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# Hybrid fuzzy MCDM and FMEA integrating with linear programming approach for the health and safety executive risks: a case study

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## Abstract

**Purpose** – The purpose of this study is to present a new failure mode and effects analysis (FMEA) approach based on fuzzy multi-criteria decision-making (MCDM) methods and multi-objective programming model for risk assessment in the planning phase of the oil and gas construction projects (OGCP) in Iran.

**Design/methodology/approach** – This research contains multiple steps. First, 19 major potential health and safety executive (HSE) risks in OGCP were classified into six categories with the Delphi method. These factors were distinguished by the review of project documentation, checklist analysis and consulting with experts. Then, using the fuzzy SWARA method, the authors calculated the weights of major HSE risks. Subsequently, FMEA and PROMETHEE approaches were used to identify the priority of main risk factors. Eventually, a binary multi-objective linear programming approach was developed to select the risk response strategies, and an augmented e-constraint method (AECM) was used.

**Findings** – Regarding the project triple well-known constraints of time, cost and quality, which organizations usually confront, the HSE risks of OGCP were identified and prioritized. Also, the appropriate risk response strategies were also suggested to the managers to be adopted regarding the situations.

**Originality/value** – The present research points at the HSE risks' assessment integrating the fuzzy FMEA, step-wise weight assessment ratio analysis and PROMETHEE techniques with the AECM. Further to the authors' knowledge, the quantitative assessment of the HSE risks of OGCP has not been done using the combination of the fuzzy FMEA, MCDM and AECMs.

**Keywords** Risk management, Risk assessment, Fuzzy set theory, FMEA, Multi-criteria decision-making (MCDM), Linear programming, project management

**Paper type** Research paper

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## 1. Introduction

With the increasing growth of technology in oil and gas construction projects (OGCP), we always face with increasing risks arising from work. Controlling these risks requires a type of management system that reduces these risks and ensures increased safety and employee well-being and protects the environment. Every year, a large portion of the country's budget is allocated to OGCP. Billions of dollars are invested annually in OGCP, and this shows the high importance of this sector. Every year, organizations confront a lot of damage to human resources, equipment and reputation due to work-related accidents and environmental pollution caused by their activities.

The National Iranian Oil Company (NIOC) is responsible for the development of Iran's oil and gas reservoirs, which are the second largest in the world (van Groenendaal and Mazraati, 2006). In the recent years, many OGCP have been executed like South Pars, and more projects are about to be initiated soon. OGCP are composed of high levels of risk because of intensive investment, numerous stockholders, complex technology and unique nature (Van Thuyet *et al.*, 2007). Identifying the risks of energy is crucial for the oil and gas (O&G) industry and its upstream and downstream sectors (De Maere d'Aertrycke *et al.*, 2017). Construction projects has a remarkable role in the O&G supply chain (Berends, 2007; Hong *et al.*, 2016). Therefore, the governments of developing countries need to ascertain these projects will be accomplished on time with the minimum threats and risks (Bacon and Besant-Jones, 1998). Hence, it is necessary to perform successful risk management processes in OGCP, which assist firms to gain more value-added deliverables and to endure in the growing competitiveness (Denney, 2006). Various research studies have been done on health and safety executive (HSE) risk assessment in different industries, such as construction and research and development, nevertheless, few studies introduced appropriate organized methodologies for risk management in OGCP.

Failure mode and effects analysis (FMEA) is known as an authentic technique in the field of risk management to ensure the reliability and safety of the product and system in diverse industries. The approach can be implemented to determine the possible component failures and errors of a process or system effectively (Tooranloo and sadat Ayatollah, 2016). It generally prioritizes failure modes regarding risk priority number (RPN), which is calculated by simply multiplying the three RPN components, namely, the severity of the failure effect (S), probability of failure-mode occurrence (O) and probability of the failure being detected (D). However, the traditional FMEA has been dispraised by scholars for some shortcomings as follow:

- The RPN value does not consider the relative importance of severity (S), occurrence (O) and detection (D) (Kutlu and Ekmekçioğlu, 2012; Liu *et al.*, 2012; Chang, 2016).
- Precisely evaluation of S, O and D is difficult because evaluators need to base their FMEA opinions on ambiguous or uncertain information (Yang and Wang, 2015).
- This method considers only three elements of the RPN In terms of safety aspects and neglects other significant elements of the RPN, such as the consequences of cost, time and quality (Chang, 2016; Ahmadi *et al.*, 2017; Lo and Liou, 2018).

Risk assessment process of FMEA is mostly affected by uncertain data in real-world applications (Lo and Liou, 2018). Fuzzy set theory is the tool for transforming the vagueness of human perception into a mathematical formula (Zadeh, 1965). Comparing to the numerical models, the fuzzy logic methods have outstanding advantages (Braglia *et al.*, 2003; Liu *et al.*, 2012), some of them are expressed as follows: First, both quantitative and qualitative data can be used and managed properly throughout the FMEA analysis. Second, the risk of failure modes can be analyzed with the linguistic variables. Finally, imprecise data can be used in fuzzy logic methods, so it enables the presentation of different states of the components and systems in FMEA.

In this study, to overcome the aforementioned weaknesses of the RPN, a new FMEA model is extended on fuzzy multi-criteria decision-making (MCDM) methods and multi-objective programming model for HSE risk assessment in OGCP in the country that will respond to the below questions:

*Q1.* What are the major HSE risks in OGCP?

*Q2.* How the likelihood, impact and rank of each risk are determined?

*Q3.* What are the appropriate response strategies for these risks?

The major contributions of this paper are briefly stated as follows:

- The common risks of the OGCP were identified through the review of historical documents, checklist analysis and consulting with experts.
- For enhancing the assessment capability of FMEA, the fuzzy SAWARA method was applied to determine the weights of the RPN elements, namely, severity, occurrence, detection, cost, time and quality through the judgments of decision-makers. SWARA makes comparisons in a structured manner that requires fewer pairwise comparisons to obtain the weight values.
- The PEOMETHEE method was developed to compute the RPN value and find a compromised RPN. To deal with the ambiguity and imprecision of the risk assessment, linguistic terms, which are shown with triangular fuzzy numbers, are used to determine the fuzzy relative importance of risk factors.
- A binary multi-objective optimization model was proposed to select the optimal risk response strategies for the project.

The rest of this paper is structured as follows: the Section 2 reviews the research literature. Section 3 describes the research methodology. Section 4 presents a case study and discusses the numerical results. Section 5 proposes managerial discussion. Finally, Section 6 concludes the paper with some suggestions for future research.

## 2. Literature review

Risk, an inevitable incident in whole facets of projects, could be defined as "an uncertain event that, if it occurs, has a negative or positive effect on at least one of the project objectives" (Seyedhoseini *et al.*, 2009). Risk management is a set of structured and formal processes such as risk identification, risk analysis and assessment, risk response planning and risk monitoring to assure that project goals are attained (Jia *et al.*, 2013; Al Subaih, 2015; Carvalho and Rabechini Junior, 2015). Risk assessment is the process of qualitative and quantitative analysis of risk potential and the actual rate of potential risks arising from project implementation, as well as the sensitivity or vulnerability of the environment.

Risk factors may threaten project safety throughout the whole phases of project. Risk avoidance and mitigation in projects is very valuable and many prevent or lessen injuries, disruptions, repair costs, environmental problems and other issues (Kraidi *et al.*, 2019). Risks in OGCP are categorized into technical, social, natural, financial, environmental and political risks (Aven *et al.*, 2007). Bhalaji *et al.* (2020) used fuzzy PROMETHEE approach to prioritize risks in green production. Identified risks were divided into environmental, economic and social risks. The case study was an Indian medical equipment-manufacturing firm, the results of which indicated the priority of environmental risks over other risks. Zhu *et al.* (2020) used a PROMETHEE and FMEA hybrid approach to prioritize risks of supercritical water gasification system. The use of regret theory and linguistic neutrosophic were among the innovations of this research. The results indicated the appropriate performance of the proposed model in prioritizing risks. Ghandi and Roozbahani (2020) prioritized Drinking Water Supply in Critical Conditions for Tehran. Fuzzy PROMETHEE approach was used for prioritization. The considered criteria included the reliability and quality of drinking water as well as implementation costs. The results led to risk management during transportation and distribution of drinking water in disaster situations.

Zhang *et al.* (2019) ranked risks of Equipment Failures in the Geothermal Power Plant using the PROMETHEE approach. FMEA and linguistic Z-number approaches were used to achieve this objective. Distance-based weighting method was used to weight the criteria. Liu (2019) identified and prioritized risks in the emergency department. FMEA and PROMETHEE approaches were used to achieve this goal. The use of fuzzy approach with cognitive model was one of the innovations of this research. Jaber (2019) examined and prioritized risks in construction projects in Iraq. So, a hybrid COPRAS-SWARA approach was used. The weights of the criteria were estimated with SWARA approach and prioritization was done using COPRAS approach. By identifying and prioritizing risks, results indicated saving on project costs. Akcan and Taş (2019) identified and ranked risk factors in selecting green suppliers. SWARA approach was used to determine the weights of the criteria and TOPSIS method was used for ranking. The case study was the international yachting company operating in Turkey. The results indicated that environmental risks are the most important risks relative to other risks. Jafarzadeh Ghoushchi *et al.* (2020) used a SWARA and gray relational analysis (GRA) hybrid approach to prioritize the failures of solar panel systems. The criteria were weighted by the SWARA approach and ranked by the GRA approach. The use of Z-number theory and FMEA were among the innovations of this research. The results indicated the proper performance of the SWARA and GRA hybrid approach.

Tabaraee *et al.* (2018) prioritized investment projects using the fuzzy PROMETHEE approach. Therefore, different power plants were prioritized for investment. The weights of the criteria were determined by the TOPSIS approach and power plants were prioritized using the fuzzy PROMETHEE approach. The results indicated the appropriate performance of the proposed approach. Zarbakhshnia *et al.* (2018) prioritized Sustainable third-party reverse logistics suppliers. The identified criteria were weighted by the fuzzy SWARA approach and then the options were ranked by the fuzzy COPRAS approach. Consideration of Sustainability criteria and prioritization of risk factors based on these criteria were among the innovations of this research. Ghorabaee *et al.* (2018) presented a new hybrid decision-making method based on the fuzzy SWARA for ranking construction equipment.

Baloi and Price (2003) comprehensively examined the risk factors in OGCP and identified a set of key factors, including: insufficient skills; poor quality of materials; and unreliable equipment and inefficient management. Employees are exposed to risks such as noise, vibration, long shifts, chemicals, heavy physical work, dangerous work operations and lack of privacy (Bjerkan, 2010; Gardner, 2003; Høivik *et al.*, 2009; Katharine R. Parkes, 2012; Lee and Kim, 2017). In OGCP, traditionally the main focus is on technical risk factors such as leaking valves and flanges as well as the age and general technical condition of the equipment (Vinnem *et al.*, 2006). Koulinas *et al.* (2019) proposed a safety risk assessment process using the fuzzy extended AHP for prioritizing the risks in worksite in the Greek construction sector. Rezaee *et al.* (2020) introduced a hybrid approach based on the

Linguistic FMEA, Fuzzy Inference System (FIS) and Fuzzy Data Envelopment Analysis (DEA) model for HSE risk assessments in chemical industry.

Van Thuyet *et al.* (2007) assessed 59 major risk factors related to OGCP in Vietnam. Greening and Bernow (2004) applied MCDM methods to OGCP. Mousavi *et al.* (2012) proposed a MCDM method to assess the proper risk response strategies for major risks in mega projects. Dey (2012) represented an integrated analytical framework for effective management of project risks based on AHP and Decision Tree Analysis in Oil refinery construction projects. Dehdasht *et al.* (2017) proposed a hybrid MCDM approach based on DEMATEL and Analytic Network Process (ANP) to assess the overall risk factors of OGCP. Mukhtar *et al.* (2019a) investigated the risk factors in OGCP in Yemen. Also, Mukhtar *et al.* (2019b) applied probability–impact matrix to identify and assess the major risks in Yemen OGCP. They concluded that the major risk factors have great impacts on the success of OGCP. Mete *et al.* (2019) developed a decision-support system (DDS) based on Pythagorean fuzzy VIKOR for occupational risk assessment of a natural gas pipeline construction.

A brief review of the related literature is shown in Table 1.

According to studies in the literature, we can admit that the FMEA-MCDM approach for risk evaluation of OGCP has not been used widely. Hence, in this paper, the integration of FMEA, fuzzy SWARA and the PROMETHEE methods are presented to identify and prioritize crucial risks of OGCP. Additionally, a binary multi-objective optimization model is proposed for assigning response strategies to risk factors.

## 3. Proposed FMEA approach

FMEA is a systematic method which is applied to identify, mitigate and/or eliminate potential and practical failures throughout production and service processes before delivery by determining the RPN (Barends *et al.*, 2012):

$$RPN = S \times O \times D \tag{1}$$

where S is he severity of the failure effect, O is the probability of failure-mode occurrence, and D is the detectability of the failure. To determine the RPN of a potential failure mode with the conventional FMEA, an integer number scaling from 1 to 10 is used for each of the three risk factors. Normally, the failure modes with greater RPNs are taken into consideration with higher priorities for corrective actions and the team should take proper action to mitigate or avoid it (Liu *et al.*, 2012). As mentioned in introduction section, traditional FMEA method considers only three elements of the RPN (severity, occurrence and detection) and neglects other significant elements of the RPN, such as cost (C), time (T) and quality (Q). In the other hand, RPN value does not consider the weight of RPN elements. Therefore, we propose a new risk evaluation model for FMEA, which is based on integrating fuzzy SWARA and PROMETHEE method to compute the RPN value and find a compromise priority ranking of the failure modes. First, fuzzy SWARA is applied to calculate the relative importance of the RPN element according to linguistic scales as defined in Table.

Second, PROMETHEE method prioritizes the major identified risk. Finally, the appropriate strategy to respond to each risk is chosen by using a binary mathematical programming model. The framework of the proposed model is shown in Figure 1.

Figure 2 shows the decision-making section in this study. As can be seen, first, after defining the research problem, selecting the required criteria and selecting the experts, the weight of the criteria will be determined using Fuzzy SWARA method. In this method, fuzzy

**Table 1.**
Summary of the related literature

| References | Type of research |  |  | Parameters |  |  | Methodology |
|---|---|---|---|---|---|---|---|
|  | SA | DT | MP | D | F | G |  |
| Rezaee *et al.* (2020) |  |  | ✓ |  | ✓ |  | Fuzzy PROMETHEE |
| Bhalaji *et al.* (2020) |  | ✓ |  |  | ✓ |  | FMEA, PROMETHEE, Regret theory |
| Zhu *et al.* (2020) |  | ✓ |  |  |  | ✓ | Fuzzy PROMETHEE |
| Ghandi and Roozbahani (2020) |  | ✓ |  |  | ✓ |  | SWARA, GRA |
| Jafarzadeh Ghoushchi *et al.* (2020) |  | ✓ |  |  |  | ✓ | FMEA, Fuzzy PROMETHEE |
| Zhang *et al.* (2019) | ✓ | ✓ |  |  | ✓ |  | Pythagorean Fuzzy VIKOR |
| Mete *et al.* (2019) |  |  | ✓ |  | ✓ |  | FMEA, Fuzzy PROMETHEE |
| Liu (2019) |  | ✓ |  |  | ✓ |  | Hybrid COPRAS-SWARA |
| Jaber (2019) |  | ✓ |  | ✓ |  |  | TOPSIS-SWARA |
| Akcan and Taş (2019) |  | ✓ |  | ✓ |  |  | Fuzzy Extended AHP |
| Koulinas *et al.* (2019) |  | ✓ |  |  | ✓ |  | Fuzzy PROMETHEE, TOPSIS |
| Tabaraee *et al.* (2018) |  | ✓ |  |  | ✓ |  | Fuzzy SWARA, Fuzzy COPRAS |
| Zarbakhshnia *et al.* (2018) |  | ✓ |  |  | ✓ |  | Fuzzy SWARA, CRITIC |
| Ghorabaee *et al.* (2018) |  | ✓ |  |  | ✓ |  | FMEA, Fuzzy SWARA, PROMETHEE, Multi-objective optimization |
| This Study |  | ✓ | ✓ |  | ✓ |  |  |

**Notes: SA**: statistical analysis; **DT**: decision theory; **MP**: mathematical programming; **D**: deterministic; **F**: fuzzy; and **G**: gray

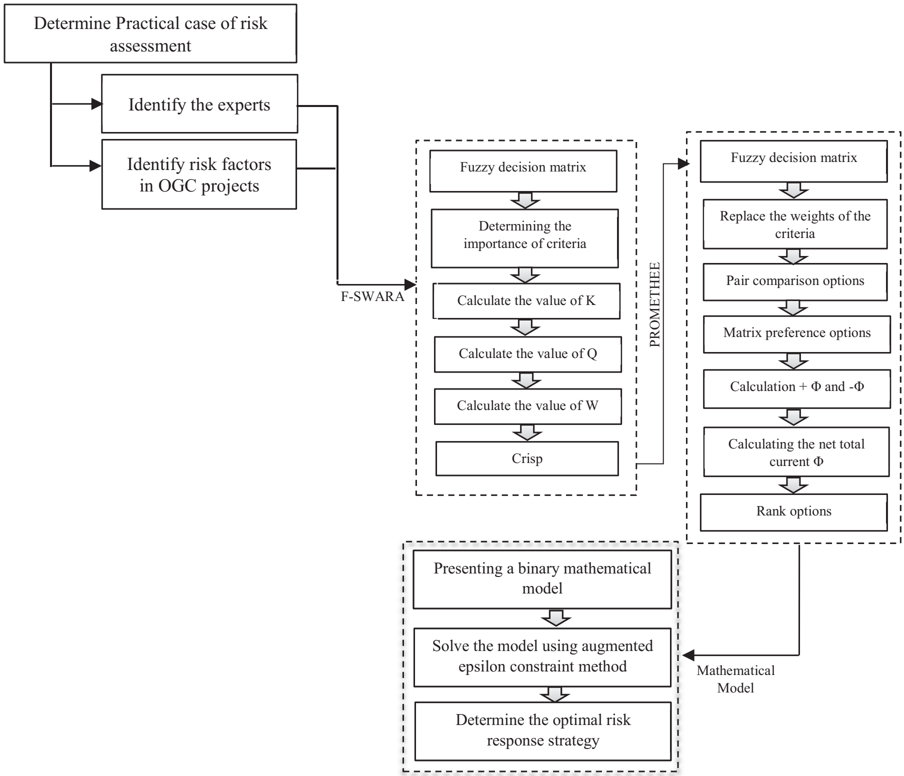


**Figure 1.**
Flowchart of proposed FMEA model

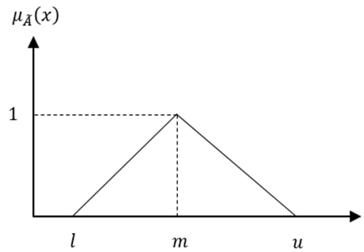


**Figure 2.**
Membership function

decision matrices are defined first and the importance of each criterion is determined. Then the coefficient of comparative importance, $\tilde{k}_j$, $\tilde{q}_j$ and finally the relative weights of the criteria are calculated and the fuzzy weights are converted to crisp.

After calculating the weights of the criteria, the options are ranked using the PROMETHE method. In this method, after forming the decision-making matrix, the weights of the criteria which were calculated by the SWARA approach, will enter this method. Then, after comparing the criteria and calculating the preference function, the PHI+, PHI− and net PHI values are determined. Finally, the options are ranked and the results are analyzed.

### 3.1 Fuzzy set theory

*3.1.1 Fuzzy set.* The fuzzy set theory was introduced by (Zadeh, 1965) to deal with the uncertainty existed in real-life world problems and human decisions. A membership function, which is between [0,1], is assigned to each fuzzy set. In the classic theory, the truth-value for a statement is expressed by membership function as follows (Wu *et al.*, 2009):

$$\mu_A(x) = \begin{cases} 1, & if \,|x \in A \\ 0, & if \ \ |x \notin A \end{cases} \tag{2}$$

According to the definition by the (Dubois and Prade, 1978), fuzzy numbers are a fuzzy subset from real numbers that are used for extension of confidence interval idea. The fuzzy number $\tilde{A}$ is of a fuzzy set, and its membership function is $\mu_{\tilde{A}}(x): \ R \rightarrow [0,1](0 \leqq \mu_{\tilde{A}}(x) \leqq 1, x \in X)$, where $x$ represents criterion which is characterized as follows: $\mu_{\tilde{A}}(x)$ is a continuous mapping from R (Real Numbers) to the closed interval of [0,1]; $\mu_{\tilde{A}}(x)$ is a convex fuzzy subset; and $\mu_{\tilde{A}}(x)$ is a normalized fuzzy subset, which means there exist a number $x_0$ such that $\mu_{\tilde{A}}(x_0)$. Therefore, the triangular fuzzy number (TFN), $\tilde{A} = (l,m,u)$, can be defined as equation (3), and the TFN membership function is demonstrated as Figure 2 in geometric space:

$$\mu_{\tilde{A}}(x) = \begin{cases} (x-l)/(m-l), & |if \ \ l \le x \le m \\ (u-x)/(u-m), & |if \ \ m \le x \le u \\ 0, & |Otherwise \end{cases} \tag{3}$$

Let $\tilde{A}_1 = (l_1,m_1,u_1)$ and $\tilde{A}_2 = (l_2,m_2,u_2)$ be two triangular fuzzy numbers, some algebraic operations of the triangular fuzzy numbers $\tilde{A}_1$ and $\tilde{A}_2$ can be represented as follows (Rezaei *et al.*, 2014; Tadić *et al.*, 2014):

Addition of two TFNs:

$$\tilde{A}_1 \oplus \ \tilde{A}_2 = (l_1, m_1, u_1) \oplus (l_2, m_2, u_2) = (l_1 + l_2, m_1 + m_2, u_1 + u_2) \tag{4}$$

Multiplication of two TFNs:

$$\tilde{A}_1 \otimes \ \tilde{A}_2 = (l_1, m_1, u_1) \otimes (l_2, m_2, u_2) = (l_1 l_2, m_1 m_2, u_1 u_2) \tag{5}$$

Multiplication of any real number $\lambda$ and a TFN:

$$\lambda \otimes \tilde{A}_1 = (\lambda l_1, \lambda m_1, \lambda u_1), \ \ \lambda > 0 \tag{6}$$

Division of two TFNs:

$$\tilde{A}_1 \oslash \ \tilde{A}_2 = (l_1, m_1, u_1)/(l_2, m_2, u_2) = (l_1/u_2, m_1/m_2, u_1/l_2) \tag{7}$$

### 3.2 Fuzzy SWARA

The step-wise weight assessment ratio analysis (SWARA) approach was first proposed by (Keršuliene *et al.*, 2010). SWARA approach is one of the most widely used and new decision-making methods in calculating the weights of criteria. There are several successful applications of fuzzy SWARA method in recent years (Ajalli *et al.*, 2019; Dahooie *et al.*, 2019). One of the advantages of this method over other methods such as analytic hierarchy process (AHP) or ANP is that it does not require pairwise comparison and different times of weighing (Mardani *et al.*, 2017). Another advantage of this method is the simplicity of collecting data from experts and decision-makers. According to (Zarbakhshnia *et al.*, 2018) the process of calculating the weights of the criteria using the fuzzy SWARA method is as follows:

*Step 1:* According to the Table 2, sort the evaluation criteria from maximum preference to minimum, based on the expected significant opinions of decision-makers.

*Step 2:* Calculate the relative importance ratio ($S_j$) for the *j-th* criterion according to the *j-1* criterion. Start with the second criterion and continue until the last criterion. After calculating the value of $S_j$ for all decision-makers, the value of $\tilde{s}_j$ is obtained using arithmetic mean.

*Step 3:* Using equation (8), obtain the value of coefficient of comparative importance $\left(\tilde{k}_j\right)$ for all criteria.

$$\tilde{k}_j = \begin{cases} \tilde{1} & j = 1 \\ \tilde{s}_j + 1 & j > 1 \end{cases} \tag{8}$$

*Step 4:* Using equation (9), calculate the value of the fuzzy weights of the criteria $\tilde{q}_j$:

$$\tilde{q}_j = \begin{cases} \tilde{1} & j = 1 \\ \dfrac{\tilde{x}_{j-1}}{\tilde{k}_j} & j > 1 \end{cases} \tag{9}$$

*Step 5:* Using equation (10), calculate the relative weights of the criteria.

$$\tilde{W}_j = \frac{\tilde{q}_j}{\sum_{k=1}^{n} \tilde{q}_k} \tag{10}$$

where $n$ is the number of criteria and $\tilde{W}_j$ is the weight of the criterion $j$. Consider the calculated fuzzy weight as $\left(w_j^l, w_j^m, w_j^u\right)$.

**Table 2.** Fuzzy evaluation scale

| Linguistic term | Scale |
|---|---|
| Equally important | (1,1,1) |
| Moderately less important | $\left(\frac{2}{3}, 1, \frac{3}{2}\right)$ |
| Less important | $\left(\frac{2}{5}, \frac{1}{2}, \frac{2}{3}\right)$ |
| Very less important | $\left(\frac{2}{7}, \frac{1}{3}, \frac{2}{5}\right)$ |
| Much less important | $\left(\frac{2}{9}, \frac{1}{4}, \frac{2}{7}\right)$ |

**Source:** Chang (1996)

*Step 6:* The fuzzy weights calculated in the previous step are converted to non-fuzzy $w^{non}$ by equation (11):

$$w^{non} = \frac{\left(w_j^u - w_j^l\right) + \left(w_j^m - w_j^l\right)}{3} + w_j^l \tag{11}$$

*3.3 PROMETHEE*

PROMETHEE approach (Preference Ranking Organization Method for Enrichment of Evaluations) is one of the MCDM approaches that use outranking method to rank options (Behzadian *et al.*, 2010). Unlike other decision-making methods that use the same preference function (PF) to rank options, the PROMETHEE approach uses different preference functions to rank options according to their different characteristics (Sari *et al.*, 2020). This approach was first introduced by (Brans, 1982). The successful applications of this method in solving many MCDM problems have been reported (Qi *et al.*, 2019). See Ghasemi and Talebi Brijani (2014) for more information on this method. According to (Altun *et al.*, 2019) the process of solving this algorithm includes the following steps:

*Step 1:* Calculate the deviations from the comparison of the two options according to *j-th* criterion based on equation (12).

$$d_j(a,b) = f_j(a) - f_j(b) \quad j = 1,2,\ldots,k \tag{12}$$

where $j$ represents the $j$-th criterion and $k$ represents the total number of criteria considered. In addition, $f_j\,(a)$ is the value of the $j$-th criterion for option $a$.

*Step 2:* Determining the preference function using equations (13) and (14):

$$P_j(\mathrm{a,b}) = F_j\left[d_j(a,b)\right] \quad j = 1,2,\ldots,k \tag{13}$$

$$0 \leq P_j \leq 1, \quad j = 1,2,\ldots,k \tag{14}$$

where $P_j\,(a,b)$ defines the preference degree value of *j-th* criterion for the two options of $a$ and $b$.

*Step 2:* Calculation of aggregating the preference degrees for each possible pair of criteria using equation (15):

$$\pi(a,b) = \sum_{j=1}^{k} W_j P_j(a,b) \quad j = 1,2,\ldots,k \tag{15}$$

It should be noted that $\mathrm{W_j}$ is the weight of *j-th* criterion.

*Step 4:* In the fourth step, the values of outranking flows are calculated. In this step, for all possible options, the values of Phi + and Phi− are calculated according to equations 16 and 17. In these equations, "A" represents the set of options. In fact, the value of phi + indicates the preference of the considered option over other options and phi-indicates the preference of other options over the considered option.

$$\text{Ø}^{+}(a) = \sum\nolimits_{x\in A} \pi(x,a) \tag{16}$$

$$\text{Ø}^{-}(a) = \sum\nolimits_{x\in A} \pi(a,x) \tag{17}$$

*Step 5:* In the fifth step, the value of net flow Φ(a) is calculated, which is equal to the difference between the values of phi + and phi−. The higher the net phi value is, the better the option and the better the rank will be. The value of Φ(a) is defined based on equation (18):

$$\text{Ø}\ (a) = \text{Ø}^{+}(a) - \text{Ø}^{-}(a) \tag{18}$$

*3.4 Mathematical model*

It is supposed that in an organization to use risk management, there is a set of strategies for responding to critical risks. Implementing risk response strategies is generally exorbitant for firms. Hence, one or few of them may be selected to be implemented due to budget restrictions. In addition, the time for responding to each risk varies due to the risk parameters such as urgency. Taking the project common triple constraints of time, cost and quality into account (Van Wayngaad *et al.*, 2012), reducing time and cost of response and maximizing quality are considered as the principal objectives of the problem in hand. Just as projects are complex, so are their risks (Aloini *et al.*, 2012). Accordingly, the following assumptions are introduced before the model presentation.

*3.4.1 Assumptions.*

- The number of major risks is known.
- The number of strategies for responding to main risks is known.
- The implementation cost of each risk response strategy is specified.
- The risk response time is predefined.
- The quality level of each risk response strategy is specified.
- A given project is considered for risk assessment.
- The critical risks and as well as the corresponding response strategies for assigning to them are independent of each other.

*3.4.2 Sets.*

- *a:* The set of main risks $a = \{1, 2, \ldots, m\}$
- *b:* The set of risk response strategies $b = \{1, 2, \ldots, n\}$

*3.4.3 Parameters.* $f_{ab}$: The associated implementation cost of the response strategy $b$ for the main risk.

$ap_{ab}$: The associated implementation time of the response strategy $b$ for the main risk.

$al_{ab}$: The associated quality level of the response strategy $b$ for the main risk.

$apr_a$: The greatest number of permissible response strategy for assigning to the main risk $a$.

*3.4.4 Decision variables.* $z_{ab}$: 1, if the response strategy $j$ is assigned to the main risk $a$; otherwise, 0.

*3.4.5 Mathematical programming model.* The following binary multiple objectives linear programming model is given for the problem in hand:

$$\boldsymbol{MinZ_1} = \sum_{\mathbf{a}=1}^{m} \sum_{\mathbf{b}=1}^{n} \boldsymbol{f_{ab} z_{ab}} \tag{19}$$

$$MinZ_2 = \sum_{a=1}^{m} \sum_{b=1}^{n} p_{ab} z_{ab} \tag{20}$$

$$MaxZ_3 = \sum_{a=1}^{m}\sum_{b=1}^{n} l_{ab} z_{ab} \tag{21}$$

*s.t*

$$\sum_{b=1}^{n} z_{ab} \leq pr_a \quad \forall\ a \tag{22}$$

$$\forall\ a \quad \sum_{b=1}^{n} z_{ab} \geq 1 \quad \forall\ a \tag{23}$$

$$z_{ab} \in \{0,1\} \quad \forall\ a, b \tag{24}$$

Equation (19), minimizes the associated implementation cost of strategies for responding to the main risks. Equation (20) minimizes the associated implementation time of strategies for responding to the main risks. Equation (21) maximizes the associated quality level of strategies for responding to the main risks. The constraint (22) dictates that the number of allocated response strategies to any given risk cannot exceed the predefined restriction. The constraint (23) ensures that at least one response strategy is allocated to any given risk. Finally, the constraint (24) defines the model decision variables.

## 4. Case study analysis and application of the proposed methodology

In this section, the proposed methodology is applied to the case study. POGC is a subsidiary of National Iranian Oil Company (NIOC), was established in 1998. The development of the South and North Pars gas fields is the ultimate goal of POGC. In this study, the expert panel based on the Delphi method was used for getting data from the experts, wherein all the experts were called for a panel discussion and a detailed presentation was given to them regarding the case and the common major risks in OGCP. The meeting was directed by a skilled facilitator to uncover and remove the bias and settle disagreements and conflicts. The panel consisting of 10 experts was formed to conduct the study. All the experts had more than ten years of experience with great knowledge of risk management. The experts' information is presented in Table 3.

### *4.1 Finalization of major risks of POGC*

Generally, three main methods were used for data collection in this study. First, a comprehensive checklist of common risk factors associated with OGCP was gathered by thoroughly reviewing the historic documentation and lessons learned. Then, the identified risk factors were analyzed by the expert committee and reduced to a final list containing 19 principal HSE risks. Finally, 19 major potential HSE risks in OGCP were classified into six groups using the Delphi method according to Table 4.

### *4.2 Calculating the criteria weights*

The results of determining the weights of the criteria using fuzzy SWARA method are shown in Table 5. As can be seen, the values of $s_j$, $k_j$, $q_j$ and $w_j$ are calculated for fuzzy SWARA based on steps 1 to 6. Finally, the final weights for the mentioned criteria are calculated as CRISP based on equation (11). The weight of criteria of quality, time, cost, occurrence, detection and severity is 0.431, 0.215, 0.134, 0.059, 0.046 and 0.029, respectively.

**Table 3.** Experts' information

| Category | Details | No. |
|---|---|---|
| Working level | Top managers: The head of HSE department; the head of O&G engineering department; the head of O&G operation management department; the managing director of company | 4 |
| | Project managers: Member of project planning and controlling department; member of system engineering and productivity department | 4 |
| | Researcher: Faculty member of Petroleum University of Technology (PUT) | 2 |
| Education level | Bachelor | 0 |
| | Master | 2 |
| | PhD | 8 |
| Years of working experiences in POGC | $\geq$10 years and $\leq$15 years | 1 |
| | >15 years and $\leq$20 years | 7 |
| | >20 years | 2 |

**Table 4.** Major HSE risks associated with OGCP

| Row | Risk category | Major risks | Risk code |
|---|---|---|---|
| 1 | Environmental factors | Unfavorable ergonomic conditions | $R_1$ |
| | | Noise | $R_2$ |
| | | Vibrations | $R_3$ |
| 2 | Batching plant | Road accidents | $R_4$ |
| | | Cement silo fall | $R_5$ |
| | | Bucket fall during replacement | $R_6$ |
| | | Mixture or labor fall into basin | $R_7$ |
| 3 | Mechanical pre-start up | Labor fall from scaffolds due to inappropriate footstool | $R_8$ |
| | | Leakage within startup because of unsuitable bolting, torque and gasket | $R_9$ |
| | | Unforeseen crane or load fall on labor within loading and deflection tests | $R_{10}$ |
| 4 | Incident | Fracture of scaffolding clamp during scaffolding operation | $R_{11}$ |
| | | Labor Fall due to not restraining the hook of the harness belt despite wearing a seat belt when opening the scaffold | $R_{12}$ |
| | | Getting caught of technician's clothes and body between fixed and rotating and fixed machines | $R_{13}$ |
| | | Electrocution | $R_{14}$ |
| 5 | Stakeholders | Fire transfer of from neighboring contractors to the site | $R_{15}$ |
| | | Toxic and flammable gas emissions from the site and the effects on environment | $R_{16}$ |
| 6 | Construction | Respiratory injuries due to indoor painting | $R_{17}$ |
| | | Labor fall during installing windows | $R_{18}$ |
| | | Severe burns by melt bitumen while insulating | $R_{19}$ |

### 4.3 Identifying the main risks

In the aforementioned steps, the criteria's weights were determined for the assessment of the main risks in OGCP. As mentioned before, the flaws of the conventional FMEA method in calculating the RPN values directed us to integrate the fuzzy FMEA method with PROMETHEE. In this section, the results of PROMETHEE method are analyzed using visual PROMETHEE software. Table 6 shows the results of solving the decision-making model. Phi, Phi+ and Phi− values are shown in this table. As can be seen, the Phi values for all risks are calculated. For example, the value of Phi + and Phi− for R14 is 0.4122 and 0.0787, respectively, and the value of Phi, which is the difference between these two values, is 0.3335. The higher the Phi value is, the higher the rank of the risk will be.

Figure 3 shows the ranking of risk factors based on determined criteria and the opinion of decision-makers. The figure on the left shows the ranking based on PROMETHEE I (partial ranking) and the figure on the right shows the ranking based on PROMETHEEII (complete ranking). According to the partial ranking chart, R14 is selected as the first option. Where the axes intersect, this chart loses its efficiency. Therefore, complete ranking is used.

**Table 5.** Final weights obtained by fuzzy SWARA

| Criteria | $s_j$ | $K_j$ | $q_j$ | $w_j$ | Final weight |
|---|---|---|---|---|---|
| Quality | | (1.000,1.000,1.000) | (1.000,1.000,1.000) | (0.422,0.450,0.483) | 0.431 |
| Time | (1.000,1.000,1.000) | (2.000,2.000,2.000) | (0.500,0.500,0.500) | (0.211,0.225,0.242) | 0.215 |
| Cost | (0.400,0.500,0.667) | (1.400,1.500,1.667) | (0.300.0.333,0.357) | (0.126,0.150,0.173) | 0.134 |
| Occurrence | (0.667,1.000,1.500) | (1.667,2.000,2.500) | (0.120,0.167,0.214) | (0.051,0.075,0.104) | 0.059 |
| Detection | (0.222,0.250,0.286) | (1.222,1.250,1.286) | (0.093,0.133,0.175) | (0.039,0.060.0.085) | 0.046 |
| Severity | (0.400,0.500,0.667) | (1.400,1.500,1.667) | (0.056,0.089,0.125) | (0.024,0.040,0.061) | 0.029 |

**Table 6.** Calculate phi values

| Risks | Phi | Phi+ | Phi− |
|---|---|---|---|
| R14 | 0.3335 | 0.4122 | 0.0787 |
| R9 | 0.2167 | 0.3332 | 0.1165 |
| R13 | 0.1830 | 0.3410 | 0.1580 |
| R11 | 0.1815 | 0.3065 | 0.1250 |
| R19 | 0.1784 | 0.3573 | 0.1789 |
| R12 | 0.0873 | 0.3068 | 0.2194 |
| R3 | 0.0540 | 0.2488 | 0.1948 |
| R7 | 0.0448 | 0.2705 | 0.2258 |
| R17 | 0.0333 | 0.2239 | 0.1906 |
| R15 | 0.0191 | 0.2781 | 0.2590 |
| R10 | −0.0003 | 0.2420 | 0.2423 |
| R6 | −0.0312 | 0.2372 | 0.2684 |
| R18 | −0.0454 | 0.2262 | 0.2716 |
| R8 | −0.0847 | 0.2182 | 0.3029 |
| R2 | −0.1975 | 0.1633 | 0.3608 |
| R5 | −0.1985 | 0.1279 | 0.3264 |
| R1 | −0.2253 | 0.1738 | 0.3991 |
| R16 | −0.2281 | 0.2145 | 0.4426 |
| R4 | −0.3207 | 0.0875 | 0.4082 |

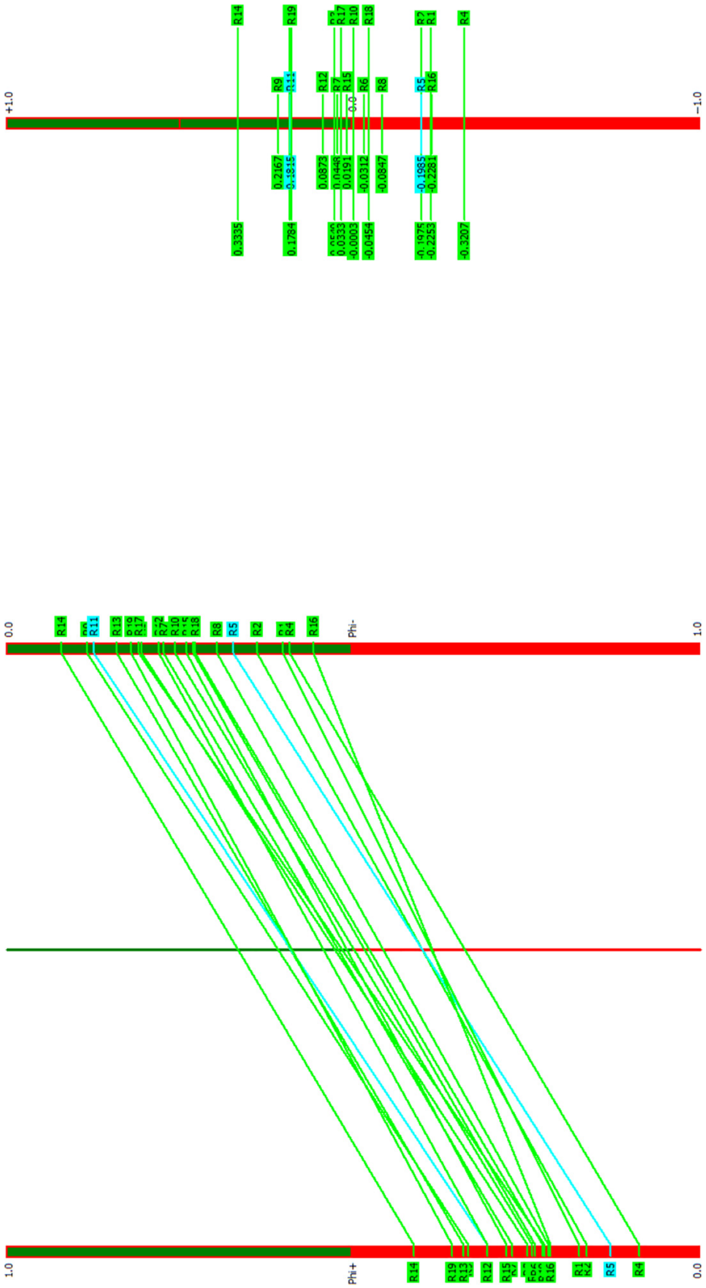

**Figure 3.** PROMETHEE ranking

As can be seen in the complete ranking chart, R14, R9 and R13, with Phi values of 0.3335, 0.2167 and 0.1830, respectively, constitute the first to third risk factors. In addition, R4 with Phi value of −0.3207 is the last risk factor.

Figure 4 shows the PROMETHEE diamond. This figure illustrates PROMETHEE I (partial ranking) and PROMETHEEII (complete ranking) simultaneously. Simultaneous display of these two charts will give the decision-makers a complete understanding at the effectiveness of the two charts. Risks with a positive phi are shown in green part, and risks with a negative phi are shown in red part. In this chart, if a rectangle can completely cover other rectangles, that option is completely superior to other options. If a rectangle intersects other rectangles, the incomparability state occurs; therefore, the net phi value is displayed in the vertical axis in the middle of the chart.

According to the PROMETHEE diamond diagram, the final ranking of risk factors using the PROMETHEE approach is shown in Table 7.

### *4.4 Individual ranking and analysis*

GAIA plane is a multidimensional diagram that was first introduced (Mareschal and Brans, 1988). This plane is used for analysis in the PROMETHEE method. In this plane, the criteria

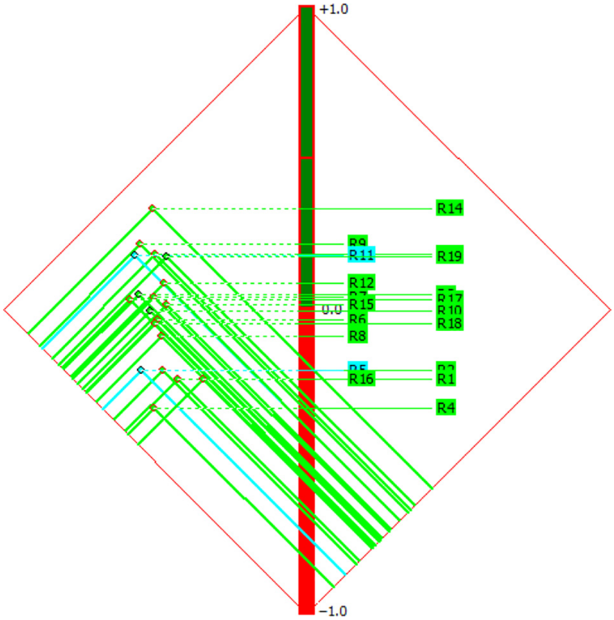


**Figure 4.**
PROMETHEE diamond

**Table 7.**
Overall ranking of risks factors

| Risks | R1 | R2 | R3 | R4 | R5 | R6 | R7 | R8 | R9 | R10 |
|---|---|---|---|---|---|---|---|---|---|---|
| Ranks | 17 | 15 | 7 | 19 | 16 | 12 | 8 | 14 | 2 | 11 |
| **Risks** | R11 | R12 | R13 | R14 | R15 | R16 | R17 | R18 | R19 | |
| Ranks | 4 | 6 | 3 | 1 | 10 | 18 | 9 | 13 | 5 | |

are identified by vectors and the options (risk factors) are shown by points. The longer the length of a criterion vector, the more power of distinction it has. The vectors of the criteria with same preferences are aligned, while the vectors of the criteria with opposite preferences are unaligned. The risk factors that are in the direction of a criterion have a good performance in terms of that criterion. As shown in Figure 5, risk factors R15 and R16 had a good performance in terms of the severity criterion, while they had a weak performance in terms of the criteria such as time and cost. In addition, the R8 and R12 options had a good performance in terms of the quality criterion and a weak performance in terms of the detection criterion. The decision brain vector indicates that the R14, R9 and R13 risks had a weak performance compared to other options. In addition, the alignment of criteria such as quality, time and cost with decision brain indicates the high weight of these criteria compared to other criteria, and therefore, the options that are aligned with these criteria are preferred.

Figure 6 shows the PROMETHEE rainbow diagram. Options with a positive phi value are shown at the top of the chart and options with a negative phi value are indicated at the bottom of the chart. According to this figure, R14 had a good performance in terms of all criteria. R9 risk had a weak performance in terms of severity and detection and had a good performance in terms of the criteria of occurrence, cost, quality and time. In addition, R16 had had a good performance in terms of occurrence and severity criteria and had a weak performance in terms of other criteria. Finally, R4 had a weak performance in terms of all criteria and is chosen as the last option.

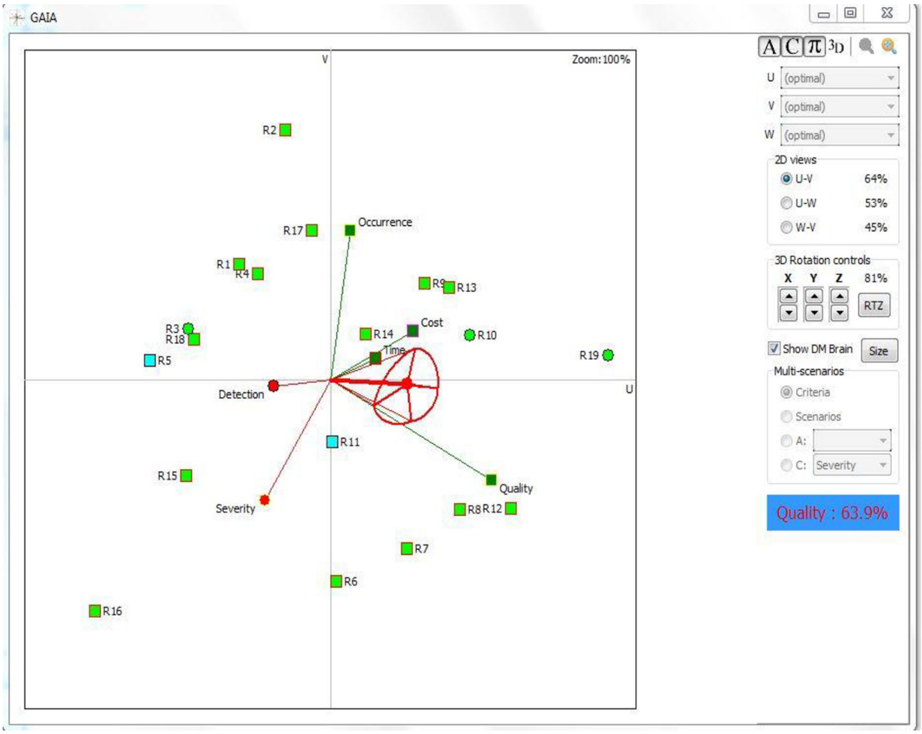


**Figure 5.**
GAIA plane analysis

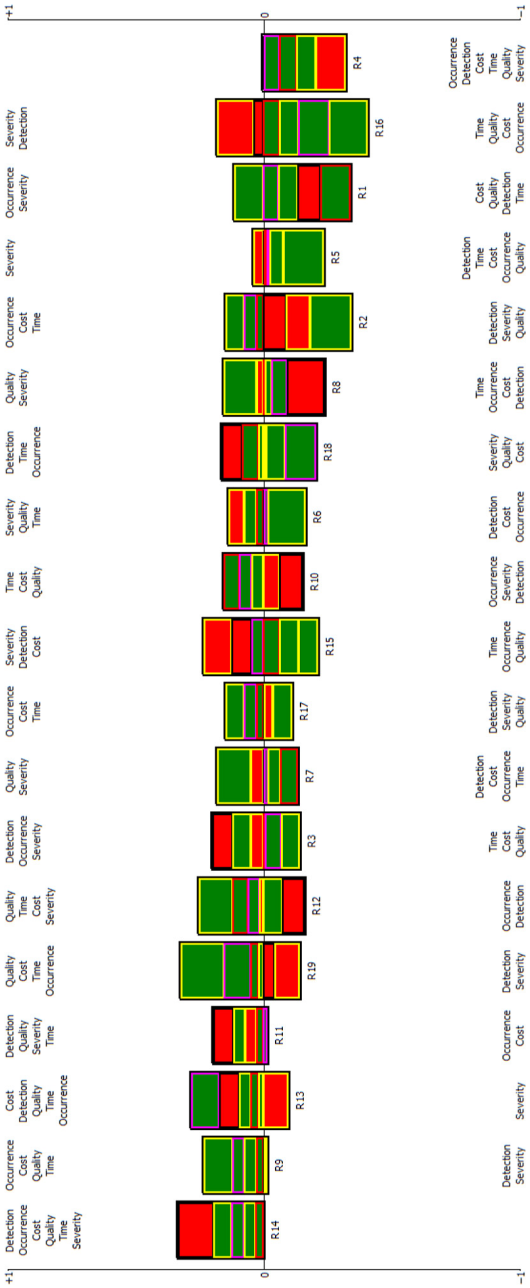


**Figure 6.**
PROMETHEE rainbow

Figure 7 shows the GAIA web plane. The figure on the right shows the web plane for R14 and the figure on the left shows this plane for R9. This plane shows the quality of the criteria based on the various risk factors. As can be seen, R14 had the best performance in terms of detection criterion. Moreover, this risk factor had a good performance in terms of the criteria of occurrence, quality and cost; and the reason for choosing it as the best option was its good performance in terms of all criteria. R9 risk had the best performance in terms of occurrence criterion. Additionally, this risk factor has had a good performance in terms of the criteria of time, cost and quality.

*4.5 Assigning the risk response strategy*

In this step, the risks were ranked through expert judgment. The results were handed over to the expert panel to select major risks. They chose those ones with the Phi amount of greater than zero as major risks to respond to them. Subsequently, AECM was applied to obtain the optimal strategies for responding to the major risks. Several response strategies for the main risks were collected through document analysis and expert judgments, which are shown in Table 8. As seen, a set of strategies was allocated to any major risk through solving a binary multiple objectives linear programming model. Table 8 displays the model parameters. The result analysis was performed merely for a single project with a predefined cost and duration mentioned in the project agreement. Also, some figures were randomly generated by a uniform distribution function as some information was inaccessible.

The utmost number of allowable response strategies to assign to each major risk is given in Table 9 with predefined time and cost.

*4.6 The results of the AECM*

As the results of solving the proposed model by GAMS software, 18 solution points were found on the Pareto frontier. The amounts of the objective functions for each point are shown in Table 10.

The Figures 8–10 shows the Pareto frontiers obtained by the three objective functions.

Figure 8 indicates the Pareto frontier created regarding the time and cost objectives. As seen in the above figure, the graph is declining, as the objective function value of cost increases, the objective function value of time decreases (and vice versa).

Figure 9 depicts the Pareto frontier created based on the quality and cost objectives. As seen in the figure, the graph is initially ascending, as the objective function value of cost increases, so does the quality (and vice versa).

Figure 10 shows the Pareto frontier created according to the quality and time objectives. As seen in the figure, the graph is declining, as the objective function value of time increases, the objective function value of quality decreases (and vice versa).

According to the amounts of the objective functions, point 12 was selected by the expert panel as the ideal solution for the management decision. Eventually, the final strategy allocation to any major risk is displayed in Table 11.

## 5. Managerial discussion

This study highlighted the major risks of OGCP in Iran, which may have significant adverse impacts on the success of the megaprojects in Iran. The findings of this research assist the managers with making appropriate decisions to mitigate or avoid the likelihood and/or consequences of major risks. The suggested response to each major risk was given to be implemented, taking the situation into consideration.

*Electrocution:* The technicians should regularly check the equipment before and during the operation according to the checklists.

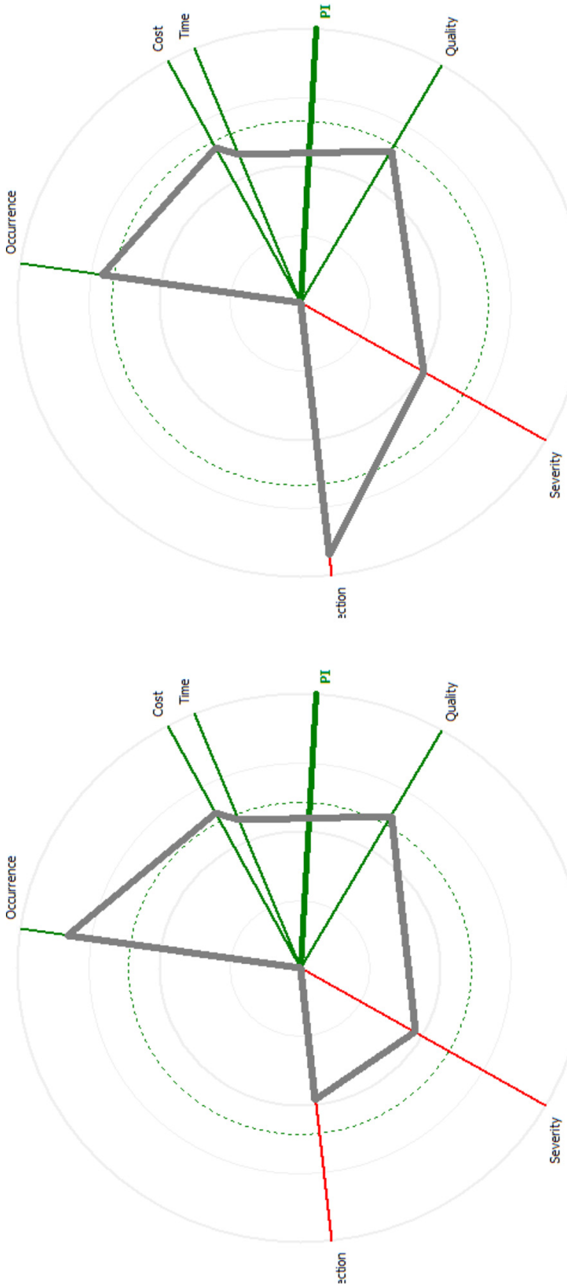


**Figure 7.**
GAIA web plane

| Risk code | Response strategy | Strategy code | Cost | Time | Quality |
|---|---|---|---|---|---|
| $R_{14}$ | Monitor employee safety | $x_1$ | 20 | 2 | 0.713 |
| | Explaining work-related hazards to employees | $x_2$ | 41 | 6 | 0.361 |
| | Placing appropriate informative and warning signs at site | $x_3$ | 13 | 4 | 0.500 |
| | Following the procedure exactly | $x_4$ | 17 | 2 | 0.433 |
| | Following all health and safety instructions at work | $x_5$ | 16 | 3 | 0.528 |
| | Forming a well-trained team to act urgently | $x_6$ | 15 | 2 | 0.858 |
| | Performing all necessary checks before and within startup regarding the checklists | $x_7$ | 12 | 1 | 0.738 |
| | Regular training and monitoring of operators | $x_8$ | 8 | 4 | 0.398 |
| $R_9$ | Locking the belts in compliance with the standard | $y_1$ | 8 | 4 | 0.282 |
| | Wearing standard and appropriate gasket | $y_2$ | 21 | 2 | 0.167 |
| | Carrying out the required tests | $y_3$ | 32 | 3 | 0.538 |
| | Circling the workplace site by installing a warning rope | $y_4$ | 26 | 2 | 0.446 |
| | Swiftly evacuating individuals from the workplace | $y_5$ | 24 | 4 | 0.530 |
| | Wearing proper personal protective equipment (PPE) | $y_6$ | 14 | 1 | 0.674 |
| $R_{13}$ | Exploiting high quality machinery and equipment to minimize the probability of repair | $z_1$ | 32 | 3 | 0.241 |
| | Inspecting equipment regularly by qualified and trained personnel | $z_2$ | 34 | 5 | 0.632 |
| | Acquiring repair permission in front | $z_3$ | 17 | 2 | 0.259 |
| | Disconnecting the electrical equipment completely before any activity | $z_4$ | 12 | 3 | 0.461 |
| | Using guards on the rotating parts | $z_5$ | 11 | 7 | 0.376 |
| $R_{11}$ | Following the safety instructions for scaffolding in compliance with the Article 12 of the national regulations | $m_1$ | 16 | 4 | 0.664 |
| | Following the necessary safety instructions | $m_2$ | 9 | 3 | 0.411 |
| | Exploiting correct and flawless components for scaffolding | $m_3$ | 10 | 3 | 0.715 |
| | Inspecting the scaffolding accurately before operation | $m_4$ | 22 | 6 | 0.517 |
| | Wearing jacket safety belt | $m_5$ | 27 | 6 | 0.434 |
| $R_{12}$ | Training the scaffolding staff regularly | $n_1$ | 19 | 3 | 0.615 |
| | The HSE officers' constant monitoring to ensure appropriate tools and barrels are used for transferring melt bitumen | $n_2$ | 13 | 2 | 0.223 |
| | Exploiting appropriate equipment such as safety net | $n_3$ | 12 | 4 | 0.457 |
| $R_{12}$ | Using ready insulating coatings | $o_1$ | 26 | 2 | 0.169 |
| | Using the proper utensils and tools for moving the melt bitumen | $o_2$ | 17 | 7 | 0.535 |
| | Placing bitumen containers and barrels in a safe and stable place | $o_3$ | 14 | 5 | 0.655 |

*(continued)*

**Table 8.** Response strategies for major risks in OGCP

Table 8.

| Risk code | Response strategy | Strategy code | Cost | Time | Quality |
|---|---|---|---|---|---|
| $R_3$ | Controlling vibration during the machinery production | $p_1$ | 7 | 7 | 0.109 |
| | Mitigating or eliminating the vibration with proper methods such as various types of isolators and air cushions | $p_2$ | 19 | 1 | 0.591 |
| | Installing dampers on the body contact areas | $p_3$ | 9 | 2 | 0.630 |
| | Appropriate managerial decisions such as exposure job and working shift rotation | $p_4$ | 16 | 3 | 0.577 |
| | Wearing suitable PPE | $p_5$ | 20 | 4 | 0.277 |
| $R_7$ | Appropriate lightening | $q_1$ | 17 | 2 | 0.674 |
| | Unloading sediments regularly | $q_2$ | 34 | 3 | 0.384 |
| | Fencing with strong guard such as concrete guard | $q_3$ | 22 | 4 | 0.101 |
| | Soil dikes or concrete walls | $q_4$ | 10 | 3 | 0.820 |
| $R_{17}$ | Appropriate ventilating | $r_1$ | 18 | 5 | 0.384 |
| | Wearing standard masks | $r_2$ | 14 | 4 | 0.608 |
| | Instructing in material safety data sheet | $r_3$ | 23 | 4 | 0.935 |
| $R_{15}$ | Detecting the probable outside hazardous points | $s_1$ | 19 | 3 | 0.847 |
| | Forming a well-trained emergency team | $s_2$ | 7 | 7 | 0.201 |
| | Actively preparing for urgent occasions | $s_3$ | 9 | 6 | 0.130 |
| | Instructing labors in possible fire outside the site | $s_4$ | 16 | 5 | 0.262 |
| | Procuring and positioning fire-fighting accessories and apparatus | $s_5$ | 25 | 4 | 0.441 |
| | Instructing staff in fire-fighting | $s_6$ | 17 | 3 | 0.398 |

*Leakage within startup because of unsuitable bolting, torque and gasket:* The technicians should regularly check and close the belts in accordance with the standards.

*Getting caught of technician's clothes and body between fixed and rotating and fixed machines:* The electrical systems should be completely disconnected after each operation to ensure.

*Fracture of scaffolding clamp during scaffolding operation:* The technicians should exploit correct and flawless components for scaffolding.

*Unforeseen crane or load fall on labor within loading and deflection tests:* The HSE officers should continuously monitor and inspect the work.

*Severe burns by melt bitumen while insulating:* Appropriate utensils and tools should be used for moving melt bitumen.

*Vibration:* The technicians should mitigate or eliminate the vibration with proper methods such as various types of isolators and air cushions.

**Table 9.** Greatest possible amount of allowable response strategies allocated to each major risk

| Risk | $R_3$ | $R_{12}$ | $R_{13}$ | $R_{11}$ | $R_9$ | $R_{19}$ | $R_{14}$ | $R_{15}$ | $R_{17}$ | $R_7$ |
|---|---|---|---|---|---|---|---|---|---|---|
| The highest possible number of allowable strategies | 4 | 3 | 3 | 3 | 4 | 3 | 5 | 5 | 3 | 3 |

**Table 10.** Obtained Pareto frontier

| Point | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
|---|---|---|---|---|---|---|---|---|---|
| Obj1 | 100 | 101 | 103 | 124 | 136 | 101 | 102 | 148 | 103 |
| Obj2 | 48 | 44 | 39 | 27 | 24 | 48 | 43 | 24 | 43 |
| Obj3 | 4.32 | 4.40 | 4.92 | 5.62 | 5.13 | 4.62 | 4.84 | 5.13 | 5.14 |
| Point | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 |
| Obj1 | 104 | 107 | 108 | 137 | 111 | 113 | 114 | 125 | 139 |
| Obj2 | 39 | 40 | 36 | 24 | 33 | 31 | 33 | 27 | 24 |
| Obj3 | 5.23 | 5.48 | 5.57 | 5.44 | 5.69 | 5.66 | 5.96 | 5.92 | 5.91 |

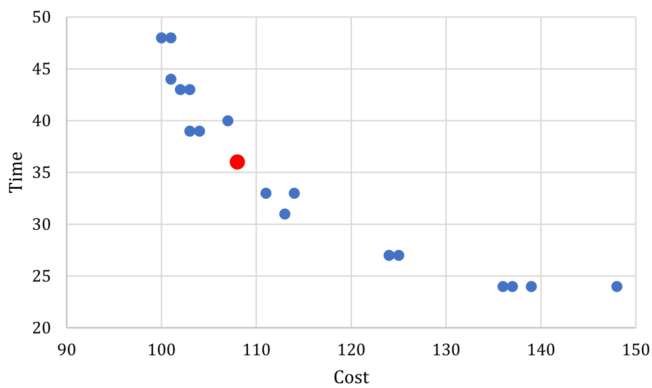


**Figure 8.** Pareto frontier based on time and cost objectives

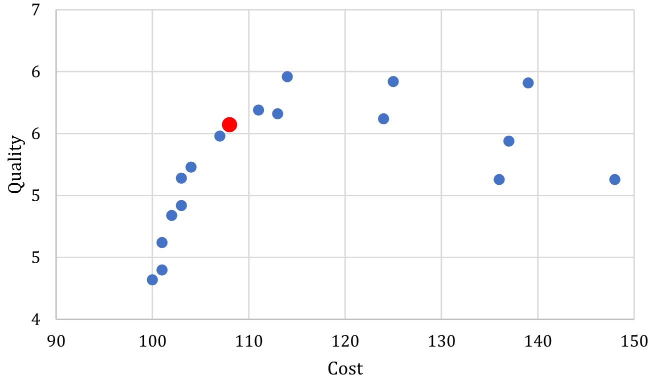


**Figure 9.**
Pareto frontier based on quality and cost objectives

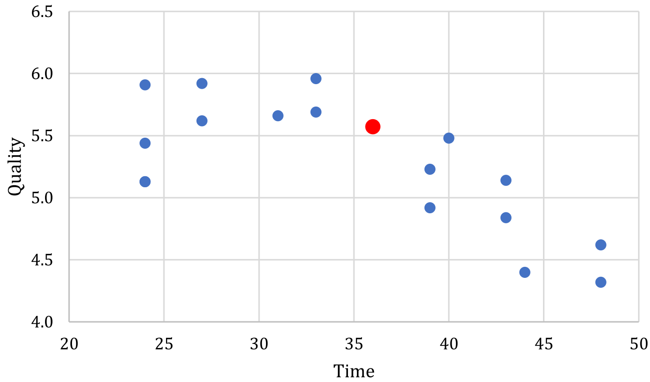


**Figure 10.**
Pareto frontier based on quality and time objectives

*Mixture or labor fall into basin:* Soil dikes or concrete walls around the pool should be built.

*Respiratory injuries due to indoor painting:* Standard masks should be worn to mitigate the negative impacts of this risk.

*Fire transfer of from neighboring contractors to the site:* An well-trained emergency team should be quickly formed to avoid fire transfer.

## 6. Conclusion

Risk management is an integral part of project management. Therefore, in the present study a novel risk assessment model based on FMEA integrating the fuzzy SWARA and PROMETHEE methods was presented to compute the RPN value and find a compromise priority ranking of the risks of OGCP in Iran. First, 19 common risks of the OGCP were identified through the historic documentation reviews, checklist analysis and consulting experts; and categorized into six general groups by using the Delphi method. Next, the weighting coefficients of the RPN elements for assessment the risk were computed using the Fuzzy SWARA. Subsequently, these major risks were prioritized by using the PROMETHEE approach. Finally, the appropriate solutions for the main risks were identified through expert judgments and the optimal risk response strategies were selected by developing a binary multiple objectives linear programming model and using the

| Risks | Strategy | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| $R_{14}$ | $x_1$ | $x_2$ | $x_3$ | $x_4$ | $x_5$ | $x_6$ | $x_7$ × | $x_1$ |
| $R_9$ | $y_1$ × | $y_2$ | $y_3$ | $y_4$ | $y_5$ | $y_6$ | | |
| $R_{13}$ | $z_1$ | $z_2$ | $z_3$ | $z_4$ × | $z_5$ | | | |
| $R_{11}$ | $m_1$ | $m_2$ | $m_3$ × | $m_4$ | $m_5$ | | | |
| $R_{19}$ | $n_1$ | $n_2$ | $n_3$ × | | | | | |
| $R_{12}$ | $o_1$ | $o_2$ | $o_3$ × | | | | | |
| $R_3$ | $p_1$ | $p_2$ | $p_3$ × | $p_4$ | $p_5$ | | | |
| $R_7$ | $q_1$ | $q_2$ | $q_3$ | $q_4$ × | | | | |
| $R_{17}$ | $r_1$ | $r_2$ × | $r_3$ | | | | | |
| $R_{15}$ | $r_1$ | $r_2$ × | $r_3$ | $r_4$ | $r_5$ | $r_6$ | | |

**Table 11.**
Strategy assignment to each major risk

augmented $\varepsilon$-constraint method (AECM). The main limitations of this study are summarized as follows: all parameters of the propose mathematical model of this study were assumed to be fixed, while in real life problems the cost and implementation time may be varied during planning period. Also, too much time has been spent on distribution, completion and collection of the questionnaires due to the administrative barriers. Moreover, high dispersion of expert opinions on the risks in oil and gas industry projects was another limitation of this study. Furthermore, it was assumed that the critical risks and as well as the corresponding response strategies for assigning to them were independent of each other, whereas they may be dependent. Therefore, for further studies, the relationships between risks may be taken into consideration. Also, the uncertainty of the model parameters can be incorporated into the mathematical programming model with fuzzy numbers. Moreover, the quantitative risk analysis such as scenario analysis may be performed.

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