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DETERMINING SAFETY-RELATED CRITICAL SUCCESS FACTORS IN PETROCHEMICAL PROJECTS THROUGH AN EXTENSIVE FUZZY RISK ASSESSMENT APPROACH

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Abstract. The construction phase of petrochemical units encounters many risks, a large number of which leads to death and disabling injuries. The purpose of this study is to provide a framework to determine safety-related critical success factors (CSFs) in petrochemical construction projects through risk assessment. The proposed approach involved two phases. At first, 15 potential risks were identified through a review of previous studies and interviews with experts. Then a combination of failure mode and effect analysis (FMEA), criteria importance through inter-criteria correlation (CRITIC) and technique for order preference by similarity to the ideal solution (TOPSIS) in a fuzzy environment was used for risk assessment, and the risks were classified based on their score. In Phase 2, safety-related CSFs were identified and ranked using the solutions provided for each risk and by consulting with experts. Results showed that falling from height and structural collapse due to excavation operations were the most and least important risks, respectively. Top management support was identified as the most important factor amongst the safety-related CSFs. The findings of this paper assist petrochemical construction project managers to adopt a structured approach for the risk assessment and determination of safety-related CSFs in their projects.

Keywords: safety-related critical success factors, petrochemical construction projects, risk assessment, fuzzy FMEA, fuzzy CRITIC-TOPSIS, experts.

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1. Introduction

Occupational accidents and the resulting injuries place a heavy financial burden on employers, workers and the society. According to the International Labor Organization, 340 million work-related accidents occur annually, and about 2.3 million people die as a result of these accidents (International Labour Organization [ILO], 2022). Meanwhile, many of these deadly accidents occur in the construction industry (Bavafa et al., 2018), and the probability of an accident resulting in death in this industry is five times higher than that in other industries (Sawacha et al., 1999). According to statistics, despite employing only about 7% of the world's workforce, the construction industry is responsible for 30%–40% of work-induced deaths worldwide (Sunindijo & Zou, 2012). In addition, 100,000 workers are killed in construction sites each year worldwide; this situation elicits concern because it means one death occurs every five minutes (Murie, 2007). The construction industry in Iran also accounts for only 29% of all industrial workers, but it induces approximately 40% of work accidents (Zaranejad et al., 2016). These statistics reveal the high rate of accidents in the construction industry due to the unique nature of this industry (Jaafar et al., 2018), harsh work environment (Guo et al., 2017), dynamic work settings and heavy equipment (Bavafa et al., 2018) and minimal attention to safety issues. They emphasise the importance of performing studies on safety in the construction industry.

The construction of petrochemical units has always been considered and prioritised in the economic development program of different countries, including Iran, given the advantages of the petrochemical sector, the most important of which include creating high added value from oil and gas resources, providing jobs and transferring advanced technologies (Torabi et al., 2021). The construction phase of petrochemical projects faces a wide range of challenges due to huge facilities, materials and equipment involved, such as the occurrence of accidents in the work sites. Many accidents have occurred since the construction of these projects began, resulting in death and disabling injuries. This situation indicates that the construction of petrochemical projects is a high-risk operation, in which the occurrence of accidents can cause many fatalities and massive financial losses. Therefore, during the construction process of petrochemical projects, project managers should always focus on safety issues to prevent accidents and their consequences. Project managers have the highest position at the project level; thus, they are mainly responsible for the success or failure of the project (Sunindijo & Zou, 2012). The success of a project in terms of safety requires the adoption of measures and necessary actions by the project managers to prevent accidents and their consequences during the project implementation process. Numerous factors affect project success given the complex conditions of construction projects, the various resources used in the project execution and the unpredictability of construction conditions. As a result, tracking and controlling the factors by the project managers are very difficult tasks, requiring considerable money and time. Therefore, identifying the factors that considerably affect the improvement and enhancement of project safety, referred to as the safety-related critical success factors (CSFs), is important for project managers to focus on these factors and take the necessary actions to prevent accidents.

The study of CSFs in construction projects is sensitive due to the dynamic and variable nature of construction. According to a search conducted in scientific databases by the authors of the present study, several studies have been conducted on CSFs in construction projects to date. However, many of these studies have identified CSFs in general, and less efforts have been made to study CSFs from the safety point of view. In addition, in none of the studies, safety-related CSFs in petrochemical construction projects have been addressed. Therefore, research in this field must be performed to prevent accidents and improve the safety level of petrochemical construction projects.

Project risk management is one of the most effective means to reduce the risk level and its effects and therefore improve the safety level (Alipour-Bashary et al., 2021). With project risk management, the risks that exert a negative effect on project objectives can be identified, and by taking necessary actions, they can be prevented or their adverse effects can be minimised. Risk assessment is the key part of the risk management process that can help project managers identify and evaluate risk occurrence and enable them to plan risk responses (Alipour-Bashary et al., 2021; Karamoozian & Wu, 2020).

The main purpose of this study is to provide a new framework for the risk assessment and determination of safety-related CSFs in petrochemical construction projects to effectively address the research gap in this area and move a step towards improving the safety level of these projects. The following objectives were set to achieve this aim: 1) Identification of potential safety-related risks in petrochemical construction projects; 2) Provision of a new framework for risk assessment by combining failure mode and effect analysis (FMEA), criteria importance through inter-criteria correlation (CRITIC) and technique for order preference by similarity to the ideal solution (TOPSIS) methods with the fuzzy approach; 3) Development of a process for determining and prioritising safety-related CSFs in petrochemical construction projects by using the proposed approach.

The current researchers used the knowledge and experience of experts in this field to identify and assess risks due to the lack of statistical data and reliable documents pertaining to accidents in petrochemical plant construction projects in Iran. The Delphi method was adopted to determine the most important risks because it is a useful method to obtain verified data on a particular topic by using expert knowledge, especially when data are lacking (Hallowell & Gambatese, 2010).

FMEA is one of the most important and well-known methods of risk assessment (Karamoozian & Wu, 2020; Liu et al., 2012; Liu & Tsai, 2012), and it has been widely used in various industries, including the construction industry. In the traditional FMEA method, the risk priority number (RPN) is used to calculate the risk of different cases of system failure. RPN is the product of three parameters: probability of occurrence (O), severity (S) and probability of not detecting (D) (Liu & Tsai, 2012). Although the method is easy to use, it has the following drawbacks (Chanamool & Naenna, 2016; Kutlu & Ekmekçioğlu, 2012; Liu et al., 2012):

- The relative importance of O, S and D parameters in calculating RPN is not considered, and their weights are assumed to be the same. In practical applications of FMEA, this may not be the case.
- Different combinations of O, S and D parameters can result in the same RPN values, but the consequences of their hidden risk may differ.
- Accurate evaluation of O, S and D parameters is difficult. Much data in FMEA are often imprecise or uncertain and can be expressed using linguistic terms.
- The use of the parameter multiplication operation in the RPN computational formula is questionable and strongly sensitive to variations in other parameters.

To overcome these drawbacks and problems, the present study used a combination of fuzzy FMEA and fuzzy CRITIC–TOPSIS for risk assessment. Expert knowledge on this field was used to assess risks due to the lack of documented, accurate, reliable data on accidents in construction projects of petrochemical units in Iran. Given that linguistic terms are commonly used in construction projects instead of quantitative values to assess risks (Alipour-Bashary et al., 2022), expert opinions were obtained qualitatively in the form of linguistic terms. These linguistic values have vague and inaccurate limits, so fuzzy set theory developed by Zadeh is an effective tool for defining linguistic terms (Alipour-Bashary et al., 2021), and it was used in the present study.

The TOPSIS method, which is one of the most popular techniques in multiple-criteria decision-making problems, was used to rank risks. Unlike in the traditional FMEA method in which the prioritisation or ranking of risks is obtained by multiplying the parameters *O*, *S* and *D*, in the present study, the three parameters were used as criteria for the risk rating on the basis of the TOPSIS method. Criteria weights are important because they reflect the amount of data contained, and the weighting must be performed correctly. Subjective, objective or combined methods can be used to weigh various criteria. Subjective weighting techniques depend entirely on expert opinion, whereas objective techniques emphasise the evaluation of statistical data in the decision matrix without considering decision-maker preferences. Considering the characteristics of these techniques, some researchers, such as Alemi-Ardakani et al. (2016) and Alipour-Bashary et al. (2022), recommended the use of combined methods that include subjective and objective weighting techniques. Therefore, in the present study, a combination of subjective and objective methods was used to weigh the criteria. The subjective weight of the criteria was obtained directly from expert opinion, and the objective weight was derived from CRITIC, which is a method for the determination of the objective weight of various criteria (Diakoulaki et al., 1995). After determining the weights of *O*, *S* and *D* criteria, the risks were ranked using the fuzzy TOPSIS method. On the basis of the risk assessment results and by using the proposed solutions, safety-related CSFs in petrochemical construction projects were identified and prioritised using expert knowledge.

In comparison to previous research on risk assessment and determination of safety-related CSFs in construction projects, the comprehensiveness and novelty of the approach proposed in this study can be expressed in four aspects. First, this study specifically examines petrochemical construction projects and their potential safety-related risks. Second, a new structured framework for determining safety-related CSFs in petrochemical construction projects through risk assessment is presented. In accordance with the literature review conducted by the authors, no comprehensive study has been conducted so far to examine risk assessment and safety-related CSFs in petrochemical construction projects. Third, a combination of fuzzy FMEA, fuzzy CRITIC and fuzzy TOPSIS methods has been used to rank the identified risks. Furthermore, due to the importance of the criteria weights, this paper has used a combination of both subjective and objective methods to determine the weights of the criteria. Fourth, a process for determining and prioritising safety-related CSFs in petrochemical construction projects is presented. This approach is highly beneficial for project managers as it allows them to gain a realistic view of safety-related CSFs in their respective projects and prevent accidents more efficiently by focusing their energy on these factors and taking the necessary actions.

The remainder of the paper is structured as follows: The literature review is presented in Section 2. The details and steps of the proposed framework are described in Section 3. Implementation of the proposed framework and obtained results are presented in Section 4 and discussed in Section 5. Conclusions are presented in the last section.

2. Literature review

The literature review is divided into three subsections, as shown in Figure 1. In Subsection 2.1, a review of the methods used to assess risks in construction projects and other related fields is provided. In Subsection 2.2, studies conducted on CSFs in construction projects are reviewed. In Subsection 2.3, the results of the two previous subsections are presented along with the innovation aspects of the present work.

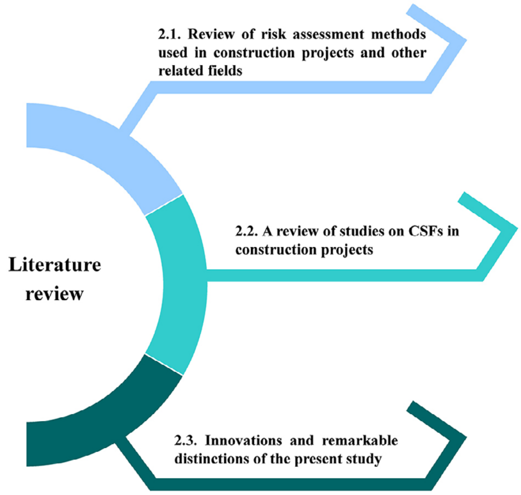

Figure 1. Structure of the literature review

2.1. Review of risk assessment methods used in construction projects and other related fields

The construction industry is undoubtedly one of the most hazardous industries, accounting for a significant proportion of work-related injuries and fatalities (Abbas et al., 2018). The occurrence of a large number of accidents is considered as a challenge in construction industry. Accordingly, risk assessment can play an important role in decreasing them (Zaranejad et al., 2016). Generally, project risk assessment can be defined as a systematic process involving the identification, analysis, evaluation and management of associated risks (Choi et al., 2004). The importance of risk assessment lies in supporting decision-making for selecting appropriate solutions and convincing managers to allocate resources for safety solutions (Arghami et al., 2014).

Various methods have been used to assess risk in different fields. Although the main focus of the present study is on research conducted in the field of construction projects, several recent studies in other fields have also been reviewed to examine the different approaches and provide a more comprehensive picture of the methods used thus far. There are numerous studies on risk assessment, and a selection of these can be found in Table 1.

As shown in Table 1, various methods have been used in previous studies on risk assessment. The present study provides a structured and comprehensive approach for risk assessment and determination of the safety-related CSFs in petrochemical construction projects. In this regard, a combination of fuzzy FMEA and fuzzy CRITIC–TOPSIS methods has been used for risk assessment.

2.2. A review of studies on CSFs in construction projects

Critical success factors (CSFs) refer to the few key areas of activity in which obtaining positive outcomes is essential for a particular manager to achieve his goals (Bullen & Rockart, 1981). One of the biggest and most important goals of managers in construction projects is to achieve success in terms of safety. Safety issues are main concerns in the construction industry; despite rapid technological advancements, it has been revealed that the fatality rate is extremely high therein (Bavafa et al., 2018). Due to the complex conditions of construction projects, the number of factors affecting the success of a project in terms of safety is very large, and in practice, it is difficult to follow up and control all of them by those involved in project, and specifically the project manager, and requires significant time and cost. Therefore, the safety-related CSFs are important for project managers and should be identified so that by focusing on these factors and taking necessary actions, they can act more effectively in preventing accidents. Thus far, numerous studies have been conducted on CSFs in various fields. Table 2 presents a selection of studies conducted on CSFs in construction projects.

Table 1. An overview of methods used for risk assessment

Authors (year)	Study purpose	Analytical method	Field of activity
Abdelgawad and Fayek (2010)	Extending the application of FMEA for risk management in the construction industry	Fuzzy FMEA, fuzzy AHP	Pipeline project
Mohammadi and Tavakolan (2013)	Assessing risks in construction projects	Fuzzy FMEA, AHP	Subway construction project
Cheng and Lu (2015)	Presenting a risk assessment model for pipe jacking construction projects based on improved FMEA	FMEA, fuzzy inference system	Pipe jacking construction projects
Ghobadi et al. (2015)	Providing a fuzzy model for environmental impact assessment of petrochemical industries	Fuzzy rapid impact assessment matrix	Petrochemical industry
Ahmadi et al. (2017)	Proposing a comprehensive framework to manage risk events in highway construction projects	Fuzzy FMEA, fuzzy AHP	Highway construction projects
Amooshahi et al. (2018)	Assessing environmental impacts in the construction and operation phases of a petrochemical complex	Shannon's entropy, PROMETHEE	Petrochemical industry
Norouzi and Namin (2019)	Evaluating and prioritising risk factors in megaprojects	Fuzzy BWM, fuzzy TOPSIS	Railway construction projects
Darvishi et al. (2019)	Assessing environmental risk of Balarood Dam in Iran at construction phase	EFMEA, entropy, VIKOR	Dam construction
Alipour-Bashary et al. (2021)	Providing a hybrid fuzzy risk assessment framework to determine the building demolition safety index	Fine–Kinney, fuzzy FTA, fuzzy TOPSIS, FIS	Building demolition
Ostadi and Abbasi Harofteh (2022)	Presenting a new approach based on Monte Carlo simulation for risk assessment considering the co-occurrence of risk factors	Monte Carlo simulation, system dynamic model	Petrochemical project
Alipour-Bashary et al. (2022)	Proposing a framework for identifying, analysing, and evaluating risks in building demolition operations	Fuzzy FTA, fuzzy CRITIC–TOPSIS	Building demolition
Mahdi and Erzaij (2024)	Developing a hybrid model for evaluating and ranking potential trouble factors in construction projects	FMEA, ANFIS, fuzzy AHP	Building construction projects
Erdem et al. (2025)	Assessing the sustainability and risk performance pillars for logistics networks, taking into account a business continuity plan	Fuzzy-based AHP (with novel linguistic scales and operators), TOPSIS	Urban logistics networks
Özdemir et al. (2025)	Evaluating the sustainable and intelligent urban transportation systems of fifty global economies	Intuitionistic fuzzy-based AHP, VIKOR	Urban transportation systems
Erdem and Özdemir (2025)	Introducing a digital, innovative, and sustainable business economy model with cyber security and risk indicators to assess the performances of digital economies	FFSAHP, FSDEA, FSDEA-embedded TOPSIS	Digital economy
Hatefi et al. (2025)	Risk assessment in mass building projects	Fuzzy Shannon entropy, fuzzy EDAS	Mass building projects
Mohammadi et al. (2025)	Developing and implementing a hybrid decision-making framework for assessing and ranking contracting risks in construction projects under uncertainty	FMEA, fuzzy SWARA, fuzzy MOORA, fuzzy MABAC, fuzzy sets	Construction projects

Table 2. An overview of studies on CSFs in construction projects

Authors (year)	Study purpose	Analytical method
Arslan and Kivrak (2008)	Investigating CSFs in construction companies	SMART
Al Haadir and Panuwatwanich (2011)	Identifying CSFs for implementing safety programmes amongst construction companies in Saudi Arabia	AHP, Pareto analysis
Banihashemi et al. (2017)	Identifying and analysing the CSFs influencing the integration of sustainability into management practices of construction projects in developing countries	PLS-SEM
Maghsoodi and Khalilzadeh (2017)	Identifying and ranking CSFs in construction projects	Fuzzy Shannon entropy, fuzzy TOPSIS, fuzzy Multi-MOORA
Bavafa et al. (2018)	Identifying and assessing the causal relationships of safety programme factors in construction projects in Malaysia	FDM, DEMATEL
Chai et al. (2022)	Determining CSFs influencing the implementation of safety programmes in regeneration of abandoned industrial building projects	Fuzzy DEMATEL
Iqbal et al. (2022)	Analysing CSFs for energy-efficient supply chain in construction projects, Pakistan	FDM, ISM-MICMAC
Yamany et al. (2024)	Investigating CSFs affecting the performance of infrastructure construction projects	Statistical techniques: One-sample t-test, mean score, factor analysis
Singh and Kumar (2024)	Identifying and investigating CSFs of blockchain technology in the supply chain of circular economy-driven construction materials	PESTEL (for CSFs categorisation), fuzzy DEMATEL
Alghuried (2026)	Identifying and assessing CSFs for sustainable management of construction projects in Saudi Arabia	Relative importance index, AHP

2.3. Innovations and remarkable distinctions of the present study

On the basis of the studies reviewed in Tables 1 and 2, the innovations and remarkable distinctions of the present study in comparison with previous studies are established as follows:

- Despite the high risk in petrochemical construction projects, according to the review of the authors, no detailed and comprehensive study on risk assessment and safety-related CSFs has been conducted for these projects so far. This gap was addressed in the present study.
- The present study proposes a new structured framework that examines risks and the safety-related CSFs in petrochemical construction projects in the form of a comprehensive approach.
- To rank the identified risks, a combination of fuzzy FMEA, fuzzy CRITIC, and fuzzy TOPSIS methods has been used. Unlike the traditional FMEA method where the prioritisation and ranking of risks are realised by multiplying the parameters O, S, and D, in the present study, the three parameters were used as the criteria for ranking risks based on the TOPSIS method. In addition, due to the importance of the criteria weights, a combination of subjective and objective methods has been used in this study to determine the weight of the criteria.
- A process for determining and prioritising safety-related CSFs in petrochemical construction projects is presented. This approach is highly beneficial for project managers as it allows them to have a realistic view of safety-related CSFs in their projects and act efficiently in preventing accidents by focusing on these factors and taking necessary actions that will result in improving the project safety level.

3. Methodology

Figure 2 shows the research process for the risk assessment and determination of safety-related CSFs in petrochemical construction projects in two phases. The first phase consists of two risk identification and risk assessment parts, and the second phase is related to the identification and prioritisation of safety-related CSFs. The proposed framework combines FMEA and CRITIC–TOPSIS methods in a fuzzy environment and will be described hereafter.

3.1. First phase

The first phase consists of risk identification and risk assessment parts.

3.1.1. Section 1: Risk identification

3.1.1.1. Risk identification in petrochemical construction projects

At this stage, by reviewing various sources and available studies (i.e., journal papers, books, theses, reports, etc.), the potential risks in petrochemical construction projects are identified and listed. Experts are then interviewed to complete the list of risks. The purpose of the interview is to take advantage of the maximum experience and knowledge of experts about risks that may have been ignored in previous studies. In this regard, the list of risks obtained from the literature review is provided to experts, who are then asked to identify other existing risks that are not listed on the basis of their experience.

3.1.1.2. Selection and listing of the most important risks using the Delphi method

The Delphi method is used in this study to select the most important risks using the following steps (Alipour-Bashary et al., 2022).

Step 1: To determine the importance level of each risk and decide on their acceptance or rejection, questionnaires are designed and provided to experts, who are then asked to determine the importance level of each risk by using an ordinal five-level scale (5: very high; 4: high; 3: medium; 2: low; 1: very low).

Step 2: To achieve a common understanding of the opinions of all experts, all expert opinions are integrated by averaging them on the basis of Eqn (1).

If x_{rk} indicates the importance level of risk k (k = 1, 2, 3, ..., n) according to the opinion of expert r (r = 1, 2, 3, ..., m), then the weight (W_k) of the kth risk can be calculated using the following equation:

$$W_k = \sum_{r=1}^{m} \frac{x_{rk}}{m}, \tag{1}$$

where m is the number of experts.

Step 3: Upon calculation of the risk weight, it is accepted or rejected by referring to the threshold value (α) as follows. Notably, the threshold value (α) is obtained by the average weight of all risks.

If $W_k \geq \alpha$, then accept No. k risk,

If $W_k < \alpha$, then reject No. k risk.

3.1.2. Section 2: Risk assessment

A combination of fuzzy FMEA and fuzzy CRITIC–TOPSIS methods is used in this work to assess and rank risks. The

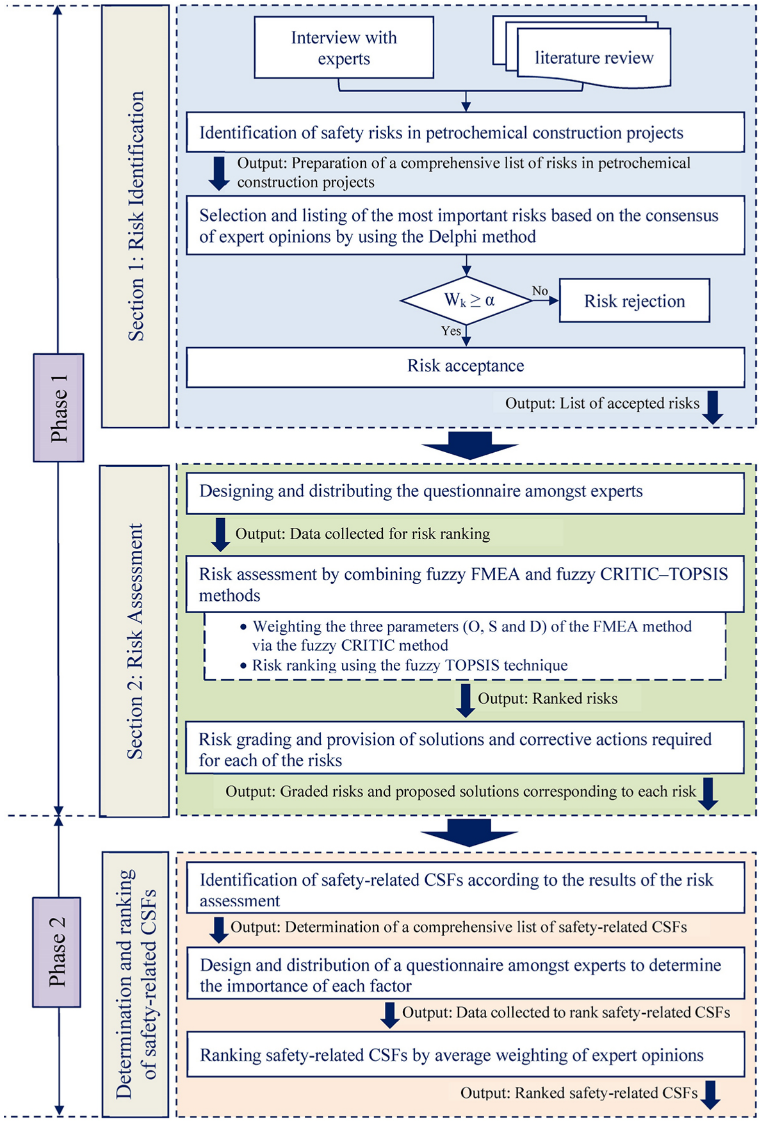

Figure 2. Safety-related CSF framework

FMEA method's parameters included *O*, *S* and *D*, which are regarded as the criteria for risk ranking. The criteria are weighted according to the fuzzy CRITIC method. Afterwards, the risks are ranked according to these criteria and based on the fuzzy TOPSIS method. These methods and their application in this study are described hereafter.

3.1.2.1. Design and distribution of the questionnaires amongst relevant experienced experts

This step requires the collection of data to assess the risks. Therefore, a questionnaire is designed and filled out by experts.

3.1.2.2. Fuzzy theory

Fuzzy set theory is proposed to deal with uncertainties caused by the vagueness and imprecision of human systems and decision-making processes. In the present study, the opinions of experts are used with the help of a questionnaire given the complex nature of the petrochemical construction projects and the lack of documented, accurate and reliable data on accidents in these projects. In addition, due to the difficulty of providing an accurate numerical value for each parameter by the experts, their opinions are obtained qualitatively and in the form of linguistic terms. These linguistic values have vague and inaccurate limits, so fuzzy set theory developed by Zadeh is an effective tool for defining linguistic terms (Alipour-Bashary et al., 2021), and it is used in the present paper. To perform fuzzy calculations, fuzzy numbers such as triangular, trapezoidal, Gaussian and bell-shaped can be used. Given that trapezoidal and triangular fuzzy numbers are the most common forms used in the construction industry (Abbasianjahromi et al., 2018), the trapezoidal fuzzy numbers are used in the present study to define the linguistic terms, as shown in Table 3. Notably, Table 3 is adapted from Ahmadi et al. (2017), with the difference being that the values of fuzzy numbers in the present study are normalised in the range of zero to one.

In continue, some concepts and definitions related to fuzzy sets and fuzzy numbers are presented as follows.

Definition 1. Assume that $\tilde{A}=(a_1,a_2,a_3,a_4)$ is a trapezoidal fuzzy number $(a_1 \le a_2 \le a_3 \le a_4)$, then its membership function can be defined as follows (Ölçer & Odabaşi, 2005):

$$\mu_{\tilde{A}}(x)=\begin{cases} \dfrac{(x-a_1)}{(a_2-a_1)}, & a_1 \le x \le a_2 \\ 1, & a_2 \le x \le a_3 \\ \dfrac{(a_4-x)}{(a_4-a_3)}, & a_3 \le x \le a_4 \\ 0, & \text{otherwise} \end{cases}. \quad (2)$$

Definition 2. Assume that k is a crisp number, and $\tilde{A}=(a_1,a_2,a_3,a_4)$ and $\tilde{B}=(b_1,b_2,b_3,b_4)$ are two positive trapezoidal fuzzy numbers ($a_1 \ge 0$ and $b_1 \ge 0$). The arithmetic operations with these fuzzy numbers are defined as follows (Rostamzadeh et al., 2018).

Table 3. Linguistic scales

Linguistic terms	Trapezoidal fuzzy number
Very low	(0, 0, 0.1, 0.2)
Low	(0.1, 0.2, 0.3, 0.4)
Medium	(0.3, 0.4, 0.6, 0.7)
High	(0.6, 0.7, 0.8, 0.9)
Very high	(0.8, 0.9, 1, 1)

Addition:

$$\tilde{A} \oplus \tilde{B}=(a_1+b_1, a_2+b_2, a_3+b_3, a_4+b_4); \quad (3)$$

$$\tilde{A}+k=(a_1+k, a_2+k, a_3+k, a_4+k). \quad (4)$$

Subtraction:

$$\tilde{A} \ominus \tilde{B}=(a_1-b_4, a_2-b_3, a_3-b_2, a_4-b_1); \quad (5)$$

$$\tilde{A}-k=(a_1-k, a_2-k, a_3-k, a_4-k). \quad (6)$$

Multiplication:

$$\tilde{A} \otimes \tilde{B}=(a_1 \times b_1, a_2 \times b_2, a_3 \times b_3, a_4 \times b_4); \quad (7)$$

$$\tilde{A} \times k=\begin{cases} (a_1 \times k, a_2 \times k, a_3 \times k, a_4 \times k) & \text{if } k \ge 0 \\ (a_4 \times k, a_3 \times k, a_2 \times k, a_1 \times k) & \text{if } k < 0 \end{cases}. \quad (8)$$

Division:

$$\tilde{A} \oslash \tilde{B}=\left(\frac{a_1}{b_4}, \frac{a_2}{b_3}, \frac{a_3}{b_2}, \frac{a_4}{b_1}\right); \quad (9)$$

$$\tilde{A}/k=\begin{cases} \left(\dfrac{a_1}{k}, \dfrac{a_2}{k}, \dfrac{a_3}{k}, \dfrac{a_4}{k}\right) & \text{if } k>0 \\ \left(\dfrac{a_4}{k}, \dfrac{a_3}{k}, \dfrac{a_2}{k}, \dfrac{a_1}{k}\right) & \text{if } k<0 \end{cases}. \quad (10)$$

Definition 3. Assuming that $\tilde{A}=(a_1,a_2,a_3,a_4)$ is a trapezoidal fuzzy number, the defuzzified (crisp) value of this fuzzy number can be calculated using the following equation (Kaya & Kahraman, 2011):

$$\kappa(\tilde{A})=\frac{1}{6}(a_1+2(a_2+a_3)+a_4). \quad (11)$$

3.1.2.3. Fuzzy CRITIC

The CRITIC method was introduced by Diakoulaki et al. (1995) and is used to determine the objective weights of criteria in decision-making problems. To determine the weights in this method, the contrast intensity of each criterion and conflict between criteria are considered. Standard deviation and correlation coefficient are adopted to measure contrast intensity of criteria and conflict between criteria, respectively. The implementation steps of the fuzzy CRITIC method to determine the weight of the criteria are as follows (Rostamzadeh et al., 2018):

Suppose that:

$$\tilde{x}_{ij}=(x_{ij1}, x_{ij2}, x_{ij3}, x_{ij4}), \quad (12)$$

where $i = 1, 2, 3, \ldots, n$, $j = 1, 2, 3, \ldots, m$, and

$$\tilde{w}_j^o=(w_{j1}^o, w_{j2}^o, w_{j3}^o, w_{j4}^o), \quad (13)$$

where $\tilde{x}_{ij}$ and $\tilde{w}_j^o$ indicate the value of the fuzzy performance of the ith alternative based on the jth criterion and the fuzzy objective weight of the jth criterion, respectively. In addition, B and N are the sets of beneficial and non-beneficial criteria, respectively. The fuzzy objective weights of the criteria are determined as follows.

Step 1: Calculate the transformations of performance values, and determine the criteria vectors using Eqn (14).

$$x_{ijk}^T = \begin{cases} \dfrac{x_{ijk} - x_{jk}^-}{x_{jk}^* - x_{jk}^-} & \text{if } j \in B \\ \dfrac{x_{jk}^- - x_{ijk}}{x_{jk}^- - x_{jk}^*} & \text{if } j \in N \end{cases}, \tag{14}$$

$$\mathbf{X}_{jk} = (x_{1jk}^T, x_{2jk}^T, \ldots, x_{njk}^T),$$

where x_{ijk}^T is the transformed value of the kth element of $\tilde{x}_{ij}$; $\mathbf{X}_{jk}$ is kth vector of jth criterion; and x_{jk}^* and x_{jk}^- are the ideal and anti-ideal values with respect to the jth criterion and kth element of $\tilde{x}_{ij}$, respectively. If $j \in N$, then x_{jk}^* = $\min_i x_{ijk}$ and x_{jk}^- = $\max_i x_{ijk}$, and if $j \in B$, then x_{jk}^* = $\max_i x_{ijk}$ and x_{jk}^- = $\min_i x_{ijk}$.

Step 2: Calculate the standard deviation (σ_{jk}) of each vector ($\mathbf{X}_{jk}$).

Step 3: Form four symmetrical matrices with dimensions of $m \times m$ and $r_{jj'}^k$ elements, where j' = 1, 2, 3, ..., m, and k = 1, 2, 3, 4. The elements of this matrix are the linear correlation coefficient between vectors $\mathbf{X}_{jk}$ and $\mathbf{X}_{j'k}$.

If all elements of $\mathbf{X}_{jk}$ or $\mathbf{X}_{j'k}$ vectors are identical, then no correlation exists $(r_{jj'}^k = 0)$.

Step 4: Calculate the information measures for each criterion using Eqn (15):

$$H_{jk} = \sigma_{jk} \sum_{j'=1}^{m} \left(1 - r_{jj'}^k\right). \tag{15}$$

Step 5: Determine the unsorted objective weights using Eqn (16):

$$w'_{jk} = \frac{H_{jk}}{\sum_{j'=1}^{m} H_{jj'}}. \tag{16}$$

Step 6: Determine the weights of fuzzy criteria using Eqn (17).

$$\begin{aligned} & w_{jk}^o = w'_{jk'}, \text{ where } k \text{ and } k' \in \{1, 2, 3, 4\} \text{ and} \\ & w_{j1}^o = \min_k w'_{jk}; \\ & w_{j4}^o = \max_k w'_{jk}. \end{aligned} \tag{17}$$

3.1.2.4. Risk ranking by combining fuzzy FMEA and fuzzy CRITIC–TOPSIS

FMEA is one of the most popular risk assessment methods used in construction projects. Although this method is simple to use, it has drawbacks. To overcome and improve the drawbacks of this method, the present study combined fuzzy FMEA and fuzzy CRITIC–TOPSIS methods.

The TOPSIS technique is a popular and effective technique for solving MCDM problems (Huang & Jiang, 2018). In the present study, the technique is used to rank risks. Unlike in the traditional FMEA method in which risk ranking is performed by multiplying the numerical values of O, S and D parameters, in the present study, the three parameters are used as the criteria for risk ranking via the fuzzy TOPSIS method. The weights of the criteria can be determined through subjective, objective or combined methods. Given the characteristics of each technique, some researchers, such as Alemi-Ardakani et al. (2016) and Alipour-Bashary et al. (2022), recommended the use of combined methods that include subjective and objective weighting techniques. Therefore, in the present study, a combination of subjective and objective methods is used to weigh the criteria. The subjective weight of the criteria is obtained directly from the opinions of the experts, and the objective weight is obtained from the CRITIC technique. Upon determination of the three criteria's weights, the risks are ranked using the fuzzy TOPSIS method. The following steps present the proposed combined process in which FMEA and CRITIC–TOPSIS methods are used in a fuzzy environment.

Suppose that a decision-making problem has n alternatives (risks) $\left(A = \{A_1, A_2, \ldots, A_n\}\right)$ with three risk assessment criteria $\left(C = \{O, S, D\}\right)$ and k decision-makers. The implementation steps of the combined approach that includes FMEA, CRITIC and TOPSIS methods in the fuzzy environment are as follows.

Step 1: Development of an average decision matrix (Y) to rank the risks. The O, S and D parameters related to each risk are regarded as criteria in the decision matrix. To obtain the average decision matrix, the opinion of each expert about each risk is initially asked according to the three criteria O, S and D, and each expert's reply is then obtained as a linguistic term. Subsequently, fuzzy numbers according to Table 3 are used to define each of the linguistic terms. Next, the average decision matrix is formed based on the aggregation of the experts' judgements according to the following equations:

$$Y = \left[\tilde{y}_{ij}\right]_{n \times 3} = \begin{array}{c} \\ A_1 \\ \vdots \\ A_i \\ \vdots \\ A_n \end{array} \begin{array}{c} \begin{array}{ccc} O & S & D \end{array} \\ \begin{bmatrix} \tilde{y}_{11} & \tilde{y}_{12} & \tilde{y}_{13} \\ \vdots & \vdots & \vdots \\ \tilde{y}_{i1} & \tilde{y}_{i2} & \tilde{y}_{i3} \\ \vdots & \vdots & \vdots \\ \tilde{y}_{n1} & \tilde{y}_{n2} & \tilde{y}_{n3} \end{bmatrix} \end{array}, \tag{18}$$

where

$$\tilde{y}_{ij} = \sum_{t=1}^{k} \tilde{y}_{ij}^t \cdot w_t, \tag{19}$$

where $\tilde{y}_{ij}^t$ is the alternative performance A_i ($1 \le i \le n$) considering the criterion C_j ($1 \le j \le 3$) and based on the opinion of the tth decision maker ($1 \le t \le k$) and w_t is the corresponding weight to each expert. To calculate w_t, each of the experts was given a point from 1 to 4 according to their position (technician, project engineer, supervisor/senior project engineer and project manager/HSE manager/CEO of the engineering company), degree (less than a bachelor's degree, bachelor's degree, master's degree and doctoral degree), executive work experience (less than 5 years, 5–10 years, 10–15 years and 15 years or more), experience in the field of safety (less than 5 years, 5–10 years, 10–15 years and 15 years or more) and duration of safety training (less than 3 months, 3–6 months, 6–12 months and 12 months or more). Then, the weight for each expert was determined through dividing the total score obtained by the expert by the total points of all experts.

Step 2: Determination of the weight matrix of subjective criteria by using the following equations:

$$W=\left[\tilde{w}_j^s\right]_{1\times 3}, \tag{20}$$

where:

$$\tilde{w}_j^s=\sum_{t=1}^{k}\tilde{w}_{jt}^s\cdot w_t, \tag{21}$$

where $\tilde{w}_{jt}^s$ is the subjective weight of the C_j criterion based on the opinion of the tth decision maker.

Step 3: Calculation of the normal subjective weight for each of the three criteria by using the following equation:

$$\tilde{w}_j^{sn}=\widetilde{w}_j^s / \kappa\left(\sum_{j=1}^{3}\tilde{w}_j^s\right). \tag{22}$$

Step 4: Determination of the objective weights of all three criteria by using the fuzzy CRITIC method (Section 3.1.2.3).

Step 5: Calculation of the final weights of all three criteria by combining the subjective and objective weights as follows (Rostamzadeh et al., 2018):

$$\tilde{w}_j=\beta.\tilde{w}_j^{sn}+\left(1-\beta\right)\cdot\tilde{w}_j^o, \tag{23}$$

where $\tilde{w}_j$ is the criterion weight of C_j, and β is the relative importance between the subjective and objective weights of the criteria. The value of β can be considered in the range of 0 to 1, and was considered 0.5 in the present study.

Step 6: Obtaining the normalised fuzzy decision matrix (R):

$$R=\left[\tilde{r}_{ij}\right]_{n\times 3}, \tag{24}$$

where:

$$\tilde{r}_{ij}=\left(\frac{y_{ij1}}{u_j},\frac{y_{ij2}}{u_j},\frac{y_{ij3}}{u_j},\frac{y_{ij4}}{u_j}\right),\ j\in B; \tag{25}$$

$$\tilde{r}_{ij}=\left(\frac{l_j}{y_{ij4}},\frac{l_j}{y_{ij3}},\frac{l_j}{y_{ij2}},\frac{l_j}{y_{ij1}}\right),\ j\in N; \tag{26}$$

$$u_j=\max_i y_{ij4}; \tag{27}$$

$$l_j=\min_i y_{ij1}. \tag{28}$$

Step 7: Developing the weighted normalised fuzzy matrix by using the following equations:

$$Z=\left[\tilde{z}_{ij}\right]_{n\times 3}, \tag{29}$$

where:

$$\tilde{z}_{ij}=\widetilde{w}_j\cdot\tilde{r}_{ij}. \tag{30}$$

Step 8: Finding fuzzy positive ideal solution (FPIS) and fuzzy negative ideal solution (FNIS) by using the following equations:

$$A^+=(v_1^+,v_2^+,v_3^+); \tag{31}$$

$$A^-=(v_1^-,v_2^-,v_3^-), \tag{32}$$

where:

$$v_j^+=\begin{cases}\max_i z_{ij4} & \text{if } j\in B\\ \min_i z_{ij1} & \text{if } j\in N\end{cases}; \tag{33}$$

$$v_j^-=\begin{cases}\min_i z_{ij1} & \text{if } j\in B\\ \max_i z_{ij4} & \text{if } j\in N\end{cases}. \tag{34}$$

Step 9: Calculation of the distance of each alternative from FPIS and FNIS as follows:

$$d_i^+=\sum_{j=1}^{3}d\left(\tilde{z}_{ij}.v_j^+\right); \tag{35}$$

$$d_i^-=\sum_{j=1}^{3}d\left(\tilde{z}_{ij}\cdot v_j^-\right). \tag{36}$$

Step 10: Calculation of the S_i scores for all risks and ranking them in a descending order by using the following equation:

$$S_i=\frac{d_i^-}{d_i^-+d_i^+}. \tag{37}$$

3.1.2.5. Risk grading and provision of solutions and corrective actions required for each risk

After calculating the score of each risk and ranking them, Table 4 is used to determine the level of importance of the identified risks and provide the necessary strategies based on the criticality of each risk. Notably, Table 4 is prepared following Ardeshir et al. (2016) with some modifications made by the authors to adapt to the present study. In this study, the necessary preventative solutions are specifically indicated for each risk.

Table 4. Grade of risks based on their score

Grade of risks	RS	Corrective action categories
IV: High risk	0.55 ≤ RS	Immediate action
III: Medium risk	0.40 ≤ RS < 0.55	Measures to be adopted for immediate improvement
II: Low risk	0.20 ≤ RS < 0.40	Monitoring
I: Very low risk	RS ≤ 0.20	No action is required

3.2. Second phase

3.2.1. Identification of safety-related CSFs according to the risk assessment results

In this step, safety-related CSFs in petrochemical construction projects are determined and listed by using the solutions presented in the first phase and consulting with experts on the basis of the risk assessment results.

3.2.2. Design and distribution of a questionnaire to determine the importance level of each CSF

In this step, a questionnaire is prepared to determine the importance level of each CSF and is filled out by experts who are active in petrochemical projects. The experts are asked to rank the importance level of each factor by using an ordinal five-level scale (1: very low; 2: low; 3: medium; 4: high; and 5: very high).

3.2.3. Ranking of CSFs

After collecting the questionnaires, the score of each of the safety-related CSFs is obtained through average weighting of the opinions of the experts, and the factors are ranked in a descending order.

4. Implementation of the proposed framework and obtained results

Two case studies were selected to illustrate the practical application of the framework developed in the present study, including two active companies in the petrochemical field with more than 12 years of related experience in Iran. For the sake of anonymity, the details of the mentioned companies are not disclosed. This study attempts to use the knowledge and experience of the experts working in these companies in the construction of petrochemical projects by conducting interviews and distributing questionnaires. In the following, the step-by-step implementation of the research process is discussed according to Figure 2.

4.1. Risk identification

The potential risks in petrochemical construction projects were identified and listed in Table 5 by reviewing existing literature from various sources and interviewing 10 active experts in the field of petrochemicals in Iran with experience of over 15 years. The Delphi method was used to determine the importance of each risk and select the most important ones. For this purpose, a questionnaire was designed, and a total of 11 questionnaires were filled out by experts in the field of petrochemicals who had at least a bachelor's degree (Table 6). According to Hallowell and Gambatese (2010), 8-12 panel members are considered suitable for the Delphi method. The obtained results regarding the acceptance or rejection of the risks in petrochemical projects are given in Table 5.

Table 5. Results of acceptance or rejection of the risks

Risk	$(\text{Weight})_{\text{Avg}}$	Selection / Rejection
Structural collapse due to excavation operations	3.0000	Select
Overall structural collapse	2.9091	Select
Slipping	3.0000	Select
Falling from height	3.5455	Select
Objects falling on individuals	3.8182	Select
Objects falling on machines	2.9091	Select
Being hit by machinery	2.6364	Reject
Electrocution	3.1818	Select
Fire	4.0909	Select
Explosion	3.5455	Select
Injuries due to working with tools	3.0000	Select
Stuck between objects	2.4545	Reject
Burns due to work	2.8182	Reject
Injuries due to welding	2.6364	Reject
Exposure to harmful and hazardous materials/chemical spray	2.9091	Select
Injuries induced by moving, lifting or carrying loads	2.7273	Reject
Being trapped due to collapse/overturning	2.5455	Reject
Accidents related to the transportation and installation of heavy equipment and structures	3.5455	Select
Accidents related to heavy machinery (e.g. overturning of heavy cranes)	3.4545	Select
Gas choking	3.0909	Select
Poisoning and dizziness due to exposure to gas from materials during work	2.9091	Select
Earthquake accidents	2.2727	Reject
Accidents due to heavy rainfall and floods	2.3636	Reject
Accidents caused by strong winds	2.5455	Reject
Accidents due to night vision loss	2.1818	Reject
Accidents caused by drug abuse by workers	2.1818	Reject
Accidents caused by workers' drowsiness	2.1818	Reject
Accidents caused by inappropriate jokes by employees	2.4545	Reject
Threshold	2.8896	

Table 6. Background of experts

Expert's number	Position	Degree	Years of experience
1	HSE manager	Master	More than 15
2	CEO of engineering company	PhD	More than 15
3	CEO of engineering company	Master	More than 15
4	Project manager	Bachelor	More than 15
5	Project manager	Bachelor	More than 15
6	Project control supervisor	PhD	Between 5 and 10
7	Senior project engineer	PhD	More than 15
8	Senior project engineer	Bachelor	More than 15
9	Senior project engineer	PhD	More than 15
10	Senior project engineer	PhD	More than 15
11	Project engineer	Bachelor	Between 10 and 15

4.2. Risk assessment

A combination of fuzzy FMEA and fuzzy CRITIC–TOPSIS methods was used to rank the risks. The FMEA method's parameters, namely, *O*, *S* and *D*, were adopted as the risk-ranking criteria. To determine the weight of each criterion and measure the effect of each risk on the criteria, a questionnaire was prepared and distributed amongst 40 experts active in the field of petrochemical construction in Iran. Thirty-six of the questionnaire copies were filled out and returned. Notably, to weigh the answers, as described in Section 3.1.2.4, each of the experts was given a point from 1 to 4 according to their position, degree, executive work experience, experience in the field of safety and duration of safety training. Then, the weight for each expert was determined by dividing the total score obtained by the expert by the total points of all experts. Next, because the data collected from the experts were in linguistic terms, fuzzy numbers were used to define them (Table 3). The risks were assessed based on the three criteria (*O*, *S* and *D*), and the decision matrix was obtained from a combination of expert responses based on the weighted average (corresponding weight to each expert) by using Eqn (19). The average decision matrix is shown in Table 7.

The subjective and objective weights of the criteria were determined through the average weighting of the experts' responses regarding the importance of each criterion and by using the fuzzy CRITIC method, respectively. By combining the two weights via Eqn (23), the final weight of each criterion was obtained, as shown in Table 8. Then, the ranking of each risk was obtained with the fuzzy TOPSIS method, the results of which are shown in Table 9.

After ranking the risks, the importance grade of each risk was determined (Figure 3) by considering each risk score and on the basis of Table 4. Table 4 shows the corrective actions required for each risk in consideration of its criticality level. In addition, a set of solutions is presented in Table 10 for each risk in the present study.

Table 7. Average decision matrix

Risk	Criteria		
	Occurrence (*O*)	Severity (*S*)	Not detection (*D*)
Structural collapse due to excavation operations	(0.163, 0.231, 0.337, 0.437)	(0.416, 0.516, 0.633, 0.710)	(0.164, 0.216, 0.324, 0.424)
Overall structural collapse	(0.102, 0.161, 0.282, 0.382)	(0.516, 0.600, 0.700, 0.768)	(0.178, 0.240, 0.348, 0.448)
Slipping	(0.366, 0.466, 0.617, 0.708)	(0.292, 0.377, 0.508, 0.600)	(0.328, 0.411, 0.519, 0.612)
Falling from height	(0.407, 0.507, 0.640, 0.731)	(0.578, 0.678, 0.778, 0.831)	(0.271, 0.360, 0.475, 0.566)
Objects falling on individuals	(0.405, 0.497, 0.634, 0.734)	(0.538, 0.638, 0.746, 0.846)	(0.253, 0.353, 0.472, 0.572)
Objects falling on machines	(0.277, 0.377, 0.520, 0.620)	(0.288, 0.381, 0.538, 0.638)	(0.246, 0.338, 0.457, 0.557)
Electrocution	(0.271, 0.363, 0.507, 0.607)	(0.569, 0.662, 0.767, 0.833)	(0.284, 0.384, 0.499, 0.590)
Fire	(0.314, 0.406, 0.528, 0.628)	(0.634, 0.734, 0.851, 0.909)	(0.214, 0.298, 0.418, 0.518)
Explosion	(0.206, 0.272, 0.391, 0.483)	(0.749, 0.849, 0.949, 0.974)	(0.351, 0.427, 0.542, 0.615)
Injuries due to working with tools	(0.424, 0.524, 0.666, 0.758)	(0.361, 0.461, 0.601, 0.701)	(0.341, 0.441, 0.562, 0.651)
Exposure to harmful and hazardous materials/ chemical spray	(0.226, 0.317, 0.441, 0.541)	(0.431, 0.531, 0.668, 0.756)	(0.184, 0.261, 0.369, 0.469)
Accidents related to the transportation and installation of heavy equipment and structures	(0.361, 0.461, 0.584, 0.684)	(0.656, 0.756, 0.863, 0.924)	(0.226, 0.318, 0.457, 0.557)
Accidents related to heavy machinery	(0.282, 0.373, 0.527, 0.627)	(0.663, 0.763, 0.879, 0.924)	(0.261, 0.352, 0.476, 0.564)
Gas choking	(0.208, 0.286, 0.401, 0.493)	(0.594, 0.694, 0.814, 0.868)	(0.325, 0.404, 0.541, 0.622)
Poisoning and dizziness due to exposure to gas from materials during work	(0.273, 0.359, 0.484, 0.576)	(0.436, 0.528, 0.682, 0.760)	(0.294, 0.378, 0.515, 0.615)

Table 8. Final weight of each criterion

Criterion	Subjective weights	Normalized subjective weights	Objective weights	Aggregated weights
Occurrence (*O*)	(0.504, 0.604, 0.728, 0.818)	(0.218, 0.261, 0.314, 0.353)	(0.242, 0.246, 0.252, 0.260)	(0.230, 0.253, 0.283, 0.306)
Severity (*S*)	(0.709, 0.809, 0.917, 0.951)	(0.306, 0.349, 0.396, 0.410)	(0.242, 0.243, 0.257, 0.258)	(0.274, 0.296, 0.327, 0.334)
Not detection (*D*)	(0.651, 0.751, 0.869, 0.917)	(0.281, 0.324, 0.375, 0.396)	(0.231, 0.235, 0.248, 0.285)	(0.256, 0.280, 0.312, 0.340)

Table 9. Ranking of the risks

Risk	Score	Rank
R_1: Structural collapse due to excavation operations	0.3370	15
R_2: Overall structural collapse	0.3511	14
R_3: Slipping	0.4769	11
R_4: Falling from height	0.5542	1
R_5: Objects falling on individuals	0.5427	4
R_6: Objects falling on machines	0.4216	12
R_7: Electrocution	0.5135	8
R_8: Fire	0.5137	7
R_9: Explosion	0.5505	3
R_{10}: Injuries due to working with tools	0.5375	6
R_{11}: Exposure to harmful and hazardous materials/chemical spray	0.4013	13
R_{12}: Accidents related to the transportation and installation of heavy equipment and structures	0.5516	2
R_{13}: Accidents related to heavy machinery	0.5394	5
R_{14}: Gas choking	0.5057	9
R_{15}: Poisoning and dizziness due to exposure to gas from materials during work	0.4790	10

Table 10. Solutions for each risk

	Solutions														
Risk	S_1	S_2	S_3	S_4	S_5	S_6	S_7	S_8	S_9	S_{10}	S_{11}	S_{12}	S_{13}	S_{14}	S_{15}
R_1: Structural collapse due to excavation operations	✓	✓	✓	✓	✓							✓			
R_2: Overall structural collapse	✓	✓	✓	✓	✓							✓			
R_3: Slipping	✓	✓	✓	✓	✓	✓	✓				✓	✓			
R_4: Falling from height	✓	✓	✓	✓	✓		✓				✓	✓			
R_5: Objects falling on individuals	✓	✓	✓	✓	✓			✓			✓	✓			
R_6: Objects falling on machines	✓	✓	✓	✓	✓			✓			✓	✓			
R_7: Electrocution	✓	✓	✓	✓	✓						✓	✓			
R_8: Fire	✓	✓	✓	✓	✓				✓			✓			
R_9: Explosion	✓	✓	✓	✓	✓				✓			✓			
R_{10}: Injuries due to working with tools	✓	✓	✓	✓	✓						✓	✓	✓		
R_{11}: Exposure to harmful and hazardous materials/chemical spray	✓	✓	✓	✓	✓	✓			✓		✓	✓			
R_{12}: Accidents related to the transportation and installation of heavy equipment and structures	✓	✓	✓	✓	✓	✓						✓	✓	✓	
R_{13}: Accidents related to heavy machinery	✓	✓	✓	✓	✓	✓				✓		✓			✓
R_{14}: Gas choking	✓	✓	✓	✓	✓						✓	✓			
R_{15}: Poisoning and dizziness due to exposure to gas from materials during work	✓	✓	✓	✓	✓						✓	✓			

Notes: S_1: Development of clear safety instructions; S_2: Employing a competent executor in the construction field; S_3: Employing skilled and trained personnel in the safety field; S_4: Training on safety issues for all employees; S_5: Observance of safety principles and regulations in the project site; S_6: Proper layout of the project site; S_7: Proper installation of scaffolding and work platforms; S_8: Preparing protective caps, such as protective nets; S_9: Preventing the storage of harmful and dangerous materials in the project site; S_{10}: Employing skilled machinery operators; S_{11}: Providing personal protective equipment (PPE) for all employees; S_{12}: Continuous supervision of work by supervising engineers; S_{13}: Use of appropriate equipment; S_{14}: Transportation and installation of equipment in compliance with safety principles and in accordance with relevant instructions; S_{15}: Installation, relocation and dismantling of equipment and machinery in accordance with the instructions and requirements of the machines.

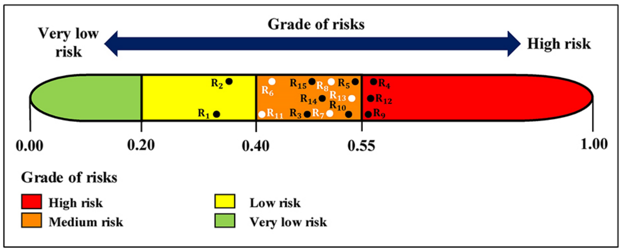

Figure 3. Importance grade of each risk

4.3. Determination and ranking of CSFs

According to the results of the risk assessment in the first phase and through using the solutions provided for each risk (Table 10) and consulting with some experts, the safety-related CSFs in the petrochemical construction projects were determined and listed (Table 11). To determine the importance level of each safety-related CSF, a questionnaire was prepared and the experts were asked to rank each factor based on its importance level by using an ordinal five-level scale (1: very low; 2: low; 3: medium; 4: high; 5: very high). After collecting the questionnaires, the score of each factor was determined through average weighting of the expert opinions, and the factors were ranked in a descending order (Table 11).

5. Discussion

This section covers three subsections. Subsection 5.1 presents the results obtained from the proposed framework and related discussions. Subsection 5.2 presents the benefits that can be derived by project managers from the present study. Subsection 5.3 describes the limitations of the present study and provides suggestions for future study for those interested in this field.

5.1. Results and related discussions

By using the framework presented in the present study for the risk assessment and determination of safety-related CSFs in petrochemical construction projects, the following results were obtained:

- As indicated in Table 9 and Figure 3, falling from height and structural collapse due to excavation operations were identified as the most and least important risks in petrochemical projects, respectively.
- Risks of falling from height, accidents related to transportation and installation of heavy equipment and structures, and explosion were ranked as high-importance risks that require immediate corrective actions to prevent their occurrence.
- Risks of objects falling on individuals, accidents related to heavy machinery, injuries due to working with tools, fire, electrocution, gas choking, poisoning and dizziness due to exposure to gas from materials during work, slipping, objects falling on machines, and exposure to harmful and hazardous materials/chemical spray were ranked as moderate-importance risks that need high priority for corrective actions to eliminate or reduce the risk effects.
- Risks of overall structural collapse, and structural collapse due to excavation operations were ranked as low-importance risks that need monitoring and appropriate responses, if necessary.
- To prevent risk occurrence and control all risks, a specific set of solutions was provided for each risk (Table 10).
- As shown in Table 11, 11 safety-related CSFs in the petrochemical construction projects were identified in the present study. According to the score obtained for each factor, the order of importance of the safety-related CSFs were as follows: 1) top management support, 2) training on safety issues for all employees, 3) employing a competent executor in the field of construction, 4) considering safety issues in the initial project design and giving priority to safety over other elements of the project, 5) providing PPE for all employees and emphasising its application necessity, 6) employing skilled and trained workers in the field of safety, 7) developing clear safety instructions, 8) regular and continuous supervision of work by supervising engineers, 9) observance of safety rules, standards and protocols in the project site, 10) continuous staff participation and good communication, and 11) holding continuous

Table 11. Ranking of safety-related CSFs

Safety-related CSFs	Rank	Score
Top management support	1	4.85
Training on safety issues for all employees	2	4.75
Employing a competent executor in the field of construction	3	4.67
Considering safety issues in the initial project design and giving priority to safety over other elements of the project	4	4.53
Providing PPE for all employees and emphasising its application necessity	5	4.42
Employing skilled and trained workers in the field of safety	6	4.41
Developing clear safety instructions	7	4.37
Regular and continuous supervision of work by supervising engineers	8	4.31
Observance of safety rules, standards and protocols in the project site	9	4.29
Continuous staff participation and good communication	10	4.28
Holding continuous safety meetings and providing the necessary platform for establishing open communication between management and employees	11	4.20

safety meetings and providing the necessary platform for establishing open communication between management and employees.

- 'Top management support' obtained the highest score in terms of importance level amongst all safety-related CSFs and thus known as the most important factor. This indicates that management's support for safety issues and his actions in this field can be highly effective in preventing accidents and improving the project safety level. Then, 'training on safety issues for all employees' and 'employing a competent executor in the field of construction' obtained the second and third highest scores, respectively, in terms of the importance level amongst the 11 safety-related CSFs, indicating the significant effect of these factors in improving the project safety level.

The results of the present study were validated by comparing with the results of previous studies in construction projects. According to the results of the first phase of the present study, falling from height was ranked as the first risk and was thus the most significant risk amongst all risks. This finding is in agreement with previous studies, such as Ardeshir et al. (2016) and Newaz et al. (2022). In addition, based on the results of the second phase of the present study, top management support scored the highest amongst the 11 safety-related CSFs and was identified as the most important safety-related CSF. This finding is also in agreement with previous studies, such as Aksorn and Hadikusumo (2008) and Al Haadir and Panuwatwanich (2011). In addition, the validity of the results obtained in the present study was confirmed by petrochemical experts.

Another remarkable distinction of the present study is the comprehensiveness and novelty of the applied approach in comparison with those presented in previous studies on risk assessment and determination of safety-related CSFs in construction projects for the following reasons:

1. Petrochemical construction projects and safety-related probable risks are specifically studied.
2. A combination of fuzzy FMEA, fuzzy CRITIC and fuzzy TOPSIS methods has been used to rank risks. According to the research conducted by the authors of the present study, such a structured and integrated approach as the one used in this study has not been presented for risk assessment in petrochemical construction projects.
3. A process for determining and prioritising safety-related CSFs in petrochemical construction projects is presented. This approach is highly beneficial for project managers as it allows them to have a realistic view of safety-related CSFs in their projects and act efficiently in preventing accidents by focusing their energy on these factors and taking necessary actions that will result in improving the project safety level.
4. According to the authors' review, the present study is a precursor to the research and determination of safety-related CSFs in petrochemical construction projects.

5.2. Implications for managers

The construction phase of petrochemical units encounters many risks, a large number of which leads to fatalities and disabling injuries. On the one hand, the success of a project, especially in terms of safety, is one of the most important goals of managers as the main responsible and decision maker in a project, and taking the necessary actions by them can be highly effective in preventing accidents and improving safety level. On the other hand, given the complexity of construction projects, the number of project success factors in terms of safety is large, and in practice, controlling all the factors is difficult and requires considerable time and money. Therefore, safety-related CSFs are important for project managers and should be identified, such that they can focus their energy on the factors and act efficiently to take the necessary actions in preventing accidents. Hence, the most important issue is how to determine and prioritise safety-related CSFs in petrochemical construction projects to control risks and improve safety.

The framework presented in the current study provides a structured and step-by-step solution to this problem. Risks in petrochemical projects can be identified and assessed using a combination of fuzzy FMEA and fuzzy CRITIC–TOPSIS methods. Then, on the basis of the results of the risk assessment and the use of presented solutions, safety-related CSFs in petrochemical construction projects can be identified and prioritised based on expert knowledge. This approach is useful, practical and applicable for project managers because it allows them to adopt a structured approach in determining safety-related CSFs and their level of importance in their projects; accordingly, they can take necessary actions to prevent accidents.

5.3. Limitations and suggestions for future studies

The findings of the present study provide useful data on the risks and safety-related CSFs in petrochemical construction projects to those involved in this field, especially project managers. However, this study has limitations also to be considered by users. Firstly, the sample size in the present study is relatively small, so great care should be taken in generalising the results and conclusions. Secondly, when using the findings of the present study, the existing differences in the safety of petrochemical construction projects between Iran and other countries should be considered. Lastly, the sustainability issue was not considered in the framework of the present study and the results were only based on safety considerations; therefore, users of the results of this study should consider this issue.

In future studies in this field, the proposed approach can be applied in other countries, and the results can be compared with those of the present study. In addition, other methods, such as fuzzy AHP and fuzzy BWM, can be used to determine the weights of the criteria. Furthermore, other MCDM methods, such as fuzzy VIKOR and fuzzy PROMETHEE, can be employed to rank risks in petrochemical projects, and the results can be compared with those of the present study.

6. Conclusions

The construction of petrochemical units is a high-risk operation due to the huge volume of facilities, materials and equipment, and the occurrence of accidents causes many fatalities and financial losses. In the present study, a comprehensive and innovative approach for the risk assessment and determination of safety-related CSFs in petrochemical construction projects was proposed. Fifteen risks were identified through a literature review and interviews with experts in the field of petrochemicals. Then, the risks were ranked and classified on the basis of their scores by using fuzzy FMEA and fuzzy CRITIC–TOPSIS methods. Falling from height, accidents related to transportation and installation of heavy equipment and structures and explosion were identified as the most important risks in the construction of petrochemical projects and belong to high-importance risks that require immediate corrective actions to prevent their occurrence. In addition, in accordance with the results of the risk assessment and by utilising the proposed solutions, safety-related CSFs in petrochemical construction projects were determined and prioritised using expert opinions. Top management support was identified as the most important factor amongst the safety-related CSFs.

The results of the present study were validated by comparing them with the results of previous studies, and good consistency was found. In addition, the validity of the results obtained in the present study was confirmed by petrochemical experts. The proposed framework is useful for petrochemical construction project managers because it enables them to adopt a structured approach for the risk assessment and determination of safety-related CSFs in their projects and prevent accidents by implementing necessary actions.

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Author contributions

Alireza Azodi and Hamidreza Abbasianjahromi designed the research framework; Alireza Azodi conducted the research; All authors contributed to the manuscript text; Hamidreza Abbasianjahromi and Emadaldin Mohammadi Golafshani Supervised the research. All authors have read and agreed to the published version of the manuscript.

Disclosure statement

The authors declare no conflict of interest.

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