij}, \tag{19}$$

Step 9: Calculate the degree of importance (R_i + C_i) and the causal degree ($R_i - C_i$).

(R_i + C_i) represents the importance of factors and the influence degree of factors. The greater the (R_i + C_i) is, the more significant the degree of influence of the factor is. When ($R_i - C_i$) > 0, it means that other factors are easily affected by these factors, which can be grouped into the cause factor. Conversely, when ($R_i - C_i$) < 0, it indicates that other factors can easily influence this factor, which can be grouped into the effect factor.

Step 10: Draw the casual relationship diagram.

The casual relationship diagram is drawn by (R_i + C_i) for the horizontal axis and ($R_i - C_i$) for the vertical axis.

5. Results

5.1. Applications of the Fuzzy-DEMATEL Method

First, A group of experts specializing in RAIB practice were invited to determine the direct influence between pair-wise factors for safety program implantation of RAIB projects. including owners, contractors, professors, and supervisors. These experts interviewed had more than 6 years of experience in the field (Table 3). In step 2, the degree of influence between pair-wise factors for safety program implantation of RAIB projects was determined by thirteen experts using linguistic variables provided in Table 2. For example, the initial evaluation result of expert 1 is shown in Table 4. In step 3, the linguistic variables of each expert were transformed into corresponding triangular fuzzy numbers according to Table 2, for example, the initial direct relation fuzzy matrix of expert 1 is shown in Table 5. In step 4–5, to construct the initial direct relation matrix, triangular fuzzy numbers are converted as crisp value by defuzzification process using Formulas (8)–(14), then the initial direct relation matrix of expert 1 is shown in Table 6 and the average initial direct relation matrix of all experts is shown in Table 7 using Formula (15). In step 6, the normalized direct relation matrix was extracted by using Formula (16). The normalized direct relation matrix of factors for safety program implantation of RAIB projects is shown in Table 8. In step 7, The total relation matrix of influencing factors for safety program implantation of RAIB projects was obtained by using Formula (17) and presented in Table 9. In step 8, the degree of influential impact R_i and influenced impact C_i of influencing factors for safety program implantation of RAIB projects was calculated by using Formulas (18) and (19) and shown in Table 10. In step 9, The degree of importance ($R_i + C_i$) and the causal degree ($R_i - C_i$) of influencing factors for safety program implantation of RAIB projects was calculated and presented in Table 10. Finally, the causal diagram is drawn with the horizontal axis ($R_i + C_i$) named "the degree of importance" and the vertical axis ($R_i - C_i$) named "the casual degree" (Figure 6).

Table 3. Details about experts.

No. Expert	Job Field	Experience (Years)	Education Level
1	Professor	6	Doctor
2	Professor	8	Doctor
3	Owner	4	Undergraduate
4	Owner	7	Undergraduate
5	Owner	6	Bachelor
6	Contractor	9	Undergraduate
7	Contractor	6	Undergraduate
10	Contractor	7	Bachelor
11	Contractor	8	Doctor
12	Contractor	6	Undergraduate
13	Contractor	7	Undergraduate

Table 4. Initial evaluation results for expert 1.

Factor	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13	C14	C15	C16
C1	-	H	VH	H	VH	VH	VH	H	VH	H	H	H	VH	H	VH	H
C2	H	-	L	H	H	H	H	L	H	H	L	L	L	L	H	H
C3	H	H	-	H	VH	VH	VH	H	VH	H	H	VH	H	H	VH	H
C4	L	L	L	-	H	H	L	L	L	L	L	H	L	H	L	L
C5	L	H	L	H	-	VH	VH	H	VH	H	H	H	VH	H	H	VH
C6	L	L	L	L	L	-	VH	H	VH	VH	VH	VH	H	H	VH	H
C7	H	H	H	H	H	H	-	L	VH	H	H	H	H	H	L	H
C8	L	L	L	L	VL	H	H	-	L	L	H	L	L	H	L	L
C9	H	L	VH	L	H	VH	VH	H	-	VH	H	VH	H	VH	H	H
C10	L	L	H	L	L	H	H	H	H	-	H	H	L	H	H	H

Table 4. *Cont.*

Factor	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13	C14	C15	C16
C11	L	H	H	L	L	H	H	VL	VH	H	-	H	VH	VH	VH	H
C12	L	L	L	H	VL	L	H	VL	L	L	L	-	L	H	L	H
C13	H	VL	VL	L	L	L	L	L	L	VL	VL	L	-	L	L	VL
C14	H	H	H	H	H	H	H	L	VH	H	H	H	H	-	H	H
C15	H	L	H	L	H	H	H	L	H	H	H	H	L	L	-	H
C16	L	L	L	L	VL	H	H	L	H	L	VL	L	L	L	H	-

Table 5. Initial direct relation fuzzy matrix for expert 1.

Factor	C1	C2	C3	C4	C13	C14	C15	C16
C1	-	(0.5, 0.75, 1)	(0.75, 1, 1)	...	(0.75, 1, 1)	(0.5, 0.75, 1)	(0.75, 1, 1)	(0.5, 0.75, 1)
C2	(0.5, 0.75, 1)	-	(0.25, 0.5, 0.75)	...	(0.25, 0.5, 0.75)	(0.25, 0.5, 0.75)	(0.5, 0.75, 1)	(0.5, 0.75, 1)
C3	(0.5, 0.75, 1)	(0.5, 0.75, 1)	-	...	(0.5, 0.75, 1)	(0.5, 0.75, 1)	(0.75, 1, 1)	(0.5, 0.75, 1)
C4	(0.25, 0.5, 0.75)	(0.25, 0.5, 0.75)	(0.25, 0.5, 0.75)	...	(0.25, 0.5, 0.75)	(0.5, 0.75, 1)	(0.25, 0.5, 0.75)	(0.25, 0.5, 0.75)
C5	(0.25, 0.5, 0.75)	(0.5, 0.75, 1)	(0.25, 0.5, 0.75)	...	(0.75, 1, 1)	(0.5, 0.75, 1)	(0.5, 0.75, 1)	(0.75, 1, 1)
C6	(0.25, 0.5, 0.75)	(0.25, 0.5, 0.75)	(0.25, 0.5, 0.75)	...	(0.5, 0.75, 1)	(0.5, 0.75, 1)	(0.75, 1, 1)	(0.5, 0.75, 1)
C7	(0.5, 0.75, 1)	(0.5, 0.75, 1)	(0.5, 0.75, 1)	...	(0.5, 0.75, 1)	(0.5, 0.75, 1)	(0.25, 0.5, 0.75)	(0.5, 0.75, 1)
C8	(0.25, 0.5, 0.75)	(0.25, 0.5, 0.75)	(0.25, 0.5, 0.75)	...	(0.25, 0.5, 0.75)	(0.5, 0.75, 1)	(0.25, 0.5, 0.75)	(0.25, 0.5, 0.75)
C9	(0.5, 0.75, 1)	(0.25, 0.5, 0.75)	(0.75, 1, 1)	...	(0.5, 0.75, 1)	(0.75, 1, 1)	(0.5, 0.75, 1)	(0.5, 0.75, 1)
C10	(0.25, 0.5, 0.75)	(0.25, 0.5, 0.75)	(0.5, 0.75, 1)	...	(0.25, 0.5, 0.75)	(0.5, 0.75, 1)	(0.5, 0.75, 1)	(0.5, 0.75, 1)
C11	(0.25, 0.5, 0.75)	(0.5, 0.75, 1)	(0.5, 0.75, 1)	...	(0.75, 1, 1)	(0.75, 1, 1)	(0.75, 1, 1)	(0.5, 0.75, 1)
C12	(0.25, 0.5, 0.75)	(0.25, 0.5, 0.75)	(0.25, 0.5, 0.75)	...	(0.25, 0.5, 0.75)	(0.5, 0.75, 1)	(0.25, 0.5, 0.75)	(0.5, 0.75, 1)
C13	(0.5, 0.75, 1)	(0, 0.25, 0.5)	(0, 0.25, 0.5)	...	-	(0.25, 0.5, 0.75)	(0.25, 0.5, 0.75)	(0, 0.25, 0.5)
C14	(0.5, 0.75, 1)	(0.5, 0.75, 1)	(0.5, 0.75, 1)	...	(0.5, 0.75, 1)	-	(0.5, 0.75, 1)	(0.5, 0.75, 1)
C15	(0.5, 0.75, 1)	(0.25, 0.5, 0.75)	(0.5, 0.75, 1)	...	(0.25, 0.5, 0.75)	(0.25, 0.5, 0.75)	-	(0.5, 0.75, 1)
C16	(0.25, 0.5, 0.75)	(0.25, 0.5, 0.75)	(0.25, 0.5, 0.75)	...	(0.25, 0.5, 0.75)	(0.25, 0.5, 0.75)	(0.5, 0.75, 1)	-

Table 6. Initial direct relation matrix for expert 1.

Factor	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13	C14	C15	C16
C1	0.000	0.733	0.967	0.733	0.967	0.967	0.967	0.733	0.967	0.733	0.733	0.733	0.967	0.733	0.967	0.733
C2	0.733	0.000	0.500	0.733	0.733	0.733	0.733	0.500	0.733	0.733	0.500	0.500	0.500	0.500	0.733	0.733
C3	0.733	0.733	0.000	0.733	0.967	0.967	0.967	0.733	0.967	0.733	0.733	0.967	0.733	0.733	0.967	0.733
C4	0.500	0.500	0.500	0.000	0.733	0.733	0.500	0.500	0.500	0.500	0.500	0.733	0.500	0.733	0.500	0.500
C5	0.500	0.733	0.500	0.733	0.000	0.967	0.967	0.733	0.967	0.733	0.733	0.733	0.967	0.733	0.733	0.967
C6	0.500	0.500	0.500	0.500	0.500	0.000	0.967	0.733	0.967	0.967	0.967	0.967	0.733	0.733	0.967	0.733
C7	0.733	0.733	0.733	0.733	0.733	0.733	0.000	0.500	0.967	0.733	0.733	0.733	0.733	0.733	0.500	0.733
C8	0.500	0.500	0.500	0.500	0.267	0.733	0.733	0.000	0.500	0.500	0.733	0.500	0.500	0.733	0.500	0.500
C9	0.733	0.500	0.967	0.500	0.733	0.967	0.967	0.733	0.000	0.967	0.733	0.967	0.733	0.967	0.733	0.733
C10	0.500	0.500	0.733	0.500	0.500	0.733	0.733	0.733	0.733	0.000	0.733	0.733	0.500	0.733	0.733	0.733
C11	0.500	0.733	0.733	0.500	0.500	0.733	0.733	0.267	0.967	0.733	0.000	0.733	0.967	0.967	0.967	0.733
C12	0.500	0.500	0.500	0.733	0.267	0.500	0.733	0.267	0.500	0.500	0.500	0.000	0.500	0.733	0.500	0.733
C13	0.733	0.267	0.267	0.500	0.500	0.500	0.500	0.500	0.500	0.267	0.267	0.500	0.000	0.500	0.500	0.267
C14	0.733	0.733	0.733	0.733	0.733	0.733	0.733	0.500	0.967	0.733	0.733	0.733	0.733	0.000	0.733	0.733
C15	0.733	0.500	0.733	0.500	0.733	0.733	0.733	0.500	0.733	0.733	0.733	0.733	0.500	0.500	0.000	0.733
C16	0.500	0.500	0.500	0.500	0.267	0.733	0.733	0.500	0.733	0.500	0.267	0.500	0.500	0.500	0.733	0.000

Table 7. Average initial direct relation matrix.

Factor	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13	C14	C15	C16
C1	0.000	0.697	0.769	0.697	0.733	0.769	0.805	0.733	0.805	0.787	0.787	0.769	0.823	0.787	0.805	0.769
C2	0.643	0.000	0.554	0.769	0.518	0.500	0.625	0.410	0.536	0.697	0.625	0.661	0.554	0.661	0.625	0.715
C3	0.805	0.518	0.000	0.518	0.464	0.823	0.823	0.572	0.841	0.715	0.733	0.769	0.643	0.751	0.787	0.787
C4	0.554	0.625	0.464	0.000	0.446	0.446	0.500	0.410	0.554	0.554	0.518	0.572	0.464	0.661	0.554	0.572
C5	0.410	0.482	0.410	0.482	0.000	0.679	0.769	0.697	0.751	0.697	0.697	0.715	0.733	0.733	0.679	0.715

Table 7. *Cont.*

Factor	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13	C14	C15	C16
C6	0.590	0.410	0.446	0.446	0.464	0.000	0.805	0.625	0.787	0.679	0.751	0.751	0.608	0.715	0.697	0.733
C7	0.733	0.608	0.625	0.661	0.446	0.733	0.000	0.500	0.751	0.715	0.679	0.733	0.590	0.769	0.608	0.697
C8	0.536	0.554	0.536	0.554	0.375	0.554	0.608	0.000	0.625	0.518	0.554	0.536	0.500	0.590	0.500	0.608
C9	0.715	0.590	0.715	0.608	0.625	0.733	0.751	0.679	0.000	0.769	0.715	0.751	0.625	0.787	0.590	0.679
C10	0.608	0.482	0.572	0.500	0.375	0.733	0.751	0.715	0.751	0.000	0.697	0.697	0.482	0.733	0.643	0.733
C11	0.446	0.554	0.590	0.464	0.392	0.715	0.751	0.482	0.697	0.554	0.000	0.733	0.482	0.715	0.500	0.733
C12	0.464	0.590	0.464	0.572	0.446	0.679	0.715	0.357	0.679	0.536	0.608	0.000	0.536	0.823	0.572	0.733
C13	0.733	0.410	0.375	0.500	0.482	0.446	0.518	0.392	0.464	0.464	0.357	0.392	0.000	0.446	0.428	0.410
C14	0.715	0.679	0.554	0.679	0.679	0.715	0.697	0.590	0.715	0.733	0.679	0.679	0.679	0.000	0.661	0.679
C15	0.661	0.536	0.661	0.500	0.572	0.769	0.715	0.518	0.751	0.554	0.590	0.733	0.482	0.661	0.000	0.661
C16	0.572	0.536	0.536	0.464	0.446	0.733	0.715	0.572	0.733	0.428	0.518	0.643	0.590	0.625	0.554	0.000

Table 8. Normalized direct relation matrix.

Factor	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13	C14	C15	C16
C1	0.000	0.060	0.067	0.060	0.064	0.067	0.070	0.064	0.070	0.068	0.068	0.067	0.071	0.068	0.070	0.067
C2	0.056	0.000	0.048	0.067	0.045	0.043	0.054	0.036	0.046	0.060	0.054	0.057	0.048	0.057	0.054	0.062
C3	0.070	0.045	0.000	0.045	0.040	0.071	0.071	0.050	0.073	0.062	0.064	0.067	0.056	0.065	0.068	0.068
C4	0.048	0.054	0.040	0.000	0.039	0.039	0.043	0.036	0.048	0.048	0.045	0.050	0.040	0.057	0.048	0.050
C5	0.036	0.042	0.036	0.042	0.000	0.059	0.067	0.060	0.065	0.060	0.060	0.062	0.064	0.064	0.059	0.062
C6	0.051	0.036	0.039	0.039	0.040	0.000	0.070	0.054	0.068	0.059	0.065	0.065	0.053	0.062	0.060	0.064
C7	0.064	0.053	0.054	0.057	0.039	0.064	0.000	0.043	0.065	0.062	0.059	0.064	0.051	0.067	0.053	0.060
C8	0.046	0.048	0.046	0.048	0.032	0.048	0.053	0.000	0.054	0.045	0.048	0.046	0.043	0.051	0.043	0.053
C9	0.062	0.051	0.062	0.053	0.054	0.064	0.065	0.059	0.000	0.067	0.062	0.065	0.054	0.068	0.051	0.059
C10	0.053	0.042	0.050	0.043	0.032	0.064	0.065	0.062	0.065	0.000	0.060	0.060	0.042	0.064	0.056	0.064
C11	0.039	0.048	0.051	0.040	0.034	0.062	0.065	0.042	0.060	0.048	0.000	0.064	0.042	0.062	0.043	0.064
C12	0.040	0.051	0.040	0.050	0.039	0.059	0.062	0.031	0.059	0.046	0.053	0.000	0.046	0.071	0.050	0.064
C13	0.064	0.036	0.032	0.043	0.042	0.039	0.045	0.034	0.040	0.040	0.031	0.034	0.000	0.039	0.037	0.036
C14	0.062	0.059	0.048	0.059	0.059	0.062	0.060	0.051	0.062	0.064	0.059	0.059	0.059	0.000	0.057	0.059
C15	0.057	0.046	0.057	0.043	0.050	0.067	0.062	0.045	0.065	0.048	0.051	0.064	0.042	0.057	0.000	0.057
C16	0.050	0.046	0.046	0.040	0.039	0.064	0.062	0.050	0.064	0.037	0.045	0.056	0.051	0.054	0.048	0.000

Table 9. Total relation matrix.

Factor	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13	C14	C15	C16
C1	0.000	0.018	0.020	0.018	0.017	0.023	0.025	0.019	0.025	0.022	0.023	0.023	0.022	0.024	0.023	0.023
C2	0.014	0.000	0.011	0.017	0.010	0.012	0.016	0.008	0.013	0.016	0.014	0.016	0.012	0.017	0.014	0.018
C3	0.021	0.012	0.000	0.012	0.009	0.023	0.024	0.013	0.025	0.019	0.020	0.022	0.016	0.022	0.021	0.022
C4	0.011	0.012	0.008	0.000	0.007	0.009	0.011	0.007	0.012	0.011	0.010	0.012	0.009	0.015	0.011	0.012
C5	0.009	0.010	0.008	0.010	0.000	0.017	0.021	0.015	0.020	0.017	0.017	0.018	0.017	0.019	0.016	0.018
C6	0.014	0.008	0.009	0.009	0.009	0.000	0.022	0.013	0.021	0.016	0.018	0.019	0.013	0.019	0.016	0.019
C7	0.018	0.013	0.014	0.015	0.009	0.019	0.000	0.011	0.020	0.018	0.017	0.019	0.013	0.021	0.014	0.018
C8	0.011	0.010	0.010	0.010	0.006	0.012	0.014	0.000	0.014	0.010	0.011	0.012	0.010	0.013	0.010	0.013
C9	0.018	0.013	0.017	0.014	0.013	0.020	0.021	0.016	0.000	0.020	0.019	0.021	0.015	0.022	0.014	0.019
C10	0.014	0.010	0.012	0.010	0.007	0.019	0.020	0.016	0.020	0.000	0.017	0.018	0.010	0.019	0.015	0.019
C11	0.009	0.011	0.012	0.009	0.007	0.017	0.019	0.009	0.017	0.012	0.000	0.018	0.010	0.018	0.010	0.018
C12	0.010	0.012	0.009	0.011	0.008	0.016	0.018	0.007	0.017	0.012	0.014	0.000	0.011	0.021	0.012	0.018
C13	0.014	0.006	0.006	0.008	0.007	0.008	0.010	0.006	0.009	0.008	0.006	0.007	0.000	0.008	0.007	0.007
C14	0.018	0.015	0.012	0.016	0.014	0.019	0.019	0.013	0.020	0.019	0.017	0.018	0.016	0.000	0.016	0.018
C15	0.015	0.011	0.014	0.010	0.011	0.020	0.019	0.011	0.020	0.013	0.014	0.019	0.010	0.017	0.000	0.017
C16	0.012	0.010	0.010	0.009	0.008	0.018	0.018	0.011	0.018	0.009	0.011	0.015	0.012	0.015	0.012	0.000

Table 10. Casual diagram.

Factor	R	Rank	C	Rank	R + C	Rank	R − C	Cause/Effect
C1	0.325	1	0.208	9	0.533	1	0.117	Cause
C2	0.206	10	0.172	13	0.378	12	0.035	Cause
C3	0.280	2	0.172	13	0.452	6	0.108	Cause
C4	0.157	15	0.179	11	0.335	15	−0.022	Effect
C5	0.233	6	0.141	14	0.375	13	0.092	Cause
C6	0.226	7	0.252	5	0.478	5	−0.026	Effect
C7	0.240	5	0.275	1	0.516	4	−0.035	Effect
C8	0.167	14	0.174	12	0.340	14	−0.007	Effect
C9	0.262	3	0.270	2	0.532	2	−0.008	Effect
C10	0.225	8	0.222	7	0.447	9	0.004	Cause
C11	0.196	11	0.228	6	0.424	11	−0.032	Effect
C12	0.193	12	0.257	4	0.451	7	−0.064	Effect
C13	0.118	16	0.196	10	0.314	16	−0.078	Effect
C14	0.251	4	0.270	2	0.521	3	−0.020	Effect
C15	0.220	9	0.212	8	0.432	10	0.008	Cause
C16	0.188	13	0.261	3	0.448	8	−0.073	Effect

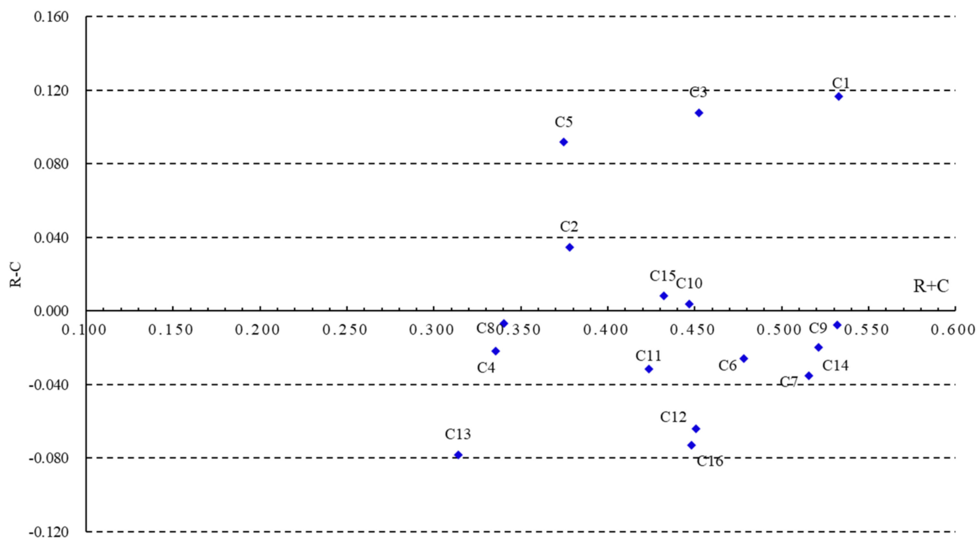

Figure 6. Causal diagram.

Further, the degree of importance ($R_i + C_i$) and the causal degree ($R_i - C_i$) the core indicator of fuzzy DEMATEL analysis. The degree of importance ($R_i + C_i$) reflects the importance of the factors in the entire system. The greater the ($R_i + C_i$) is, the more significant the degree of influence of the factor is. The degree of importance ($R_i + C_i$) order of sixteen factors for affecting safety program implementation of RAIB projects is given as C1 > C9> C14 > C7 > C6 > C3 > C12 > C16 > C10 > C15 > C11 > C2 > C5 > C8 > C4 > C13.

In addition, the causal degree ($R_i - C_i$) is classified as two group factors, including cause group factors and effect group factors. When ($R_i - C_i$) > 0, it means that other factors are easily affected by this factor, which can be grouped into the cause group factor. Conversely, when ($R_i - C_i$) < 0, it indicates that other factors can easily influence this factor, which can be grouped into the effect group factor. Management support (C1), clear safety objective (C2), Allocation of authority and responsibility (C3), control of subcontractor (C5), safety education and training (C10), and effective enforcement scheme (C15) were categorized into the cause group factors. Other factors, program evaluation (C4), employee involvement (C6), communication (C7), personal competency (C8), personal attitude (C9), safety meeting (C11), safety check (C12), safety resources (C13), safety inspections and hazard assessment (C14), safety equipment and maintenance (C16) belongs to effect group factors.

5.2. Identification of CSFs

5.2.1. Cause Group Factors

Among all the cause group factors, "management support (C1)" has the highest ($R_i - C_i$), meaning that C1 has the greatest impact on the overall system. Moreover, Table 10 shows that the R_i and ($R_i + C_i$) score of C1 is 0.208 and 0.533 respectively, which all rank first place among all factors announcing that C1 is the most important factor in the whole system. All evidence suggests that C1 has a significant influence on other factors, and that advancement of C1 can contribute to the improvement of the whole system. That is, to enhance the effectiveness of the safety program implementation of RAIB projects, management support needs to be first considered. Therefore, C1 is a CSF for the safety program implementation of RAIB projects.

"Allocation of authority and responsibility" (C3) has the second causal degree ($R_i - C_i$) value in addition to the second value of the R_i and the low ranking of the C_i. These indicate that the impact it dispatches on other factors is significant while the impact it receives is small, thus playing a critical role in the safety program implementation of RAIB projects. Accordingly, C3 can be clustered as a CSF.

The factor having the third-highest ($R_i - C_i$) is "Control of Subcontractor" (C5). However, as shown in Figure 4, its value of the ($R_i + C_i$) is relatively low. The value of other indexes can make certain the reason for it. According to the R_i and C_i of C5, it has a great influence on others while the effect it receives from others is very insignificant, which leads to a small ($R_i + C_i$). Nevertheless, this relatively small value of ($R_i + C_i$) could not negate the fact that C5 has a great influence on the overall system. So "Control of Subcontractor" can lead to the development of the whole system. Accordingly, C5 can be considered as a CSF.

The cause indexes ($R_i - C_i$) value of "Clear safety objectives" (C2) ranks fourth place in all cause-group factors. But the ($R_i + C_i$) value of C2 is the lowest in all factors. Besides, both the R_i and C_i values of C2 are not high enough in the overall system. Therefore, C2 does not have enough ability to enhance the system, therefore C2 cannot be recognized as a CSF.

The cause indexes ($R_i - C_i$) value of "Safety education and training" (C10) is positive, which indicates that C10 is a net cause factor for the overall system. However, both the R_i and C_i values of C10 are not high enough. It indicates that C10 does not have a clear impact on the improvement of the whole system, thus C10 cannot be identified as a CSF. Meanwhile, C15 is not a CSF for a similar reason.

5.2.2. Effect Group Factors

Among all 16 factors, "Personal attitude" (C9) has the second importance index ($R_i + C_i$), showing that it plays a leading role in improving the efficiency of safety program implementation of RAIB projects. However, the ($R_i - C_i$) value of C9 is −0.008, a value slightly less than zero, declaring C9 as a net effect factor. Besides, the R_i and C_i value of C9 are 0.262 and 0.270, ranking third and second place among all factors, respectively. This reveals that although C9 belongs to the effect group factor, it exerts a significant effect on other factors on the overall system. As a result, C9 is recognized as a CSF.

The causal degree ($R_i - C_i$) value of "Safety inspections and hazard assessment" (C14) is −0.020, which is slightly below zero. However, it has fairly high values in the ($R_i + C_i$), R_i and C_i. Accordingly, although the C14 is influenced by causal group factors, it is identified to be a CSF.

"Personal competency" (C8) is an effect factor with ($R_i - C_i$) as −0.007 slightly less than zero, showing that C8 is just slightly affected by other factors. That is, it also has an apparent effect on the system. But Table 10 suggests that the ($R_i + C_i$), R_i, and C_i value of C8 is all not high enough in all factors. Therefore, C8 is not a CSF. Similarly, C4 is not a CSF.

The important index ($R_i + C_i$) value of "Communication" (C7) is 0.516, which ranks in fourth place among the whole system of factors. but its value of ($R_i - C_i$) is −0.035, indicating that it is an effect factor. Besides, the C_i of C7 is the highest in the whole system, which reveals that C7 is easily affected by other factors. All these indexes indicate that C7 has a low effect on the whole system. Meanwhile, the adjustment of other factors can lead to the improvement of C7. Accordingly, C7 is not a CSF. Similarly, C6 is not a CSF.

The other effect group factors including "Safety meeting" (C11), "Safety check" (C12), "Safety resources" (C13), "Safety supervision" (C16) have similar characteristics. Their importance indexes ($R_i + C_i$) are low, and cause indexes ($R_i - C_i$) are also not high, revealing that they are strongly affected by other factors. In other words, all these factors can be easily ameliorated by adjusting and improving other factors. Therefore, these factors have no significant influence on the overall systems to achieve the success of safety program implementation of RAIB projects. So C11, C12, C13, C16 can not be identified as CSFs.

To sum up, C1, C3, C5, C9, C14 are identified as CSFs for safety program implementation of RAIB projects.

6. Discussion

Management support (C1) is the first CSF for safety program implementation of RAIB projects. Many studies also have proved that management support is the CFS for the effective implementation of safety programs [19]. Votano and Sunindijo [91] recommended that clients should actively participate in site-based safety programs in small and medium construction projects in Australia. The owner's leadership during construction is the first and foremost prerequisite to improving project safety [92–94]. In the context of RAIB projects, RAIBs practice is in the development stage, safety program of RAIB projects has not been perfected. There is a lack of guidance on safety procedures during construction, so current management support is critical to the safety performance of RAIB projects. The good safety behavior and attitude of leaders affect the safety motivation of employees and workers directly. Management support to safety also can promote the formation of a good safety culture in enterprises. Good safety culture reduces the occurrence of safety accidents [95].

Control of subcontractor (C5) is the second CSF for safety program implementation of RAIB projects. Most RMAA contracting companies found in the construction market are subsidiaries of general building contractors or small specialty contractors of RMAA works [42]. Small construction companies often employ workers with poor qualifications and awareness of safety hazards, which can lead to a high rate of construction accidents [38]. Compared with the construction of new buildings, the safety technology of RAIB projects is complex and the potential risk is large. In particular, building energy-saving transformation and structural reinforcement often involve special operations, which require more qualified, capable, and safety-conscious subcontractors. Large subcontractors have full qualifications, competent management personnel, and strong safety awareness, and the less incidence of safety accidents has been confirmed by previous literature [96].

The third CSF for safety program implementation of RAIB projects is personal attitude (C9), which is consistent with the finding of Haadir and Panuwatwanich [21]. When the RAIB projects are in one place, the total amount of the project is small, and the working time of the local working surface is short. Under this kind of condition, workers tend to spend a short time operating unsafely leading to accidents. For example, when carrying out structural reinforcement, workers do not wear safety protective equipment due to a lack of safety awareness, which leads to skin and eyes injuries by the materials used (such as structural reinforcement glue). The workers who lack the experience of RMAA works tend to ignore the potential risks on-site [43]. Hon et al. [44] indicated that low safety awareness of RMAA workers is one of the root causes of accidents in RMAA works. Further, due to the relatively small number of RAIBs practices in China, operators still lack rich experience and risk identification ability in the construction process. Therefore, personal attitude must be emphasized in the implementation of the safety program for RAIB projects.

Allocation of authority and responsibility (C3) is the fourth CSF for safety program implementation of RAIB projects, which is consistent with the finding of Bavafa et al. [61]. Due to the large number of participants in RAIB projects, the allocation of authority and responsibility of RAIB projects should also clearly specify the responsibilities of managers, employees, and workers at all levels, avoiding the potential disputes over the ownership of personnel responsibility. The clear allocation of responsibility also increases the safety motivation of personnel and improves the safety awareness of personnel to prevent the occurrence of safety accidents [97].

Safety inspections and hazard assessment (C14) is the fifth CSF for safety program implementation of RAIBs construction, The main reason for the accidents during RAIBs construction is the incomplete understanding of the actual situation on site. The AIBs were built earlier, and the contractor was unable to obtain comprehensive original structural design information and previous maintenance and renovation design documents. Therefore, prior to construction, the contractor must carry out a comprehensive survey and assessment of the site conditions of the AIBs, which will help to take the correct action, ensure a safe working environment and avoid safety accidents. In addition, targeted safety education and training based on the information of safety inspection will make workers more capable to deal with safety problems during construction, thus greatly reducing the occurrence of accidents. Terwel and Jansen [98] have also proposed that identifying the risk factors before construction has the greatest impact on structural safety, contributing to the overall safety of construction projects.

7. Implications

This section states the theoretical and managerial implications of this study towards the effective implementation of the safety program of RAIB projects.

7.1. Theoretical Implications

At present, safety programs are widely regarded as one of the effective strategies to improve the safety performance of RAIB projects. However, managers have limited knowledge on the implementation of safety programs of RAIB projects and the CSFs that influence their implementation. In this regard, our study will help them understand the CSFs for the effective implementation of safety programs of RAIB projects. Managers can apply the results of this study as a reference for designing effective safety programs of RAIB projects. The method proposed in this paper evaluates the relationship between the influencing factors and classifies each factor into causal group factors and effect group factors according to the experience and knowledge of experts. In fact, this approach of visualizing causality between factors through causal diagrams makes it easier to identify CSFs. As a result, with limited resources, managers are able to prioritize the application of resources to these factors. According to the interaction between the influencing factors, the performance of other factors can be improved to improve the effectiveness of the implementation of the RAIB projects.

7.2. Managerial Implications

This study will guide managers to implement effective safety programs to improve the safety performance of RAIB projects and further promote urban sustainable development goals. Management support is the most important factor affecting the effective implementation of the safety program of RAIB projects. Therefore, managers should pay much attention to the safety performance of RAIB projects. The Contractor should introduce high-quality technical personnel and management personnel with experience in the RAIB projects, and also set up a certain number of safety officers on site. The safety officer must have rich theoretical knowledge and practical experience of the RAIB projects. In addition, as the RAIB projects involve a number of contents and specialties, managers should actively organize, manage, communicate, coordinate and control effectively all professional subcontractors to ensure the safety performance of RAIB projects.

Second, managers should conscientiously implement the safety production responsibility system, clarify the responsibilities and obligations of all kinds of personnel, and conduct regular safety education and training and safety meetings, so as to form a good safety culture and safety atmosphere in the RAIB projects, and improve the safety awareness of workers. More importantly, workers should combine the protection of historical building culture and professional construction techniques with the improvement of safety awareness. Similarly, as for the selection of subcontractors, medium and large, experienced and reputable subcontractors should be selected as far as possible. Subcontractors should not only have the professional knowledge and safety awareness related to the general reconstruction of buildings, but also have a sense of responsibility for protecting the characteristics and culture of historical buildings. It has been agreed that the construction of RAIB projects should ensure that the original architectural characteristics are not damaged [1,2,5].

Third, managers should also attach importance to the safety check and hazard assessment of AIBs. The AIBs are built earlier and used for a long time, so their design drawings are often not preserved completely. Therefore, managers must carry out structural detection and monitoring of the original structure of the AIBs, and structural safety assessment. When conducting structural testing, the manager must select qualified testing institutions and experienced testing personnel. In addition, it is also necessary to choose qualified environmental testing institutions to conduct safety testing on the soil and indoor environment of AIBs to prevent toxic and harmful substances from causing damage to human health. Based on the results of structural safety and environmental testing, managers conduct hazard assessments and make corresponding safety control strategies, such as formulating emergency response plans.

8. Conclusions

With increasing RAIB projects in China, safety and occupational accidents of workers tend to happen due to limited space, poor sanitary environment, complex construction technology, and uncertainty of structure in RAIB projects. Safety programs have been considered as one of the most effective ways to improve safety performance in the construction industry. In order to implement an effective safety program, to disentangle the CFSs affecting the safety program implementation of RAIB projects is critically significant. In this paper, the fuzzy DEMATEL approach has been proposed to determine the CFSs. The results show that the management support (C1), allocation of authority and responsibility (C3), control of subcontractor (C5), personal attitude (C9), and safety inspections and hazard assessment (C14) are identified as the CFSs for safety program implementation of RAIB projects. According to the interdependence among factors, other factors of the whole system will be gradually improved when these five CSFs are prioritized.

The fuzzy DEMATEL method enables us to consider the interrelation between factors and categorize the various factors into cause-and-effect groups. In fact, this method is based on graph theory and visualizes the casual relationship among factors through a cause-effect relationship diagram. Moreover, the introduction of triangle fuzzy numbers eliminates the fuzziness of experts' evaluation. This method is applicable to explore the CSFs for safety program implementation of RAIB projects and can be applied to identify CSFs in other industries in the future.

This paper innovatively focuses on the CSFs affecting the implementation of the safety program of RAIB projects in China and examines the causal relationship among factors, which lays a theoretical foundation for the safety management of RAIB projects. Besides, the determination of CSFs focuses efforts in areas that affect the safety program implementation of RAIB projects, thereby conserving limited resources. It will provide useful guidance for managers and stakeholders to establish a reasonable and effective safety program for RAIB projects to improve the safety performance of RAIB projects. While this study has contributed to the literature, it does have some limitations. For example, this study is based on the background of the RAIB projects in China. Due to the different development stages and levels of RAIB projects in different countries, the outcomes of this study should be carefully applied to RAIB projects in other countries. A future study could be carried out using the methods proposed in this paper to compare these findings with those in the context of other countries.

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