Using leading and lagging indicators to select safe contractors at the prequalification stage of construction projects

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ABSTRACT

The contractor-selection decision at the prequalification stage is critical to the project success. An insufficient prediction of contractors' safety capacities using only lagging indicators may hinder the continuous improvement of safety performance in the construction industry. This research enhanced construction management and practices by proposing a comprehensive safe contractor selection model which integrated both leading and lagging indicators. First, a set of leading and lagging safety indicators were identified based on literature review and expert opinions. Then, the grey correlation analysis (GCA) was utilized to assign weights to individual indicators. We found that management commitment, safety training and education, safety risk management, and safety rules and procedures were four most influential factors to the safety performance of contractors. In addition, the fuzzy technique of ordering preference by similarity to ideal solution (Fuzzy TOPSIS) was used to condense individual indicators and create a composite safety performance indicator (c-SPI). Finally, the feasibility of the decision support tool for safe contractor selection was verified using a real-case railway construction project.

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Introduction

To minimize all project risks, the selection of an appropriate contractor to deliver the project is a crucial challenge that faces construction clients [1]. Prequalification involves a screening procedure based on a predefined set of criteria to determine the contractor's competence to perform the work [2]. The most common prequalification indicators are management capability, technical ability, financial capacity, and occupational safety and health [3,4]. This study primarily focused on the assessment of contractor's safety performance during the prequalification phase. As a prerequisite for normal organizational operations without external disturbances, the contractor's safety performance is pivotal to the client's other strategies [5]. Previous research has shown that selecting safe contractors has a positive impact on the success of construction projects [6]. Thus, this is one way in which clients can play an important safety role in the construction field [7,8].

Although previous contractor prequalification models have taken safety performance into account, they have placed too much emphasis on lagging indicators, such as injury frequency and fatality numbers [1,4,9]. Considering the inherent complexity of occupational safety and health, these lagging indicators cannot adequately describe the

actual safety capacities of contractors [10,11]. The lagging indicators are retrospective and measure the performance of activities or events that have already occurred [12,13]. In contrast, proactive or leading indicators provide early warnings and signs that pertain to the effectiveness of occupational health and safety management systems (OHSMSs), and can represent the future safety status of contractors [11,14]. Therefore, it is necessary to apply the lagging and leading indicators simultaneously to provide an overall assessment on the safety performance of contractors during the contractor-selection process [6,7]. This study would develop a composite safety performance indicator (c-SPI) that integrates the leading and lagging indicators specifically for the safe contractor selection.

The remainder of this paper is organized as follows. It begins with a review of the research questions regarding selecting safe contractors, leading and lagging indicators, and safety performance assessment. Next, a multi-stage research framework is described in detail. Furthermore, a real-life high-speed rail project is presented to verify the feasibility of the proposed approach, which is followed by a discussion of the main findings and practical implications. The final section gives the conclusion and limitations.

Literature review

Selecting safe contractors

In construction settings, accidents and failures are always accompanied by the problems with quality, extra costs, schedule delays, and image damages to the stakeholders such as contractors and clients [7,15,16]. Safe contractors that identify and attempt to eliminate on-site risks can provide better quality and complete their work on time because of their commitment to excellence and well-defined systems [17]. Recently, national and international organizations and institutes have added requirements or suggestions related to selecting safe contractors to various occupational health and safety guidelines targeting clients. The American Society of Civil Engineers (ASCE), for example, has made a policy statement about clients' safety responsibilities that includes the imposition of a safety performance requirement for contractor selection [18]. The UK's Health and Safety Executive (HSE) has produced a brief guide for clients to select contractors that can work safely and without creating health risk [19].

Health and safety accreditation schemes, such as the "SafeContractor" and "Healthy Working Lives", have provided contractor assessment services for clients to select contractors that have appropriate qualifications and sufficient systems to ensure employee health and safety [20,21]. These health and safety accreditation schemes have made the process of obtaining a list of approved contractors with suitable health and safety capacities efficient. However, the screening methods used in above accreditation schemes tend to treat health and safety merely as a threshold qualification. Therefore, candidates with "very good" safety-related programs do not have an advantage over candidates who have "good" programs [22]. Heretofore, few studies have attempted to identify critical factors for comprehensively assessing the safety performance of contractors during the prequalification phase.

Leading and lagging safety indicators

An indicator can be considered as any measure (whether quantitative or qualitative) that attempts to provide information about an issue of interest [23]. Various indicators have been used to measure workplace safety performance. Traditionally, the recordable injury rate (RIR), days away, restricted and job transfer (DART), and experience modification rate (EMR) of workers' compensation are commonly used as safety performance indicators [7,24]. These indicators are probably most widely used within the construction industry, through which contractors can track their safety status and make comparative

analyses [23,25]. However, several problems that are inherent in the use of these indicators have been criticized by the construction-industry researchers [26]. In the short-term, accidents occur with a statistically low probability within a single construction project, the rates of which may have no absolute causal relationship with the project's safety status [25,27–29]. Even a project with sound safety system will unexpectedly suffer from a variable amount of accidents [30,31]. Moreover, the response to these indicators is reactive with corrective actions occurring after injuries or economic losses [11–13].

As a compensation for limitations of traditional safety indicators, some alternative measures are increasingly used to provide enough information or insight to predict the future level of safety performance. Specifically, various measures for determining safety status proactively have been developed at three levels: the measurement of the immediate causes of accidents, such as unsafe acts and unsafe conditions [32]; safety-related organizational activities and safety management systems, such as health and safety training, safety inspections and audits [11,23,25,29]; and a safety climate survey to measure workers' attitudes and perceptions of the work environment [7,33]. With the development of these alternative measures, the terms "lagging" and "leading" have been used to distinguish two types of indicators. The lagging indicators measure the outcomes of activities or events that have already occurred (e.g. the injuries or fatalities), while the leading indicators precede the accidents [23]. When using leading indicators, proactive intervention can be initiated to address weaknesses in the safety programs once the less-than-desirable safety levels are indicated. Therefore, leading indicators can provide some hints necessary to appropriately monitor workplace safety and avoid future accidents [5,23,33].

Both leading and lagging indicators are necessary for safety improvement [34]. Previous research have revealed that the leading and lagging indicators can complement each other to provide an opportunity for "triangulation" [10,23,33,35]. For instance, Tinmannsvik and Hovden [35] developed a composite safety diagnosis criteria which combined 11 subjective measures related to safety management factors and one objective measure about the injury frequency rate. They explored the consistency between subjective (leading) and objective (lagging) indicators to ensure the validity of this composite criteria. Lingard et al. [33] provided a hierarchical safety indicator consisting of seven leading indicators and four lagging indicators. They used the leading indicators, such as safety-related perceptions and attitudes based on a safety climate survey, to verify the trends of the accident rate. These previous

research indicated that the composite indicators which combine the information of the leading indicators with traditional lagging indicators, can be more reliable for detecting the subtle changes and emerging health and safety issues [33].

Safety performance assessment for contractors

Previous studies related to the contractor safety performance are primarily concerned with the determinants of safety performance and the effectiveness of safety management practices [36–38]. However, few studies focused directly on the safety performance assessment for contractors, especially for the prequalification stage. For example, Ng et al. [24] provided a holistic safety performance index for contractors based on both lagging and leading safety indicators. They used a relative importance index (RII) method to obtain the relative weight of individual indicator, then calculated a comprehensive safety performance score based on the weighted sum method (WSM). El-Mashaleh et al. [39] used data envelopment analysis (DEA) to benchmark the safety status of construction contractors. In their research, one leading indicator (i.e. safety investment) was used as the input, whereas the output was obtained using the numbers of five types of predefined accidents. However, these above studies are not conducted specifically for safe contractor selection. The feasibility is therefore limited at the prequalification stage because they used a complicated indicator system and required a large sample.

Recently, with the development of OHSMSs, the assessment methods create additional requirements for optimizing the system effectiveness [40]. Safety performance assessment issues tend to be addressed through multiple criteria decision making (MCDM) [41–43]. As a MCDM method, the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) method developed by Hwang and Yoon (1981) has been used to address the safety performance assessment in a wide range of areas, including airports [42], ships [41], healthcare services [43], and road transportation [44]. Safety performance assessment tends to be associated with vague criteria and the subjective opinions of decision makers [42,43]. Therefore, the Fuzzy TOPSIS technique was developed to solve the problem of qualitative and ill-structured decisions [45,46].

It is essential to know that assessing the importance of each factor to the safe contractor selection involves factors with complicated inter-relationships (e.g. the potential relationship between leading and lagging indicators), and suffers from the insufficient information about these relationships. The grey correlation analysis (GCA), which is based on the grey system theory [47], is suitable for solving such problems with limited and irregular data [48,49]. The

GCA method provides a useful tool for investigating primary relationships among the influential factors, and determining importance degree of each factor to the defined objectives [50,51]. For instance, Li et al. [52] used the GCA to determine the key factors that contribute to thermal errors in mechanical processing. Jia et al. [51] applied the GCA to obtain the main elements that affect the quality of the hydraulic valve. The GCA has not previously been applied to assess safety issue at the prequalification phase. To overcome these limitations, this study proposed the GCA-Fuzzy TOPSIS approach to obtain the c-SPI for safe contractor selection.

Methodology

This research proposes an integrated GCA-Fuzzy TOPSIS framework, which aims to identify influential leading and lagging indicators, and to provide a decision-making tool for safe contractor selection. The research process includes three interdependent stages. In the first stage, critical leading and lagging indicators are identified based on safety-related literature and expert opinions. The second and third stages focus on the assessment analyses: the GCA method is utilized to assign weights to the safety indicators; thereafter, the Fuzzy TOPSIS is used to combine all safety indicators into the c-SPI for ranking the candidate bidders. Three research stages are explained in the following sections.

Identification of critical leading and lagging safety indicators

Although there are three types of leading indicators as mentioned earlier, measurements of the effectiveness of OHSMSs can be more achievable and suitable than other types of leading indicators (e.g. the unsafe behaviors or safety perception of workers) at the prequalification phase. The OHSMSs are considered as a set of integrated preventive measures in the organization, and is designed to control risks related to workers' health and safety [53]. The OHSAS (Occupational Health and Safety Assessment Series) 18001 standard introduced by British Standard Institute (BSI) is the most commonly framework used as the OHSMSs [54]. According to OHSAS 18001 standard, the OHSMSs should be developed based on the principle of Deming's plan-do-check-act cycle [55]. Therefore, certain common sections such as policy, objectives, roles, and procedures, are often used in the OHSMSs [26].

This research conducted an extensive review of the previous literature on OHSMSs [53,56–65] and the leading/lagging indicators [66–68] to identify main dimensions and indicators that are essential for the contractor safety performance. For the leading

indicators, three dimensions were defined according to the common structure of OHSMs: safety policy and objectives, safety control systems, and safety promotion. Then, a list of specific leading indicators that could affect these three dimensions were obtained. By contrast, work history is regarded as the only one dimension of lagging indicators. Work history was further explained using three specific indicators: previous incident ratio, previous schedule delay ratio, and previous cost overrun ratio. Work history can provide information about contractors' reliability by reviewing their documented experience with similar construction projects [69]. The previous schedule delay ratio and previous cost overrun ratio here are caused by the occurrence of unwanted accidents. They are selected as lagging safety indicators because cost and schedule issues always tend to accompany safety issues and can reflect the severity of accidents [36,70].

To provide qualitative validation of the dimensions and indicators developed based on the above analyses, three academic researchers and two practitioners were invited. The three researchers all focus on the construction safety area, while the two practitioners are the project managers with 19 and 21 years' experience in the construction industry, respectively. Based on these expert opinions, suggested modifications were performed (e.g. rephrasing and eliminating some inappropriate items). Finally, the safety indicator system consisted of 4 dimensions and 16 specific indicators, as shown in Table 1. The c-SPI is further determined in the following two stages.

Determining the weights of factors based on GCA

The general idea of the GCA is to measure the correlation degree among different discrete sequences in uncertain systems based on their geometric proximity [48,49]. The grey correlation degree (GCD) is an indicator to describe the degree of proximity between the comparative and reference sequences, which is used to assess the importance of each factor to the contractor safety performance.

Step 1: construct the initial data matrix

Assume that there are n experts denoted by E_i ($i = 1, 2, \dots, n$) in the assessment activities. The factors set is denoted by F_j ($j = 1, 2, \dots, m$), representing m factors. The initial data matrix can be expressed as Equation (1):

$$D = \begin{bmatrix} & E_1 & E_2 & \cdots & E_n \\ F_1 & a_{11} & a_{12} & \cdots & a_{1n} \\ F_2 & a_{21} & a_{22} & \cdots & a_{2n} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ F_m & a_{m1} & a_{m2} & \cdots & a_{mn} \end{bmatrix} \quad (1)$$

where the comparative sequence $F_i = \{a_{i1}, a_{i2}, \dots, a_{in}\}$ represents the perceived importance ratings of factor F_i with respect to the safety performance, the scores in which are determined by n experts $\{E_1, E_2, \dots, E_n\}$, respectively. Based on a five-point Likert scale, each expert determines the perceived importance ratings of m factors from 1 to 5 (where 1 is "least important" and 5 is "extremely important") with respect to safety performance. Finally, 16 comparative sequences can be obtained because a total of 16 factors are involved in this research.

Step 2: determine the reference sequence

The reference sequence is the optimal sequence in the research, denoted by $F_0 = \{a_{01}, a_{02}, \dots, a_{0n}\}$, where a_{0j} is equal to $\max_i(a_{ij})$, $i = 1, 2, \dots, m$. Considering that the highest importance rating is equal to 5, as mentioned above, the reference sequence is assumed as $F_0 = \{5, 5, \dots, 5\}$.

Step 3: calculate the grey correlation coefficient $r_{0i}(j)$

The grey correlation coefficient between a_{ij} in the comparative sequence $F_i = \{a_{i1}, a_{i2}, \dots, a_{in}\}$ and a_{0j} in the reference sequence $F_0 = \{a_{01}, a_{02}, \dots, a_{0n}\}$ is calculated in this step. The correlation coefficient is denoted by $r_{0i}(j)$, which is calculated as Equation (2):

$$r_{0i}(j) = \frac{\min_i \min_j |a_{0j} - a_{ij}| + \varepsilon \times \max_i \max_j |a_{0j} - a_{ij}|}{|a_{0j} - a_{ij}| + \varepsilon \times \max_i \max_j |a_{0j} - a_{ij}|} \quad (2)$$

where $|a_{0j} - a_{ij}|$ shows the absolute distance between a_{ij} in $F_i = \{a_{i1}, a_{i2}, \dots, a_{in}\}$ and a_{0j} in $F_0 = \{a_{01}, a_{02}, \dots, a_{0n}\}$. $\min_i \min_j |a_{0j} - a_{ij}|$ is equal to the minimum value among all $|a_{0j} - a_{ij}|$ ($i = 1, 2, \dots, m; j = 1, 2, \dots, n$). Similarly, $\max_i \max_j |a_{0j} - a_{ij}|$ is the maximum value among all $|a_{0j} - a_{ij}|$ ($i = 1, 2, \dots, m; j = 1, 2, \dots, n$). ε is the discrimination coefficient, which is introduced to increase the difference degree among the correlation coefficients. It has values of 0 to 1 and is generally set as 0.5 [51].

Step 4: determine the GCD of factor F_i

The GCD is the correlation degree between the comparative sequence $F_i = \{a_{i1}, a_{i2}, \dots, a_{in}\}$ and the reference sequence $F_0 = \{a_{01}, a_{02}, \dots, a_{0n}\}$. Generally, the higher the GCD value of factor F_i , the more important this factor. The calculation process of the GCD value is found in Equation (3):

$$r_i = \sum_{j=1}^n r_{0i}(j) / n \quad (3)$$

Step 5: determine the weight of the factor F_i

Table 1. Safety indicator system and detailed definitions of 16 safety indicators.

Dimension	Factors (code)	Sources	Definitions
Safety policy and objectives	Safety objectives (F1)	[36,56,59–61,63]	The contractor shall define and document the objectives of safety management directly and clearly. Safety objectives shall be consistent with the nature and scope of targeted project (e.g. the risk level of the project). Safety objectives shall be measurable and provide clear designation of responsibility and authority for achieving these objectives.
	Management commitment (F2)	[53,56,59,60,63]	The contractor shall document the requirements of both top and frontline management's personally involving in safety activities (e.g. safety walkthroughs inspections) and caring about workers' well beings. A clear statement shall be included about the provision of the resources necessary for implementing safety management systems.
	Safety responsibilities (F3)	[60,63]	The contractor shall provide a detailed division of responsibility for promoting workplace safety. Top management should take ultimate responsibility for safety management systems. Responsibility for performing specific safety-related tasks shall be transferred to individuals at lower levels of authority.
	Stop-work authority (F4)	[66–68]	The contractor shall assess and document a list of abnormal conditions that need stop tasks to avoid the potential accidents. The safety policy shall grant adequate authorities and assign clear responsibilities for stopping tasks when unsafe conditions or activities may result in an undesirable event.
	Safety incentives and motivations (F5)	[36,53,56,57,59,60,62,63]	The contractor shall provide safety incentive strategies to motivate workers to comply with safety rules and actively participate in safety activities (e.g. safety meetings). Danger money or safety bonuses shall be established to reward individuals or groups who can achieve excellent safety performance.
Safety control systems	Safety rules and procedures (F6)	[36,53,57,60,62,63]	The contractor shall provide reasonable and detailed safety rules and procedures on sites. Easy-to-understand safety manuals on the specific requirements for construction operations shall be prepared for frontline workers. The contractor shall establish an effective enforcement scheme for on-site safety rules and provide a statement on the penalties for safety violations.
	Equipment maintenance program (F7)	[56–58,60,62,63]	The contractor shall appoint the specific department or personnel for the maintenance program. The contractor shall establish a proper proposal for selecting safety equipment and tools to ensure the high quality and the fitness for workers. The contractor shall provide detailed maintenance programs for equipment and tools, such as the establishment of database to record the periodic implementation of maintenance activities.
	Safety professionals (F8)	[36,59,60,63,66]	The contractor shall have enough safety professionals for addressing daily safety issues. The quantity of safety professionals shall be appropriate to the safety management objectives. The contractor shall provide a requirement for safety professionals' qualifications and working experience in occupational health and safety management.
	Safety risk management (F9)	[57–59,62]	The contractor shall provide detailed procedures for early detection, analysis and classification of safety hazards. Hazard identification shall consider various possible risk sources, including poor equipment, dangerous environment, unsafe operational behaviors, and unreasonable operational procedures. Different mitigation measures shall be prepared to cope with hazards with different risk levels.
	Embedding safety into the project schedule (F10)	[53,56]	The contractor shall provide a detailed safety planning. Safety planning shall consist of both preventive planning (e.g. the time when safety protective equipment is needed) and emergency planning (e.g. the emergency response to an unexpected accident). The contractor shall balance the safety and production planning, and embed safety measures into the project schedule to avoid the conflicts between safety and production.
Safety promotion	Safety training and education (F11)	[36,57–60,62,63]	The contractor shall provide detailed safety training and education programs to promote the safety awareness, safety knowledge and skills of both frontline workers and management. Safety training and education programs shall consider varying levels of responsibility, ability, literacy and risks. For example, training materials should consider the difference among work trades.
	Near-miss reporting (F12)	[36,66,68]	The contractors shall provide detailed near-miss reporting programs, including the classification of near misses, the procedures of the near-miss data collection (e.g. an anonymous voluntary reporting) and deep data analysis (e.g. text-mining and regression analyses). Near-miss reporting programs require the appointment of personnel who is responsible for the data collection and deep analysis. Valuable information from near-miss records shall be used for further detecting the potential deficiencies existing in safety management systems.
	Safety program auditing (F13)	[36,59,60,63]	The contractor shall establish a periodic auditing program to determine whether the safety management systems have been properly implemented as the safety policy and objectives. The results of safety auditing shall be used to make corrective actions and to further promote the safety management systems.
Work history	Previous incident ratio (F14)	[68,69]	The ratio is equal to "Total number of injuries and deaths*10 million"/"Total enterprise output value in the past three years". The indicator is used to show the level of incidents relative to those of competitors.
	Previous schedule delay ratio (F15)	[68,69]	The ratio is equal to "Total days of schedule delay caused by accidents"/"Total number of contract schedule days in the past three years". The indicator is used to show the contractor's reliability in completing the project on time.
	Previous cost overrun ratio (F16)	[69]	The ratio is equal to "Total cost overrun monetary value caused by accidents"/"Total contract budget value in the past three years". The indicator is used to show the contractor's reliability with respect to completing projects within budget.

The weight of factor F_i can be calculated according to its GCD value. The weight of factor F_i is calculated as Equation (4)

$$w_i = r_i / \sum_{i=1}^m r_i \quad (4)$$

Safety performance assessment based on fuzzy TOPSIS

The TOPSIS method can identify the optimal solution among all alternatives, which has the shortest distance from the positive ideal solution (PIS) and the farthest distance from the negative ideal solution (NIS). Chen [45] extended the TOPSIS method for the fuzzy environment, where the alternatives were rated using the linguistic assessments. This research applied the Fuzzy TOPSIS method to determine the c-SPI values of contractors. The calculation process of Fuzzy TOPSIS is described as follows [45].

Step 6: determine the linguistic value

The linguistic variables are indicated by using different linguistic terms such as “low, very low, etc.” The linguistic variables are useful to describe qualitative and intangible information [45]. Triangular fuzzy numbers were used to further quantify the linguistic variables in this research, as shown in Table 2. A triangular fuzzy number $\tilde{n}$ is the fuzzy set with membership function $\mu_{\tilde{n}}(x)$ defined as Equation (5). Notably, leading safety indicators involved in the research were assessed by linguistic variables and then transformed into triangular fuzzy numbers, whereas lagging safety indicators were originally crisp numbers (e.g. the accident rate). To unify the calculation, the crisp numbers of lagging safety indicators were transformed into the associated triangular fuzzy numbers, for example, 0.4 was transformed into (0.4, 0.4, 0.4).

$$\mu_{\tilde{n}}(x) = \begin{cases} 0, & x < n_1; \\ \frac{x-n_1}{n_2-n_1}, & n_1 \leq x < n_2; \\ \frac{n_2-x}{n_2-n_3}, & n_2 \leq x < n_3; \\ 0, & x \geq n_3; \end{cases} \quad (5)$$

Step 7: construct the fuzzy decision matrix

The fuzzy decision matrix is constructed as shown in Equation (6). $\{C_1, C_2, \dots, C_m\}$ denotes m alternative contractors; $\{F_1, F_2, \dots, F_n\}$ denotes n factors involved in the assessment process. t_{ij} is the triangular fuzzy number $(t_{ij}^{(L)}, t_{ij}^{(M)}, t_{ij}^{(U)})$ for alternative contractor C_i with respect to factor F_j ,

which is determined through the linguistic assessment according to Table 2 [42].

$$\tilde{D} = \begin{bmatrix} & F_1 & F_2 & \cdots & F_n \\ C_1 & t_{11} & t_{12} & \cdots & t_{1n} \\ C_2 & t_{21} & t_{22} & \cdots & t_{2n} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ C_m & t_{m1} & t_{m2} & \cdots & t_{mn} \end{bmatrix} \quad (6)$$

Step 8: calculate the normalized fuzzy decision matrix

The normalized fuzzy decision matrix is determined using the linear scale transformation method which transforms various factor scales into a comparable scale. The transformation processes are demonstrated as Equations (7), (8), and (9) [44]. If factor F_j is the benefit indicator (namely, the more, the better), such as the management commitment, its normalized formula is shown as Equation (8); whereas, if factor F_j is the cost indicator (namely, the less, the better), such as the accident ratio, its normalization is shown as Equation (9).

$$S = [s_{ij}]_{m \times n}, \quad s_{ij} = (s_{ij}^{(L)}, s_{ij}^{(M)}, s_{ij}^{(U)}), \quad i = 1, 2, \dots, m; j = 1, 2, \dots, n \quad (7)$$

$$s_{ij} = \left(\frac{t_{ij}^{(L)}}{t_j^{(U^*)}}, \frac{t_{ij}^{(M)}}{t_j^{(U^*)}}, \frac{t_{ij}^{(U)}}{t_j^{(U^*)}} \right), \quad t_j^{(U^*)} = \max_i t_{ij}^{(U)}, \quad i = 1, 2, \dots, m \quad (8)$$

$$s_{ij} = \left(\frac{t_{ij}^{(L^-)}}{t_j^{(L)}}, \frac{t_{ij}^{(M^-)}}{t_j^{(M)}}, \frac{t_{ij}^{(U^-)}}{t_j^{(U)}} \right), \quad t_j^{(L^-)} = \min_i t_{ij}^{(L)}, \quad i = 1, 2, \dots, m \quad (9)$$

Step 9: calculate weighted normalized fuzzy decision matrix

According to the weights of factors calculated by the GCA method as mentioned above, the weighted normalized fuzzy decision matrix is determined as Equation (10). Where $\tilde{s}_{ij} = w_j \times s_{ij}$.

$$\tilde{S} = [\tilde{s}_{ij}]_{m \times n}, \quad \tilde{s}_{ij} = (\tilde{s}_{ij}^{(L)}, \tilde{s}_{ij}^{(M)}, \tilde{s}_{ij}^{(U)}), \quad i = 1, 2, \dots, m; j = 1, 2, \dots, n \quad (10)$$

Step 10: determine the fuzzy positive ideal solution (FPIS) and fuzzy negative ideal solution (FNIS)

FPIS and FNIS are defined as Equations (11) and (12) [71]. In other words, the value of each element $\tilde{s}_j^-$ in FNIS is equal to (0, 0, 0), and the value of element $\tilde{s}_j^+$ in FPIS is equal to (w_j, w_j, w_j) , where w_j is the weight of factor F_j .

$$\text{FPIS} : A^+ = (\tilde{s}_1^+, \tilde{s}_2^+, \dots, \tilde{s}_n^+);$$

Table 2. Corresponding triangular fuzzy number to each linguistic value in the research.

Linguistic value	Very low	Low	Medium	High	Very high
Triangular fuzzy number	(1,1,3)	(1,3,5)	(3,5,7)	(5,7,9)	(7,9,9)

$$\text{FNIS} : A^- = (\tilde{s}_1^-, \tilde{s}_2^-, \dots, \tilde{s}_n^-); \quad (11)$$

$$\text{where } \tilde{s}_j^+ = \left(\tilde{s}_j^{+(L)}, \tilde{s}_j^{+(M)}, \tilde{s}_j^{+(U)} \right); \tilde{s}_j^- = \left(\tilde{s}_j^{-(L)}, \tilde{s}_j^{-(M)}, \tilde{s}_j^{-(U)} \right)$$

$$\tilde{s}_j^+ = w_j \otimes (1, 1, 1); \tilde{s}_j^- = w_j \otimes (0, 0, 0) \quad (12)$$

Step 11: calculate the distances of the alternative sequence to the FPIS and FNIS

The alternative sequence for contractor C_i is denoted by $\tilde{s}_i = (\tilde{s}_{i1}, \tilde{s}_{i2}, \dots, \tilde{s}_{in})$. The distances of the alternative sequence $\tilde{s}_i$ to the FPIS and FNIS are determined in this step. The calculation processes are shown as Equations (13) and (14).

$$d_i^+ = \sum_{j=1}^n d(\tilde{s}_j^+, \tilde{s}_{ij}^+), i = 1, 2, \dots, m;$$

$$d_i^- = \sum_{j=1}^n d(\tilde{s}_j^-, \tilde{s}_{ij}^-), i = 1, 2, \dots, m; \quad (13)$$

where

$$d(\tilde{s}_j^+, \tilde{s}_{ij}^+) = \sqrt{\frac{1}{3} \left[\left(\tilde{s}_{ij}^{(L)} - \tilde{s}_j^{+(L)} \right)^2 + \left(\tilde{s}_{ij}^{(M)} - \tilde{s}_j^{+(M)} \right)^2 + \left(\tilde{s}_{ij}^{(U)} - \tilde{s}_j^{+(U)} \right)^2 \right]}$$

$$d(\tilde{s}_j^-, \tilde{s}_{ij}^-) = \sqrt{\frac{1}{3} \left[\left(\tilde{s}_{ij}^{(L)} - \tilde{s}_j^{-(L)} \right)^2 + \left(\tilde{s}_{ij}^{(M)} - \tilde{s}_j^{-(M)} \right)^2 + \left(\tilde{s}_{ij}^{(U)} - \tilde{s}_j^{-(U)} \right)^2 \right]} \quad (14)$$

Step 12: calculate the closeness coefficient ξ_i

The closeness coefficient ξ_i for each alternative sequence $\tilde{s}_i$ with respect to FPIS is calculated as Equation (15).

$$\xi_i = \frac{d_i^-}{d_i^+ + d_i^-}, i = 1, 2, \dots, m \quad (15)$$

Step 13: determine the c-SPI value and prioritize alternatives

The closeness coefficient ξ_i is in the interval of (0,1). Generally, the higher the closeness coefficient ξ_i of alternative sequence $\tilde{s}_i$, the closer the alternative to the FPIS. The ξ_i is equal to the c-SPI value of alternative contractor C_i because FPIS represents the optimal safety level here [44]. According to the c-SPI value indicated by ξ_i , the ranking of alternatives can be determined.

Empirical study

Project description

The HH railway line is a high-speed railway construction project with a design vehicle speed of 250 km/h and a total length of 286 km. The HHZQ is one package of the HH project with a length of 46.60 km and consists of 44 viaducts (15.08 km), 15 tunnels (24.11 km), and 44 parts of roadbeds (7.05 km). The total project budget is \$518 million, and the estimated project duration is 4 years. This project involves a higher proportion of viaduct and tunnel construction, greater application of innovation skills, technologies and equipment, huge investment and a tight schedule. Most of these features lead to greater safety risks for the workforce, and any improper operations might cause serious accidents [72]. Furthermore, several parts of this project need to connect, adjoin or cross other high-speed railway lines in operation, which also cause great potential safety risks for the normal operation of these adjacent lines. There is a pressing need to select experienced, serious, and mature contractors who are prepared to address safety issues both immediately and efficiently.

There were four potentially winning bidders (denoted by C1, C2, C3, and C4), all of which had been accredited by the occupational health and safety standard GB/T28001:2011 [65]. The content of the GB/T28001:2011 is consistent with OHSAS 18001:2007 [64], which has been introduced as a voluntary national standard in China. However, they did not have rich working experience in the high-speed railway construction area because the high-speed railway construction market was relatively young in China, which began to develop rapidly after the Jing-Hu high-speed railway project in 2008. To scientifically predict safety capacity, the client of the HHZQ project reviewed the bidders' OHSMSs manuals and other documents, which describe a realistic strategy consistent with the organization's approach to safety management [42,73].

The GCA-Fuzzy TOPSIS assessment framework as mentioned earlier was used to select a safe contractor. First, the leading and lagging indicators listed in [Table 1](#) were used as the references for assessment. Then, 23 safety experts from leading contractors, clients, government, and academic institutes were invited to assess the extent to which each factor contributes to the effectiveness of the contractors' OHSMSs using the five-point Likert scale. On average, these experts had approximate 15 years of work experience in the construction industry. Based on the 23 experts' ratings, importance weights of the factors were determined. Finally, nine safety experts were invited to attend the assessment and to establish a health and safety expert panel. On average, these experts had more than 20 years of experience in the field of construction safety. At this stage, safety experts reviewed the contractors' documented previous experience and OHSMSs proposal materials geared to the needs of the HHZQ project. The experts gave linguistic assessments of "Very low, Low, Medium, High, Very high" according to the desirable practices for each indicator depicted in [Table 1](#). A group consensus on the linguistic assessment results from these experts was finally obtained using the Delphi method. Afterwards, the final linguistic assessment was transformed into the fuzzy decision matrix, as set forth in [Table 2](#). The scoring checklist that was used during this stage is shown in [Table 3](#). The results are presented in the following sections.

Determining the weight of each factor

The perceived importance ratings of these 16 indicators were scored by 23 experts using a five-point Likert scale. Before calculating the importance weights, the reliability and content validity of the indicators were determined. The content validity ratio (CVR) proposed by Lawshe and the reliability indicator, Cronbach's alpha, were employed to quantify the content validity and internal consistency of

the 16 factors [67]. To use Lawshe's CVR, the ratings by the five-point scale were aggregated into three categories (1 as "not necessary"; 2,3 as "useful"; 4,5 as "essential") [74]. Lawshe provided the minimum CVR value with 95% confidence interval according to the number of panel members. With a panel size of 23 experts, the minimum CVR value of 0.42 was used to validate the indicators [75]. The CVR values of all indicators exceeded the cut-off value of 0.42 (shown as Table 4), and all indicators were significantly accepted. In addition, the Cronbach's alpha coefficients were calculated to represent the internal consistency among four dimensions. All dimensions had higher alpha values than 0.7 (shown as Table 4), which demonstrated good reliability of the established indicators.

These ratings were used to assign weights to all factors based on the GCA as the calculation processes from steps 1 to 5. The grey correlation coefficients were obtained as Equation (2). The discrimination coefficient ϵ value could be adjusted according to practical requirements and was set to 0.5 here [51]. The GCD value of each factor was then determined as Equation (3). Next, Equation (4) was used to calculate the weights of 16 factors. The GCD value, importance weights and ranking of 16 factors are shown in Table 4. The top eight influential assessment indicators are as follows: management commitment (F2), safety training and education (F11), safety risk management (F9), safety rules and procedures (F6), safety objectives (F1), near-miss reporting (F12), safety incentives and motivations (F5) and safety responsibilities (F3).

Determining contractors' c-SPI values

Linguistic assessments were used to evaluate each factor based on the triangle fuzzy numbers, and the fuzzy matrix was built as step 7. These factors were aggregated to the c-SPI using the Fuzzy TOPSIS method [45]. The FPIS and FNIS were defined as Equations (11) and (12) [71]. The distances of 16

Table 3. Contractor safety performance assessment checklist.

Contractor safety performance assessment checklist							
Project Title:							
Name of Contractor: Name of Evaluator:							
No.	Dimensions	Evaluation Factors	Very low	Low	Medium	High	Very high
1.	Safety policy and objectives	Safety objectives	☐	☐	☐	☐	☐
2.		Management commitment	☐	☐	☐	☐	☐
3.		Safety responsibilities	☐	☐	☐	☐	☐
4.		Stop-work authority	☐	☐	☐	☐	☐
5.		Safety incentives and motivations	☐	☐	☐	☐	☐
6.	Safety control system	Safety rules and procedures	☐	☐	☐	☐	☐
7.		Equipment maintenance program	☐	☐	☐	☐	☐
8.		Safety professionals	☐	☐	☐	☐	☐
9.		Safety risk management	☐	☐	☐	☐	☐
10.		Embedding safety into project schedule	☐	☐	☐	☐	☐
11.	Safety promotion	Safety training and education	☐	☐	☐	☐	☐
12.		Near-miss reporting	☐	☐	☐	☐	☐
13.	Work history	Safety program auditing	☐	☐	☐	☐	☐
14.		Previous incident ratio					
15.		Previous schedule delay ratio					
16.		Previous cost overrun ratio					
Additional Comments:							

Table 4. The validity, reliability, GCD value, weights and ranking of 16 factors.

Dimensions	Factors	Content validity ratio	Cronbach's alpha	GCD	Weights	Ranking
Safety policy and objectives	F1	0.87	0.89	0.805	0.070	5
	F2	0.91		0.917	0.080	1
	F3	0.75		0.783	0.068	8
	F4	0.75		0.712	0.062	9
	F5	0.79		0.786	0.069	7
Safety control system	F6	0.93	0.83	0.894	0.078	4
	F7	0.55		0.507	0.044	15
	F8	0.57		0.532	0.046	14
	F9	0.89		0.902	0.079	3
	F10	0.65		0.583	0.051	12
Safety promotion	F11	0.89	0.89	0.903	0.079	2
	F12	0.85		0.801	0.070	6
	F13	0.53		0.504	0.044	16
Working history	F14	0.75	0.79	0.623	0.054	10
	F15	0.65		0.579	0.051	13
	F16	0.69		0.611	0.053	11

GCD: grey correlation degree.

Table 5. The distances of four contractors from FPIS and FNIS.

$d(\tilde{s}_j^+, \tilde{s}_{ij})$	Contractors (by FPIS)				$d(\tilde{s}_j^-, \tilde{s}_{ij})$	Contractors (by FNIS)			
	C1	C2	C3	C4		C1	C2	C3	C4
F ₁	0.020	0.048	0.034	0.009	F ₁	0.056	0.027	0.041	0.065
F ₂	0.038	0.038	0.038	0.023	F ₂	0.047	0.047	0.047	0.064
F ₃	0.020	0.056	0.009	0.020	F ₃	0.054	0.015	0.063	0.054
F ₄	0.018	0.018	0.030	0.018	F ₄	0.050	0.050	0.036	0.050
F ₅	0.020	0.020	0.020	0.020	F ₅	0.055	0.055	0.055	0.055
F ₆	0.022	0.037	0.037	0.022	F ₆	0.062	0.046	0.046	0.062
F ₇	0.021	0.030	0.036	0.013	F ₇	0.026	0.017	0.009	0.035
F ₈	0.013	0.022	0.006	0.013	F ₈	0.037	0.027	0.043	0.037
F ₉	0.023	0.038	0.038	0.023	F ₉	0.063	0.046	0.046	0.063
F ₁₀	0.013	0.015	0.042	0.025	F ₁₀	0.045	0.041	0.011	0.030
F ₁₁	0.010	0.023	0.023	0.023	F ₁₁	0.074	0.063	0.063	0.063
F ₁₂	0.020	0.034	0.020	0.034	F ₁₂	0.056	0.041	0.056	0.041
F ₁₃	0.021	0.013	0.013	0.013	F ₁₃	0.026	0.035	0.035	0.035
F ₁₄	0.024	0.008	0.030	0.000	F ₁₄	0.030	0.046	0.024	0.054
F ₁₅	0.047	0.048	0.000	0.045	F ₁₅	0.004	0.004	0.051	0.006
F ₁₆	0.040	0.035	0.000	0.018	F ₁₆	0.013	0.018	0.053	0.035
d_i^+	0.370	0.482	0.375	0.316	d_i^-	0.697	0.575	0.679	0.750

FPIS: fuzzy positive ideal solution; FNIS: fuzzy negative ideal solution.

$d(\tilde{s}_j^+, \tilde{s}_{ij})$ is the distance between factor F_j in the alternative sequence $\tilde{s}_j$ and the FPIS, and $d(\tilde{s}_j^-, \tilde{s}_{ij})$ is the distance factor F_j in the alternative sequence $\tilde{s}_j$ between that and the FNIS.

d_i^+ is the sum of distance for $d(\tilde{s}_j^+, \tilde{s}_{ij})$, and d_i^- is the sum of distance for $d(\tilde{s}_j^-, \tilde{s}_{ij})$.

indicators to the FPIS and FNIS were calculated as Equation (14). Then, the distances of $d(\tilde{s}_j^+, \tilde{s}_{ij})$ and $d(\tilde{s}_j^-, \tilde{s}_{ij})$ for each factor were merged into d_i^+ and d_i^- as Equation (13). These calculation results for four contractors, namely C1, C2, C3, and C4, are shown in Table 5.

Based on the FPIS and FNIS distances, the closeness coefficient ξ_i of the alternative contractor was calculated using Equation (15). The closeness coefficient value reflects the distance of the alternative to the FPIS: the higher the coefficient, the better one contractor's safety performance compared with its competitors [42]. As noted above, the research defined the closeness coefficient value as the c-SPI of one contractor. Thus, the overall ranking of contractors C1, C2, C3, and C4 was determined in descending order of the c-SPI value – C4, C1, C3, C2 – as shown in Table 6. The specific rankings under four dimensions were further determined respectively, and the results are also presented in Table 6.

Discussion

It is now widely accepted that selecting safe contractors is a pivotal client responsibility for proactively promoting the health and safety in the construction industry. However, concerns exist about the previous employment of safety indicators during the prequalification phase: previous research have placed too

Table 6. Rankings of the four contractors under the c-SPI and four dimensions.

Contractor	C1	C2	C3	C4
c-SPI	0.6532	0.5439	0.6443	0.7039
Ranking	2	4	3	1
Safety policy and objectives	0.6936	0.5164	0.6504	0.7639
Ranking	2	4	3	1
Safety control system	0.7156	0.5527	0.4929	0.7043
Ranking	1	3	4	2
Safety promotion	0.7515	0.6689	0.7357	0.6689
Ranking	1	3	2	3
Work history	0.2999	0.4263	0.8099	0.6057
Ranking	4	3	1	2

c-SPI: Composite safety performance indicator

much emphasis on safety-related lagging indicators [1,4,9]; the screening based on health and safety certifications was a relative assessment without further consideration of the key indicators that influence contractors' safety capacities [22,67]. Leading indicators that describe the effectiveness of OHSMSs are essential for supplementing traditional lagging ones to assess and predict contractors' safety capacities and practices during the prequalification phase.

The main findings

This study proposed a composite safety indicator, the c-SPI, which integrated the information from both lagging and leading aspects to overcome the limitations inherent to a single type of measures [33]. The findings indicated that the rankings under the lagging and leading indicators were significantly different (shown as Figure 1). For instance, contractor C1 had a relatively high outcome in leading indicators but a very low value in lagging indicators. This difference can be explained from two aspects: first, the leading indicators reflected the future safety status, whereas the lagging indicators measured the outcomes of past activities [11]; then, the actual accident rates of four bidders were relatively low in past 3 years, which might be subject to random variation and could not reflect their actual safety levels [33]. To obtain a more reliable safety score, assessing the contractors' safety capacities should not be restricted to traditional lagging outcomes; instead, more attention should be turned to the leading aspects. For instance, based on the obtained weights, this study found that the total weight of leading indicators was approximately 0.84, whereas that of lagging indicators was only 0.16. This was consistent with Bergh's proportion of leading and lagging indicators, which proposed that the proportion of leading and lagging indicators should be roughly 8 to 2 for providing

enough information on contractors' project implementation efficiency [29]. This result can serve as a guide for practitioners' balancing leading and lagging indicators, and developing composite indicators to assess and track the safety performance.

Closer examination of specific safety dimensions revealed the fluctuations of rankings, which provided important insights into the health and safety deficiencies for each bidder (shown as Figure 1). For instance, the contractor C4 was top-ranked under the c-SPI, but the scores in three specific dimensions were not optimal, especially in the dimension of safety promotion. The indicator F12 (near-miss reporting) under the safety promotion was the weakest area for contractor C4 because the distance from the F12 to FPIS (0.0336) was the biggest compared to other bidders (shown as Table 5). Further investigation found that contractor C4 did not consider near-miss incidents as a strategic information for promoting safety. It did not adopt systematic activities related to reporting, collecting and learning from such incidents. Therefore, the practitioners should consider these indicators that have the highest distances to the FPIS as shown in Table 5. Some corrective actions are necessary to take to address such deficient areas based on the associated definitions in Table 1. As an illustration, to deal with the problem of indicator F12, contractor C4 should establish near-miss reporting programs including the classification of near-miss incidents, and the collection and deep analyses of near-miss data. The valuable information from near-miss analyses should be considered in the learning process for preventing unwanted accidents in the future.

This study indicated that management commitment, safety training and education, safety risk management, and safety rules and procedures were the most influential factors regarding the contractor safety performance. Both clients and contractors should not only consider these critical factors during

Figure 1. The layout of safety performance scores based on the leading and lagging safety indicators, and composite safety performance indicator.

the safe contractor selection, but also monitor these aspects for continuously promoting safety during the construction phase. Table 1 presents the desirable practices for the above indicators, based on which practitioners can assess and improve the effectiveness of their current practices related to OHSMs. For example, management commitment is the most influential factor for the contractor safety performance. Both top and frontline management should be personally involved in safety programs, such as safety walkthroughs inspections, and demonstrate their concern for workers' health and safety issues. These committed management behaviors can convey occupational safety as a core work value onsite. As a result, workers will be motivated to comply with safety rules and participate actively in more activities such as safety meetings [53].

Managerial implications

The results of this study have several managerial implications. This study provided a set of critical leading and lagging indicators for extracting necessary information about the safety capacities of contractors. The validity and reliability of these indicators have been verified. Table 1 presents detailed descriptions about the desirable practices for these indicators, especially the leading indicators. These descriptions can be considered as useful references for the clients' decision-making in safe contractor selection. Through comparing with these desirable practices, contractors can monitor and identify deficiencies in their current health and safety management programs. Furthermore, the GCA-Fuzzy TOPSIS decision-making framework can give the clients a quantitative approach to selecting a safe contractor among eligible bidders. For the contractors, this assessment approach can also be used as a benchmarking tool to continuously promote the effectiveness of health and safety management.

Conclusion

The safe contractor selection at the prequalification stage is critical to the overall success of the construction project. This study proposed an integrated GCA-Fuzzy TOPSIS model that assessed contractors' safety capacities as an additional component to the contractor selection. Based on an extensive literature review and expert opinions, 16 critical leading and lagging indicators with good reliability and validity were identified for safe contractor selection. The grey system theory and fuzzy theory were integrated into the TOPSIS to address the uncertainty and vagueness of expert opinions during the safe contractor selection. The GCA was used to determine the importance

weights of factors, and the Fuzzy TOPSIS was then employed to condense various indicators into a holistic c-SPI. Finally, a case study of high-speed railway project verified the feasibility of the proposed model in the construction industry.

According to the importance weights, management commitment, safety training and education, safety risk management, and safety rules and procedures were four most influential factors. Furthermore, the c-SPI used for safe contractor selection had a well-balanced mixture of leading and lagging indicators. The proportion of leading and lagging indicators was roughly 8 to 2. This is in accordance with Bergh's proportion of leading and lagging indicators in the construction-project level. The c-SPI receives more consideration of the effectiveness of safety management than past safety outcomes, and provides enough hints for assessing and promoting contractors' safety capacities.

It is also worth noting that safe contractors were selected among the eligible candidates where the contractors' other attributes, such as financial and technical aspects, had been checked and met the requirements. In other cases, the proposed GCA-Fuzzy TOPSIS techniques can also be recommended to assess management, technical, financial, and occupational safety and health attributes, and subsequently aggregate them into a more comprehensive contractor index. Although leading indicators are essential for supplementing traditional lagging indicators in safe contractor selection, the effectiveness of these leading indicators in actual accident prevention has not been validated. Thus, a longitudinal research is suggested in future to provide meaningful evidences on the casual relationship between the leading and lagging indicators. Another limitation of this study is that the indicators and their weights were determined based on the opinions of experts in the Chinese construction industry who are expected to be affected by safety culture and practices in the region.

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