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A comparative outline for quantifying risk ratings in occupational health and safety risk assessment

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ABSTRACT

The concept of risk assessment has been introduced as an examination of safety in the workplace to enable assessments as to whether sufficient precautions have been taken or if more should be done to prevent potential harm. Hazardous industries have faced serious fatalities related to work, workplaces, and workers as a consequence of their high-risk processes. Therefore, in this work, a novel and comparative methodology for quantifying risk ratings in occupational health and safety risk assessment is proposed. A 5 × 5 risk matrix is initially determined, and the fuzzy technique for order preference by similarity to ideal solution (FTOPSIS) method is then applied to rank identified hazards. As a novelty to the knowledge, two parameters of the 5 × 5 matrix method, likelihood and severity, are subjectively assessed by occupational health and safety experts, and then importance levels for these parameters are determined using the Pythagorean fuzzy analytic hierarchy process (PFAHP). In the proposed approach, analysts use linguistic terms and Pythagorean fuzzy sets, which provide greater independence in their evaluations. An outline that enables comparison of the results of this study with the circumcenter of centroids method and the fuzzy AHP-fuzzy VIKOR integrated method in quantifying risk ratings is also provided. In order to present the practicality of this work, a case study in an underground copper and zinc mine is carried out.

1. Introduction

Hazard is described as anything (e.g., condition, situation, practice, and behavior) that has the potential to cause harm, including injury, disease, death, or damage to environment, property, and equipment. Identification of hazards is the process of examining each workplace and work task for the purpose of identifying all the hazards that are *inherent in the job*. This process is about finding what could cause harm in a work task or workplace. Risk is defined as the likelihood, or possibility, that harm (injury, illness, death, damage, etc.) may occur from exposure to a hazard. In the light of these descriptions, risk assessment is the process of assessing the risks associated with each of the hazards identified so the nature of the risk can be understood. This includes the nature of the harm that may result from the hazard, the severity of that harm, and the likelihood of this occurring. The usual risk assessment process consists of four main phases called identifying hazards, assessing associated risks, controlling risks, and reviewing control measures (Health and Safety Authority, 2006). Fig. 1 shows these consecutive steps as a loop chart. Quantifying the risk rating is the second process in the usual risk assessment process for estimating the likelihood and severity of risks likely to occur due to actual or predicted interaction with a hazardous event (Samantra et al., 2017).

The objective of risk assessment within occupational health and safety (OHS) is to ensure the protection and safety of occupational stakeholders. It also aims to minimize the possible losses and damages resulting from work-related, worksite-related, and worker-related activities, and contributes to a more productive and competitive business (Gul, 2018). Risk assessment may be carried out quantitatively or qualitatively. In quantitative risk assessment, risk value is determined by using mathematical formulas. In qualitative risk assessment, numerical scales are assigned to the likelihood of a potential hazard and its severity; and these are processed by mathematical and logical methods to find a risk rating. A list of a limited number of quantitative and qualitative risk

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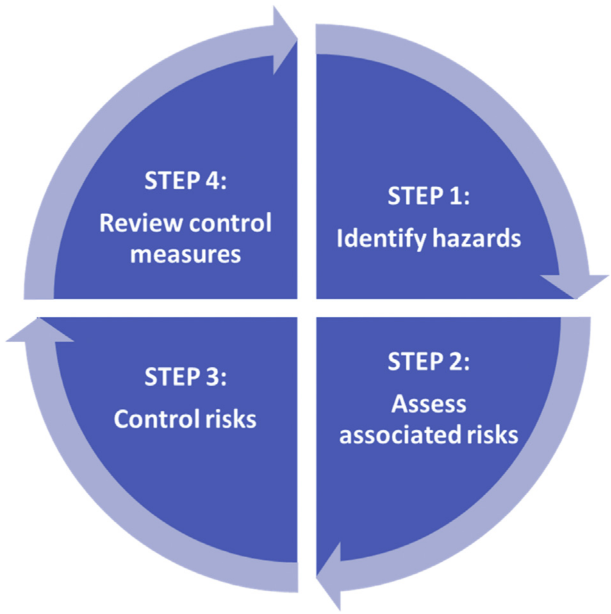

Fig. 1. Steps of the usual risk assessment procedure.

assessment methods can be found in Ilbahar et al. (2018). Being reactive in OHS means being compensated. Being proactive in OHS means measuring and including preventive measures. One must be proactive, not reactive, in OHS. There is no risk assessment method appropriate for all business areas. OHS experts should decide on the methodology to apply, considering the characteristics of their work, workplace, and workers. The experience of OHS experts influences the outcome of the risk assessment, which is not an operation that an expert can perform alone, even if he or she is highly experienced in OHS. Risk assessment succeeds with the participation of everyone in the workplace, from the top management team to the lower level employees.

Hazardous industries have faced serious fatalities related to work, workplaces, and workers as a consequence of their high-risk processes. Underground mining is considered the most hazardous industry worldwide (Vingard and Elgstrand, 2013; Samantra et al., 2017). Mining is classically categorized as being metalliferous or coal-related, and as being either surface or underground mining (Donoghue, 2001; Donoghue, 2004). Underground coal mining is one of the most dangerous categories, where accidents causing thousands of deaths or injuries occur frequently (Qiaoxiu et al., 2016). Recently, several accidents have occurred in Turkey. Turkey has the third-highest occurrence of coal mining accidents of any country in the world. (Demiral and Ertürk, 2013). On the 13th of May, 2014, an explosion caused by failure to detect carbon monoxide gas in the Soma coal mine caused 301 fatalities and more than 80 injuries (Badri et al., 2013; Spada and Burgherr, 2016). To date, it is the most devastating coal mining accident in Turkey's history (Spada and Burgherr, 2016). A report published by Demiral and Ertürk (2013) stated that there were a number of issues that needed to be resolved primarily for improved OHS in mining in Turkey. These prompted stakeholders to adopt an appropriate risk assessment and management culture as a safeguard against probable occupational accidents in the future. According to another report by The Union of Turkish Bar Associations (TBB) Human Rights Centre (2014) on the Soma incident, the general cause of mining accidents in Turkey stems from the lack of any comprehensive or effective risk assessment. Therefore, in order to provide strong awareness for the implementation of and compliance to OHS policy by all sectors of the underground mining industry, risk assessment must be fulfilled and an appropriate methodology must be followed under the newly-enacted OHS Law No. 6331 (Guneri et al., 2015). Other than this legal obligation, the main reason for conducting a risk assessment is to support decision-making, so that the industry can provide a solid basis for finding the right balance between safety and cost (Aven, 2008).

In the literature, a number of qualitative, quantitative, and hybrid risk assessment studies have been performed (Tixier et al., 2002; Marhavilas et al., 2011; Gul and Guneri, 2016; Ilbahar et al., 2018; Gul, 2018). Multi-criteria decision-making (MCDM), which is considered an innovative field of operations research and explicitly considers multiple criteria in decision-making environments, contributes to risk assessment by combining its methods with classical qualitative and quantitative risk analysis methods. Proposed MCDM-based approaches have the ability to solve some of the limitations that classical methods face. In applying classical risk assessment methods, experts often encounter difficulties in giving a precise rating for a hazard with respect to the related risk parameter. Therefore, carrying out risk assessment may not give satisfactory results due to the lack of historical risk data, or due to the high level of uncertainty. To this end, the fuzzy sets and MCDM methods are integrated to model the situation. Evaluating the relative importance of risk parameters using linguistic terms that are converted to fuzzy numbers is one of the most important advantages of the fuzzy MCDM-based approaches.

In this study, risk is described as a function of two parameters: (a) likelihood, and (b) severity. Therefore, using a common MCDM method with interval-valued Pythagorean fuzzy sets, called the Pythagorean fuzzy analytic hierarchy process (PFAHP), two parameters of the 5×5 matrix method, likelihood and severity, are both assessed by the subjective judgment of OHS experts, and then importance levels for these parameters are determined. Generally, likelihood can be assessed by either subjective judgment or objective analysis. Subjective judgment is easier to use and more practical than objective analysis. It requires OHS expert experience (Samantra et al., 2017) rather than historical data. Therefore, this study takes advantage of subjective OHS expert judgment to assess both the likelihood of occurrence and the severity of occurrence of identified hazards. The subjectivity associated with expert judgment of these two risk parameters (expressed in linguistic terms) is considered by means of interval-valued Pythagorean fuzzy numbers. Then, in the second step of the assessment, the TOPSIS method is used with trapezoidal fuzzy sets for the prioritization of hazards. In addition, an improved MCDM-based risk assessment approach using linguistic terms for Pythagorean and trapezoidal fuzzy set theory is implemented. OHS expert's linguistic data are transformed to numeric risk ratings. Additionally, a comparative outline that enables the comparison of the results of this study with the circumcenter of centroids method and the fuzzy AHP-fuzzy VIKOR integrated method in quantifying risk ratings is provided.

The rest of this paper is organized as follows: A state-of-the-art review is given in Section 2. The concept of OHS risk assessment is provided in Section 3. Proposed methodology, including the 5×5 risk matrix method, preliminaries on Pythagorean fuzzy sets, the steps of the PFAHP, and the fuzzy technique for order preference by similarity to ideal solution (FTOPSIS) are examined in Section 4. A case study done on an underground copper and zinc mine using the proposed method, and its conclusions are presented in Sections 5 and 6, respectively.

2. State of the art

Risk assessment in OHS management has become an obligatory procedure under new OHS Law number 6331 in Turkey.

International institutions such as the International Organization for Standardization (ISO) and the International Electrotechnical Commission (IEC) collaborate with each other in introducing documents about risk management procedures and standards. ISO has developed a new standard, ISO 45001, *Occupational health and safety management systems—Requirements*, that helps organizations all over the world reduce this burden by providing a framework to improve employee safety, reduce workplace risks, and create better, safer working conditions (ISO 45001, 2018). Within this context, another popular standard, ISO 31000:2018, *Risk management—Guidelines*, provides principles, framework, and a process for managing risk. It can be used by any organization of any size, activity, or sector (ISO 31000, 2018). A generic risk management standard, IEC 31010:2009, on the selection and application of systematic techniques for risk assessment is a supporting standard of ISO 31000. This standard lists 31 different risk assessment techniques (ISO/IEC 31010, 2009). Some of these techniques include brainstorming, interviews, Delphi, checklists, preliminary hazard analysis, hazard and operability analysis (HAZOP), root causes analysis, failure modes and effects analysis (FMEA), fault tree analysis (FTA), event tree analysis (ETA), human reliability assessment (HRA), bow tie analysis, Markov analysis, Monte Carlo simulation, Bayesian Networks, cost-benefit analysis, and MCDM analysis. Some of these are commonly used in Turkish mining and other hazardous industries. Each has its own specific purpose and outcome, as listed below (Joy, 2004):

HAZOP—A systematic identification of hazards for process plant design
FMEA—A detailed analysis of hardware component reliability risks
FTA—A detailed analysis of contributors to major unwanted events, potentially using quantitative risk analysis methods
ETA—A detailed analysis of the development of major unwanted events, potentially using quantitative methods

There are several studies that use above-mentioned methods or MCDM-based approaches in OHS risk assessment in the literature. For a comprehensive review of MCDM and its fuzzy set version-based approaches in the area of OHS risk assessment, readers can refer to Gul (2018). That state-of-the-art review highlighted that occupational health and workplace safety for companies operating in risky industries like mining, manufacturing, construction, energy, transportation, and maritime sectors are vital because they are directly related to workers' health and life. From now on, OHS risk assessment should be implemented by mining environments in order to control their risks and improve their safety capability. Because underground mining is an industry that includes serious fatality hazards, several risk assessment studies with classical methods and MCDM, and their fuzzy version-based approaches have been performed. Because of the rapid increase in the application of OHS risk assessment approaches, much attention has been paid to research in underground mine safety assessment, which has resulted in a number of valuable findings.

A limited number of studies in the literature integrate MCDM, fuzzy sets, and OHS risk assessment related to the mining industry. A recent paper by Amirshenava and Osanloo (2018) was developed to manage mine closure risks using a 3D risk matrix and MCDM techniques. The proposed risk assessment approach was carried out in an iron ore mine in Iran. Compared with the 2D risk model, which did not take into consideration the time value of risk, the assessment results were found to be more practical in budget planning for risk treatment. Lang and Fu-Bao (2010) determined influential factors that lead to the spontaneous combustion of coal seams and proposed a framework that included a holistic scoring method and an analytic hierarchy process (AHP) for evaluating the hazard of spontaneous combustion. To validate the applicability of the proposed framework, it was applied to Chinese coal mines. In another study, Badri et al. (2013) integrated a novel concept called hazard concentration with an AHP. All hazards and associated risks in gold mines throughout Quebec, Canada were dealt with. Alongside the AHP-based risk assessment studies, a fuzzy analytic hierarchy process (FAHP) is also applied to determine the weights of risk parameters or sub-parameters in vague hierarchical structures, or to determine the precedence of risk parameters. Where Özfırat (2014) integrated an FAHP with FMEA, Verma and Chaudhri (2014) used fuzzy reasoning approach to evaluate the risk levels associated with identified hazard factors weighted by an FAHP. Petrović et al., 2014 focused on performing a risk assessment of technical systems failure in a Serbian coal mine rather than directly concentrating on mining risk assessment. Severity, occurrence, and detectability factors were given as linguistic variables. Mahdevari et al. (2014) proposed an FTOPSIS-based approach to assess the risks to human health in order to manage control measures and support decision-making in underground coal mines in Iran. After applying the FTOPSIS model, twelve groups with different risks were obtained. Control measures for each group were taken into consideration. Qiaoxiu et al. (2016) used an FAHP to estimate and rank the risk factors involving managerial, environmental, operational, and individual criteria to develop a management model and to guide safety managers in the mining process. They also used the logarithmic fuzzy preference programming (LFPP) method to analyze risk data. In a recent study by Samantra et al. (2017), a unique hierarchical structure on various occupational health hazards, including physical, chemical, biological, ergonomic, and psychosocial hazards, and associated adverse consequences in relation to an underground coal mine was presented using fuzzy aggregation rules. In order to evaluate risks, three important measurement parameters were considered, which were consequence of exposure, period of exposure, and probability of exposure. On conclusion of this study, health hazards were categorized into different risk levels, and potential control measures were suggested.

It is very difficult to find a study that specifically integrates Pythagorean fuzzy sets and MCDM when considering normal risk assessment. One study that combined interval-valued PFAHP, the Fine-Kinney method, and fuzzy inference systems in OHS risk assessment is that of Ilbahar et al. (2018). The current study is different from Ilbahar et al. (2018) on several points: (1) Where this study deals with the integration of the 5×5 risk matrix method, PFAHP, and FTOPSIS, Ilbahar et al. (2018) includes the Fine-Kinney method, PFAHP, and a fuzzy inference system. (2) The study of Ilbahar et al. (2018) does not include a comparative outline as the current study does. (It has a comparative outline that enables comparison of results with the circumcenter of centroids method proposed by Samantra et al. (2017) and the fuzzy AHP-fuzzy VIKOR integrated method in quantifying risk ratings.) (3) While this study presents an underground copper and zinc mine case study, the first such study of its kind, Ilbahar et al. (2018) presents the real case of a specific excavation process in a construction yard.

After examining the relevant literature, it was concluded that the current study contributes to the knowledge of mining risk assessment in the following ways: (1) It is the first application of the PFAHP to provide importance weights to the risk parameters of a 5×5 risk matrix method by using interval-valued Pythagorean fuzzy linguistic scale in a pairwise-comparison manner for risk assessment in the mining industry. (2) In the current literature, there has been no attempt to evaluate hazards and associated risks in underground copper and zinc mines. Therefore, this paper aims to fill the gap in this particular area using the proposed approach (PFAHP-FTOPSIS). This approach offers the opportunity to make assessments considering the subjective judgments of OHS experts, which are closer to human decision-making than other options in risk quantification. (3) Hazards were managed by taking advantage of the comparable results of rankings with two other methods. On concluding this comparison, all three approaches were shown to result in similar ranking orders. Moreover, preventive action plans according to the compared approaches are suggested. These suggestions are expected to represent a basis for decisions and policies that must be made by mine authorities as part of their risk review process.

3. Proposed methodology

This section initially describes the theoretical background of the methods used in the proposed approach. In the first sub-section, a 5×5 risk matrix method is described. In the second and third sub-sections, preliminaries of Pythagorean fuzzy sets, steps of the PFAHP, and related linguistic terms are provided. In the fourth sub-section, the FTOPSIS method that is used to assess the hazards with respect to the parameters of likelihood and severity is presented. Finally, an overview of the proposed methodology using the 5×5 risk matrix and the PFAHP and FTOPSIS methods is demonstrated.

3.1. 5 × 5 risk matrix method

The 5×5 risk matrix method, also called *the decision matrix risk-assessment technique,* is a systematic approach that is widely used in OHS risk assessment with the incorporation of measurement and categorization of risks on an informed judgment basis with respect to both severity and likelihood (Marhavilas and Koulouriotis, 2008; Marhavilas et al., 2011; Ceylan and Başhelvacı, 2011; Önder et al., 2011). A measure of risk value is obtained simply by multiplying severity and likelihood through this method.

Firstly, likelihood and severity ratings are determined with this method (see Supplementary file for more details of likelihood and severity ratings). Then, the risk matrix and the decision-making table are constructed. The acceptability level of the risks is also interpreted according to this table. In this paper, an integrated approach was proposed, enabling OHS experts to use linguistic terms for evaluating two parameters of the 5×5 risk matrix method using the PFAHP.

3.2. Pythagorean fuzzy sets

Intuitionistic fuzzy sets first proposed by Atanassov (1986) and have been used by many researchers in different fields to address uncertainty. These sets can be expressed in terms of membership functions, non-membership functions, and hesitancy degree. However, in some cases, when the sum of membership and non-membership degree is larger than 1, the condition is not fulfilled. Obviously, intuitionistic fuzzy sets are unable to describe the situation. As a result, Yager (2014) developed Pythagorean fuzzy sets. These sets are the generalization from intuitionistic fuzzy sets for certain conditions where intuitionistic fuzzy sets cannot address uncertainty. This achievement makes Pythagorean fuzzy sets more powerful and flexible in solving problems involving uncertainty (Mohd and Abdullah, 2017; Ilbahar et al., 2018).

In Pythagorean fuzzy sets, unlike intuitionistic fuzzy sets, the sum of membership and non-membership degrees can exceed 1, but the sum of squares cannot (Zhang and Xu, 2014; Zeng et al., 2016; Ilbahar et al., 2018). This situation is shown below in Definition (1).

Definition 1. Let a set X be a universe of discourse. A Pythagorean fuzzy set P is an object having the form (Zhang and Xu, 2014):

$$P = \{ < x,\ P(\mu_P(x), \nu_P(x)) > | x \in X \} \tag{1}$$

where $\mu_P(x) : X \mapsto [0,1]$ defines the degree of membership and $\nu_P(x) : X \mapsto [0,1]$ defines the degree of non-membership of the element $x \in X$ to P, respectively, and, for every $x \in X$, it holds that:

$$0 \le \mu_P(x)^2 + \nu_P(x)^2 \le 1 \tag{2}$$

For any Pythagorean fuzzy set P and $x \in X$, $\pi_P(x) = \sqrt{1 - \mu^2{}_P(x) - \nu^2{}_P(x)}$ is called the degree of indeterminacy of x to P.

Definition 2. Let $\beta_1 = P(\mu_{\beta_1}, \nu_{\beta_1})$ and $\beta_2 = P(\mu_{\beta_2}, \nu_{\beta_2})$ be two Pythagorean fuzzy numbers, and $\lambda > 0$, then the operations on these two Pythagorean fuzzy numbers are defined as follows (Zhang and Xu, 2014; Zeng et al., 2016):

$$\beta_1 \oplus \beta_2 = P\left(\sqrt{\mu_{\beta_1}^2 + \mu_{\beta_2}^2 - \mu_{\beta_1}^2 \mu_{\beta_2}^2}, \nu_{\beta_1}\nu_{\beta_2}\right) \tag{3}$$

$$\beta_1 \otimes \beta_2 = P\left(\mu_{\beta_1}\mu_{\beta_2}, \sqrt{\nu_{\beta_1}^2 + \nu_{\beta_2}^2 - \nu_{\beta_1}^2 \nu_{\beta_2}^2}\right) \tag{4}$$

$$\lambda\beta_1 = P\left(\sqrt{1 - \left(1 - \mu_{\beta_1}^2\right)^{\lambda}}, \left(\nu_{\beta_1}\right)^{\lambda}\right), \lambda > 0 \tag{5}$$

$$\beta_1^{\lambda} = P\left(\left(\mu_{\beta_1}\right)^{\lambda}, \sqrt{1 - \left(1 - \nu_{\beta_1}^2\right)^{\lambda}}\right),\ \lambda > 0 \tag{6}$$

3.3. PFAHP and related linguistic terms

In this sub-section, the steps of the PFAHP method are given.

Step 1: The compromised pairwise comparison matrix $A = (a_{ik})_{mxm}$ is structured based on the linguistic evaluation of experts using the scale proposed by (Ilbahar et al., 2018) in Table 1.

Step 2: The difference matrices $D = (d_{ik})_{mxm}$ between lower and upper values of the membership and non-membership functions are calculated using Eqs. (7) and (8):

$$d_{ik_L} = \mu_{ik_L}^2 - \nu_{ik_U}^2 \tag{7}$$

$$d_{ik_U} = \mu_{ik_U}^2 - \nu_{ik_L}^2 \tag{8}$$

Table 1
Weighting scale for PFAHP (Ilbahar et al., 2018).

Linguistic term	Pythagorean fuzzy numbers			
	μ_L	μ_U	ν_L	ν_U
Certainly low important (CLI)	0.00	0.00	0.90	1.00
Very low important (VLI)	0.10	0.20	0.80	0.90
Low important (LI)	0.20	0.35	0.65	0.80
Below average important (BAI)	0.35	0.45	0.55	0.65
Average important (AI)	0.45	0.55	0.45	0.55
Above average important (AAI)	0.55	0.65	0.35	0.45
High important (HI)	0.65	0.80	0.20	0.35
Very high important (VHI)	0.80	0.90	0.10	0.20
Certainly high important (CHI)	0.90	1.00	0.00	0.00
Exactly equal (EE)	0.1965	0.1965	0.1965	0.1965

Step 3: The interval multiplicative matrix $S = (s_{ik})_{mxm}$ is computed using Eqs. (9) and (10):

$$s_{ik_L} = \sqrt{1000^{d_L}} \tag{9}$$

$$s_{ik_U} = \sqrt{1000^{d_U}} \tag{10}$$

Step 4: The determinacy value $\tau = (\tau_{ik})_{mxm}$ is calculated using Eq. (11):

$$\tau_{ik} = 1 - \left(\mu_{ik_U}^2 - \mu_{ik_L}^2\right) - \left(\nu_{ik_U}^2 - \nu_{ik_L}^2\right) \tag{11}$$

Step 5: The determinacy degrees are multiplied by the $S = (s_{ik})_{mxm}$ matrix to obtain the matrix of weights, $T = (t_{ik})_{mxm}$ before normalization using Eq. (12).

$$t_{ik} = \left(\frac{s_{ik_L} + s_{ik_U}}{2}\right)\tau_{ik} \tag{12}$$

Step 6: The normalized priority weights w_i are computed by using Eq. (13).

$$w_i = \frac{\sum_{k=1}^{m} t_{ik}}{\sum_{i=1}^{m}\sum_{k=1}^{m} t_{ik}} \tag{13}$$

3.4. Fuzzy TOPSIS

The TOPSIS method was developed by Hwang and Yoon (1981) to find the best alternative based on the compromise solution concept. The compromise solution concept selects the solution with the shortest distance from the ideal solution, and the farthest distance from the negative ideal solution. Because the ratings usually refer to subjective uncertainty when evaluating alternatives against criteria, TOPSIS is extended to consider the situation of fuzzy numbers (Tzeng and Huang, 2011; Celik et al. 2012). The procedure used in Chen (2000) FTOPSIS method was followed for the hazard prioritization aim in the case study presented in this paper. The steps are as follows (Tzeng and Huang, 2011; Kutlu and Ekmekçioğlu, 2012; Gul and Guneri, 2018; Carpitella et al., 2018):

Step 1: The scores of alternatives with respect to each criterion are obtained considering a decision-making group with K experts by the following formula: $\tilde{x}_{ij} = \frac{1}{K}[\tilde{x}_{ij}^1(+)\tilde{x}_{ij}^1(+)....(+)\tilde{x}_{ij}^K]$. While $A = \{A_i | i = 1, ..., m\}$ shows the set of alternatives, $C = \{C_j | j = 1, ..., n\}$ represents the criteria set. $X = \{X_{ij} | i = 1, ..., m; j = 1, ..., n\}$ denotes the set of fuzzy ratings, and $\tilde{w} = \{\tilde{w}_j | j = 1, ..., n\}$ is the set of fuzzy weights. The linguistic variables are described by trapezoidal fuzzy number as follows: $\tilde{x}_{ij} = (a_{ij}, b_{ij}, c_{ij}, d_{ij})$. Tables 2 and 3 show linguistic terms and the corresponding fuzzy numbers (Samantra et al., 2017) used by the OHS experts to rate hazards against the two risk parameters of likelihood and severity, respectively.
Step 2: Normalized ratings are determined by Eq. (14).

Table 2
Seven-point fuzzy linguistic scale for assessing hazards with respect to likelihood (Samantra et al., 2017).

Linguistic term	Fuzzy number
Absolutely certain (AC)	(0.8,0.9,1,1)
Very frequent (VF)	(0.7,0.8,0.8,0.9)
Frequent (F)	(0.5,0.6,0.7,0.8)
Probable (P)	(0.4,0.5,0.5,0.6)
Occasional (O)	(0.2,0.3,0.4,0.5)
Rare (R)	(0.1,0.2,0.2,0.3)
Very rare (VR)	(0,0,0.1,0.2)

Table 3
Five-point fuzzy linguistic scale for assessing hazards with respect to severity (Samantra et al., 2017).

Linguistic term	Corresponding fuzzy number
Very high (VH)	(0.7,0.8,0.9,1)
High (H)	(0.5,0.6,0.7,0.8)
Moderate (M)	(0.3,0.4,0.5,0.6)
Low (L)	(0.1,0.2,0.3,0.4)
Very low (VL)	(0,0.1,0.2,0.3)

$$\tilde{r}_{ij} = \begin{cases} \left(\frac{a_{ij}}{d_j^*}, \frac{b_{ij}}{d_j^*}, \frac{c_{ij}}{d_j^*}, \frac{d_{ij}}{d_j^*}\right), \text{where } d_j^* = \max_i d_{ij} \text{ if } j \in \text{benefit criteria} \\ \left(\frac{a_j^-}{d_{ij}}, \frac{a_j^-}{c_{ij}}, \frac{a_j^-}{b_{ij}}, \frac{a_j^-}{a_{ij}}\right), \text{where } a_j^- = \min_i a_{ij} \text{ if } j \in \text{cost criteria} \end{cases} \tag{14}$$

Step 3: Weighted normalized ratings are obtained by Eq. (15).

$$\tilde{v}_{ij} = w_j(x)\tilde{r}_{ij}, \quad i = 1, ..., m; j = 1, ..., n \tag{15}$$

Step 4: The fuzzy positive ideal point (FPIS,A*) and the fuzzy negative ideal point (FNIS,A⁻) are derived as in Eqs. (16) and (17). Where J_1 and J_2 are the benefit and the cost attributes, respectively.

$$\text{FPIS} = \text{A}* = \left\{\tilde{v}_1^*, \tilde{v}_2^*, ..., \tilde{v}_n^*\right\} \quad \text{where } \tilde{v}_j^* = (1, 1, 1, 1) \tag{16}$$

$$\text{FNIS} = \text{A}^- = \left\{\tilde{v}_1^-, \tilde{v}_2^-, ..., \tilde{v}_n^-\right\} \quad \text{where } \tilde{v}_j^- = (0, 0, 0, 0) \tag{17}$$

Step 5: The next step is about calculating the separation between the FPIS and the FNIS among the alternatives. The separation values can also be obtained by means of the vertex method as in Eqs. (18) and (19):

$$\tilde{S}_i^* = \sqrt{\frac{1}{4}\sum_{j=1}^{n}\left[\tilde{v}_{ij} - \tilde{v}_j^*\right]^2}, \quad i = 1, ..., m \tag{18}$$

$$\tilde{S}_i^- = \sqrt{\frac{1}{4}\sum_{j=1}^{n}\left[\tilde{v}_{ij} - \tilde{v}_j^-\right]^2}, \quad i = 1, ..., m \tag{19}$$

Step 6: Then, the defuzzified separation values are derived using the CoA (center of area) defuzzification method to calculate the similarities to the ideal solution. Next, the similarities to the ideal solution are given as Eq. (20).

$$C_i^* = \tilde{S}_j^- \Big/ \left(\tilde{S}_j^* + \tilde{S}_j^-\right), \quad i = 1, ..., m \tag{20}$$

The preferred orders are ranked according to C_i^* in descending order to select the best final alternatives. Thus, referring to the proposed analysis, and according to the obtained C_i^* values, the ranking order of all hazards can be determined.

3.5. Proposed PFAHP-FTOPSIS methodology

The proposed approach consists of the 5 × 5 matrix method, and the PFAHP and FTOPSIS methods. The theoretical bases of these methods are given above in detail. The main steps of the proposed approach are given in Fig. 2.

As mentioned previously, the problem of risk assessment with the proposed approach can be considered as an MCDM issue. First, as in all risk assessment studies, component and process information should be collected. The expert group and hazard list are determined. Secondly, the risk parameters should be weighted. In this step, the PFAHP is applied to weight the two risk parameters of the 5 × 5 risk matrix method. Thirdly, it is possible to assess the hazards as listed by the OHS expert group (herein, the 333 different hazards) with respect to the likelihood and severity risk parameters by applying the FTOPSIS method. Finally, a comparative outline that enables comparison of the results of this study with the circumcenter of centroids method and the fuzzy AHP-fuzzy VIKOR integrated method in quantifying risk ratings is provided. Moreover, a control measure proposal outline for high-level risk scores is provided.

4. Case study

In order to present the practicality of the proposed risk assessment approach, a case study was conducted in an underground copper and zinc mine. It is expected that the outcome of this research may help the executives of the mining authority to prioritize hazards and associated risks herein, and to develop appropriate action plans to eliminate (or reduce) the severity of such risks. In this study, an OHS expert group survey was conducted on mine executives and managers. Information about the expert team and their corresponding working experience is set out in Table 4. A group of eight experts (Experts; Es) that had more than ten years' experience in the underground mining sector and was familiar with the existing hazards was selected to participate in the survey. For reasons of anonymity, the identity of the experts is not revealed in this report, and they have therefore been labeled as *E1*, *E2*,*E3*, *E4*, *E5*, *E6*, *E7*, and *E8*.

Two questionnaires were circulated amongst the experts in order to (1) determine the importance levels of the likelihood and severity parameters by using pairwise comparisons of the PFAHP method, and (2) prioritize hazards with respect to these two parameters by using the FTOPSIS. The second questionnaire contained a total number of 333 hazards, and each hazard was described in terms of risk likelihood and risk severity.

4.1. Risk identification

Identification of hazards and associated risks is directly related to the process of finding, listing, and characterizing hazards and associated risks. It is the primary phase of the risk assessment process. Hazard identification, assessment, and control is an ongoing process that is best conducted in the context of full consultation between a person in control of a business, or undertaking, and their workers. It should be undertaken under various circumstances, including: (1) if it has not been done before, (2) when a hazard has been identified, (3) when a change to the workplace occurs, (4) after an incident, accident, or workplace illness, and (5) at regularly scheduled times appropriate to the workplace. Once a hazard to health and safety has been identified, the risk associated with that hazard must be examined. As a prelude to Risk Assessment, it is useful to identify factors that may contribute to the risk. A review of existing health and safety information, such as local workplace accident records or information about the hazard or risk, can assist in understanding the risk

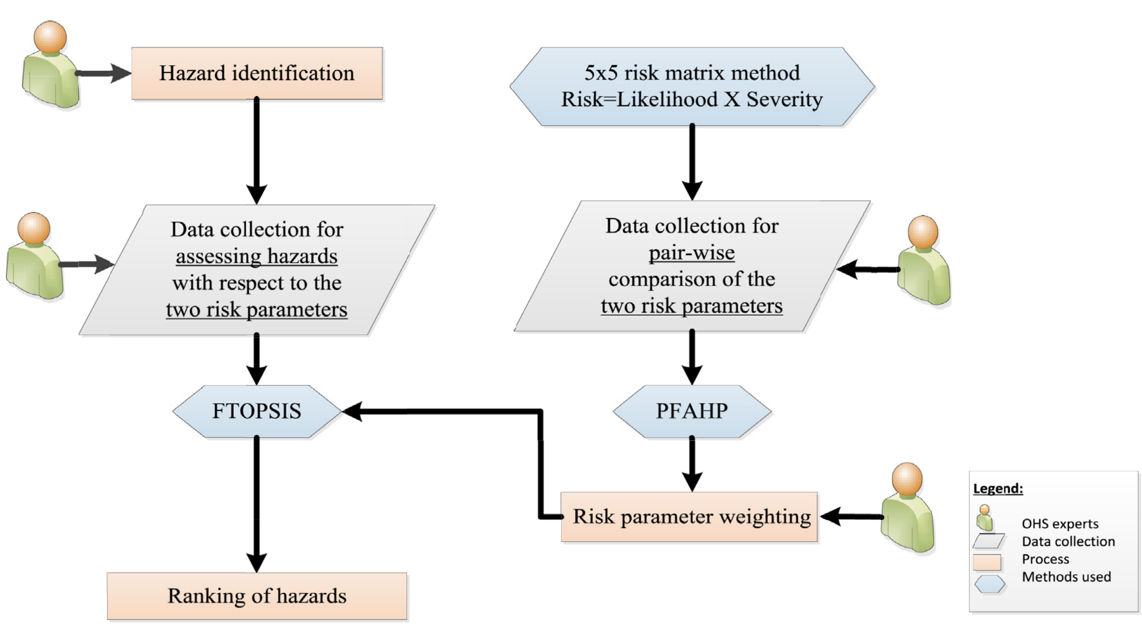

Fig. 2. Flowchart of the proposed approach.

Table 4
Expert profile details.

Mine expert	Title	Years of experience in mining
E1	Mine planning engineer	12
E2	Geological engineer	24
E3	OHS specialist	22
E4	Underground operations manager	18
E5	Occupational physician	7
E6	Drilling and blasting engineer	19
E7	Rock mechanic engineer	11
E8	Chemical safety specialist	10

associated with the hazard in question (WorkSafe ACT, 2012; Samantra et al., 2017).

In this work, 333 different hazards influencing stakeholders were determined in the studied underground copper and zinc mine. The list of these hazards is given in Appendix A. Activity areas where hazards emerged, and the related number of hazards (given in brackets) are as follows: Oxygen works (5), Barricade construction (12), Scaling (6), Fan assembly (26), Sputnik (7), Installation with remote control (12), Personnel transport with shaft (14), Emplacement of steel timbering (11), Mirror drilling (13), Filling the stope (8), Filling the mirror (8), Continuous Paste Fill (9), Unplanned power cut (7), Working under hanging materials (7), Passing through ventilation doors (5), Piping to Cubex brand hole (10), Sheet pipe placement to V30 shaft (6), Piston pump cleaning (9), Explosive transport (9), Vehicle and pedestrian traffic (6), Material handling (10), Opening of clogged drainage (5), Bringing of sulfurous tallow to the side of concrete plant (4), Explosive storage (7), Vehicle fueling and lubrication (15), 620 Ore pass new ladle usage (6), Dust (4), Sledging materials and vehicles (12), SO2 formation and working in SO2 environment (5), Placement of reinforcing cage (12), Drilling stope (7), Transport of ore and tallow (9), Shotcrete (12), Bolting (10), Tallow filling (4), Cement filling (8), Cement filling assembly line (9) and Others (4).

4.2. Linguistic scale and corresponding fuzzy picture

In Samantra et al. (2017), a fuzzy linguistic scale is defined as a set of linguistic variables that can be represented as fuzzy numbers, resulting in fuzzy representation for each property. In this study, the fuzzy scales by Samantra et al. (2017) are used. The likelihood of risk occurrence and the possible risk severity is quantified by using the seven-point fuzzy linguistic scale and the five-point fuzzy linguistic scale, respectively (Tables 2 and 3).

4.3. Data collection

The linguistic data on likelihood and severity against each of the identified risk factors were collected from the eight mine experts. The collected data were further used to quantify the risk ratings. Mine experts provided their judgment in linguistic terms, rather than crisp scores. During the evaluation process, they were requested to keep confidential their judgment, and not to share their personal view amongst themselves. The linguistic data used for determining the weights of the likelihood and severity risk parameters using the PFAHP is provided in Table 5. At this stage, the scale given in Table 1 was followed. For the second stage of the proposed approach, the FTOPSIS, the linguistic dataset expressing the likelihood and severity of various hazards as assigned by the mine experts was arranged. Then, the linguistic information, as obtained from the experts, was converted to appropriate trapezoidal fuzzy numbers according to the scales (shown in Tables 2 and 3) to quantify the risk rating.

4.4. Quantification of risk ratings using the proposed PFAHP-FTOPSIS methodology

Quantification of risk ratings using the proposed FPAHP-FTOPSIS approach includes two main stages. The first is concerned with the determination of weights of the risk parameters derived from the 5×5 risk matrix method. In this first stage, the mine expert group scored and assigned weights to these two risk parameters using the PFAHP method. According to the PFAHP method, particularly its pair-wise comparison manner, the experts used the linguistic terms in Table 1 to assess the relative importance of the risk parameters (Table 5). By applying the PFAHP formulations given in Eqs. (7)–(13), the weights of the risk parameters were obtained as 0.483 and 0.517 for likelihood and severity, respectively. It should be noted that the consistency index of the pairwise comparison matrix was computed and considered as consistent, and the questionnaire was valid in terms of the PFAHP.

Then, by using the risk parameters' weights from the PFAHP, and the fuzzy evaluations of each risk parameter with respect to hazards, the FTOPSIS was applied. The mine experts evaluated 333 hazards using linguistic variables, as shown in Table 6. The fuzzy linguistic variables in Table 6 were then transformed into fuzzy trapezoidal numbers. This is the first stage of the FTOPSIS analysis. The fuzzy risk parameter weights were added to the calculation in the FTOPSIS analysis. The next step was to generate the weighted fuzzy decision matrix, which was obtained using Eq. (15). The FPIS and FNIS values were set to: (1, 1, 1, 1) and (0, 0, 0, 0). For the next step, the distance of each alternative from S_k^+ and S_k^- was calculated using Eqs. (18) and (19). The next step presented the similarities to an ideal solution using Eq. (20). The resulting closeness coefficient values of the FTOPSIS were computed. According to the FTOPSIS method, the highest hazard is the one that has the shortest distance from the fuzzy positive ideal solution, and the longest distance from the fuzzy negative ideal solution. The ranking of the hazards is determined by ranking the risks having a C_i^* value closest to 1 as highest risk, while risks having a C_i^* value farthest from 1 are ranked as lowest risk.

Table 6 reports the ranking of hazards deemed to be the most critical as characterized by their C_i^* values close to the negative solution. Rankings from 1 to 10 (the ones in the first ten ranking orders) are considered as the most critical hazards. The ones in the last ten rankings (from 324 to 333) are deemed to be the least critical hazards. The full list of ranking of hazards by the PFAHP-FTOPSIS proposed approach is provided as a supplementary file.

4.5. Comparison of risk ranking orders

Within the scope of this ongoing work, a comparative outline

Table 5
Mine expert pairwise judgments for risk parameter weight computation by PFAHP.

Risk parameter of 5×5 risk matrix method	L (*E1, E2, E3, E4, E5, E6, E7, E8*)	S (*E1, E2, E3, E4, E5, E6, E7, E8*)
L	(EE, EE, EE, EE, EE, EE, EE, EE)	(BAI, BAI, EE, EE, AAI, AI, AI, AI)
S	(AAI, AAI, EE, EE, BAI, AI, AI, AI)	(EE, EE, EE, EE, EE, EE, EE, EE)

Table 6
Ranking of hazards by PFAHP-FTOPSIS proposed approach.

Ranking	ID-Hazard no.	Ranking	ID-Hazard no.
1	H37	324	H58
2	H55	325	H133
3	H39	326	H220
4	H107	327	H23
5	H2	328	H85
6	H194	329	H59
7	H246	330	H4
8	H31	331	H52
9	H229	332	H34
10	H38	333	H45

that enables a comparison of the results of this study (proposed PFAHP-FTOPSIS approach) with the circumcenter of centroids method and the fuzzy AHP-fuzzy VIKOR integrated method in quantifying risk ratings is provided. In doing so, we aim to show the applicability and validity of this novel approach by comparing final risk ranking orders. As the first attempt of this comparative outline, the risk ratings are initially quantified following the procedure of the circumcenter of centroids method (employing generalized trapezoidal fuzzy numbers), which was successfully applied by Samantra et al. (2017) to a particular metropolitan construction project risk assessment.

Therefore, hazards and associated risk factors were ranked according to their crisp risk ratings. The computation results of aggregated fuzzy preferences, fuzzy ratings, and defuzzified crisp risk ratings are available in the Supplementary material file. The hazards ranking in the first ten and last ten places are also provided in Table 7. It was observed that amongst the 333 hazards studied herein, working at height, load lifting and suspension during assembly and disassembly of fans, engaging the fan: diffuser and adapter selection, ventilation during filling the stope, planning and traffic management issues in the work of sledging materials and vehicles, moving parts during barricade construction, and working at height in material handling process appeared to be the hazards posing relatively high-risk ratings. It was also observed that the ranking order of the first five hazards are the same for the PFAHP-FTOPSIS proposed approach and the circumcenter of centroids method.

Apart from determining the ranking order of hazards with respect to likelihood and severity parameters; an additional analysis was also conducted to compute the percentage (%) contribution of risk in each activity area of the studied underground copper and zinc mine where hazards emerged toward overall risk rating as made by Samantra et al. (2017) (It was assumed that hazard in each activity area consisted of several risk sources, as indicated in the Supplementary material file). The results obtained from this analysis are demonstrated in Fig. 3.

The percentage contribution of the fan assembly area to the overall risk was found to be about 8.14%. The hazard risks in the activity area of vehicle fueling and lubrication was found to contribute the second-highest percentage. By verifying the ranking results of hazards using the circumcenter of centroids method, it was shown that H37 stood in first place, H38 in sixth place, and H39 in third place of the fan assembly area hazards.

Table 7
Ranking of hazards by circumcenter of centroids method.

Ranking	ID-Hazard no.	Ranking	ID-Hazard no.
1	H37	324	H100
2	H55	325	H136
3	H39	326	H141
4	H107	327	H142
5	H2	328	H145
6	H38	329	H167
7	H246	330	H177
8	H16	331	H180
9	H194	332	H185
10	H253	333	H204

Second, a comparison was performed between the ranks obtained from the proposed approach in this study and the fuzzy AHP-fuzzy VIKOR approach (employing symmetric triangular fuzzy numbers), which has been applied successfully to several areas by Gul et al. (2017a), Gul et al. (2017b), Ozdemir et al. (2017), and Gul et al. (2018). As shown in Table 8, the proposed method and the circumcenter of centroids method consider H37, H55, H39, H107, and H2 as ranking first, second, third, fourth, and fifth, respectively. However, the other hazards ranking near the middle of the list are different between the two methods. Table 8 also shows that the top five ranking hazards are the same for the two methods, except for H37 and H55. The priority order of these two hazards are switched. While H37 is considered to have the greatest risk in the first two approaches, it is considered the second-greatest risk according to the fuzzy AHP-fuzzy VIKOR approach. This may be caused by the different importance levels of the risk parameters used in fuzzy VIKOR related studies.

4.6. Discussion on risk prevention

In this sub-section, discussions are presented on the preventive measures that should be taken in each activity area of the observed underground mine to control the most serious risks as determined by the proposed approach. Regarding the hazards during fan assembly, which had the highest possible risk rating (*H37* and *H39*), the following control measures were required: providing suspension and lifting procedures, determination of appropriate location, providing proper fortification standards, providing well-qualified and experienced personal and suitable personal protective equipment (PPE), selection and procurement of suitable transportation vehicles, periodic examination of and improvement on transportation vehicles, immobilization of equipment during transportation, giving advance education and authorization before work, ventilation standards, creating a hot work permit form, a locking procedure, and a procedure for working at height. As stated by Donoghue (2004), there are still many ergonomic hazards in mines, especially during the suspension of pipes and electrical cables, although the work has become increasingly mechanized. Also, *H37: Working at height during assembly and disassembly of fans* is expressed as one of the most common causes of fatal injuries among the physical hazards in mines (Donoghue, 2004). According to another study by Sari et al. (2009), falls from height, and the handling of tools and supports that are directly related to the most serious risks mentioned above are considered as primary causes of accidents in underground mines.

H55: Blasting in shift, which was determined as the second-most serious hazard, releases harmful gases into the underground environment. Due to these adverse effects, Hermanus (2007) stated that it is one of the most vital hazards in underground mining environments. For *H55*, several control measures, including notification of all workers before an explosion by mine control, providing suitable PPE procedures for transporting explosives, ergonomic design of the sputnik window, providing systems to prevent mobile falling, not using cords in explosions, providing a night vision camera system, installation requirements for gas and electric structures, preparation procedures for the sputnik, controlling all valves before starting activity, employing authorized and experienced personal, appropriate vehicles, follow-up legislation, and regular and periodic controls of the work area should be taken into

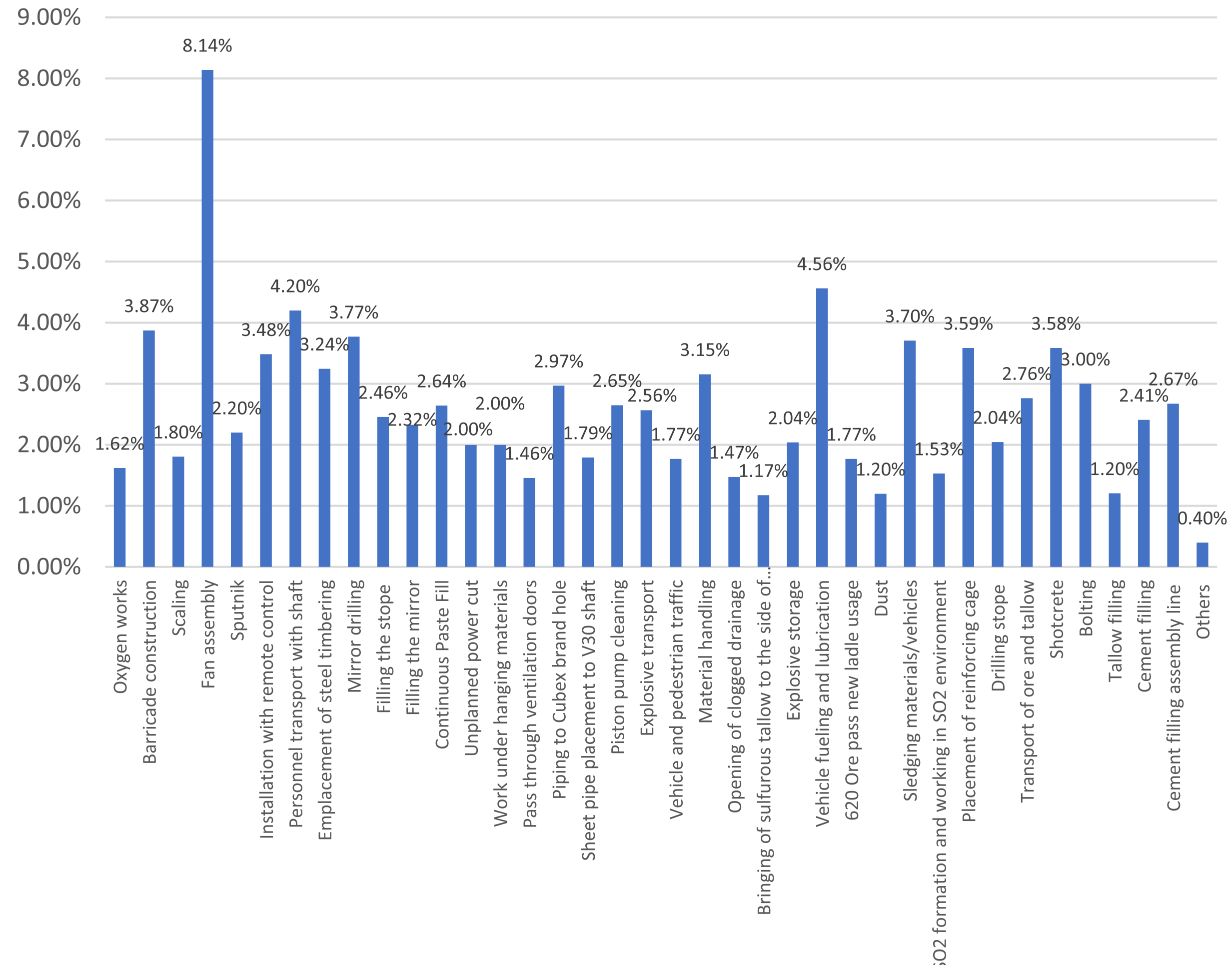

Fig. 3. Risk percentages for each activity area of the studied copper and zinc mine toward overall risk.

Table 8
The first five ranking results of the hazards according to the three approaches.

Hazards	Ranking order		
	PFAHP-FTOPSIS	circumcenter of centroids	fuzzy AHP-fuzzy VIKOR
H2	5	5	5
H55	2	2	1
H107	4	4	4
H37	1	1	2
H39	3	3	3

consideration by mine experts and authorities.

Providing personal escape masks, follow-up legislation, regulations for ventilation, a follow-up scaling procedure, providing appropriate energy insulation systems, use of mobile and ergonomic equipment, providing regular and periodic control of suitable PPE, giving advance education and authorization before work are major control measures for *H107: Ventilation during filling the stope*. Donoghue (2004) stated that improvements in underground ventilation would substantially reduce the risk of silicosis, lung cancer, and worker's pneumoconiosis.

In relation to the oxygen works activity area inside the mine, H2 (describing pressurized gas hazard) represents the fifth most important risk priority value closest to the ideal solution, which means it has the fifth most serious risk compared with others. For the H2 hazard and associated risk (*H2*), creating a general workplace inspection checklist, giving advance mine rescue training, building a hot work permit form, temporary lane closures with signs for the workplace, building safety and health regulations for oxyacetylene shielding, regular checks of load and pressure limits, preferring certified and experienced mine operators, regular control of pressure tubes, maintenance and proper fixing of vehicles, providing safety lamps, providing suitable PPE, filling individual identification numbers, regular checks of valves, and providing suitable equipment for oxyacetylene sets are the control measures and necessities with respect to OHS.

The 5×5 risk matrix method was also applied to categorize various risks into different levels based on the presumed range of crisp risk ratings. The 5×5 risk matrix defines various risk levels as computed by the product of the parameters associated with the likelihood and severity. As a follow-up work to the proposed approach, risk categories obtained from the circumcenter of centroids method of Samantra et al. (2017) are presented in Table 9. In Table 9, 0.9536 appears as the highest possible risk rating, and 0.1734 is the lowest possible risk rating that could be assigned to a particular risk. Therefore, different risks have been categorized into five different risk levels (0–4) as shown in Table 9. Following this categorization, a preventive action plan was suggested by mine experts and executives to effectively control different risks placed at different levels. Various risks at each level and their corresponding control action plan are presented in Table 9 for successful management and mitigation of risks.

Table 9
Suggested preventive actions plan for five different risk levels.

Risk level	Hazards and associated risks	Preventive actions
Category 4 (Rating 0.7741–0.9536)	Not available	● Immediate improvements need to be made—consider stopping the operation. Risk committee shall immediately inform the General Manager of the measures to be used to eliminate the risk, or of the risk reduction plans. The General Director shall decide on the continuation of the operation and the operation of the plant. These risks should be actively addressed by the Department Manager using the relevant parts of the following possible controls: o Relevant Serious high protocol guidelines o Formal inspections at certain times during the work activity o Use case-specific Secure Work Procedures o Hanging of Bow-tie flowcharts at workplaces o Work team meetings before serious risk tasks
Category 3 (Rating 0.4955–0.7740)	H2, H8, H9, H16, H31, H37, H38, H39, H55, H107, H193, H194, H227, H229, H246, H253	
Category 2 (Rating 0.4306–0.4954)	H1, H5, H6, H7, H10, H14, H15, H17, H19, H20, H21, H27, H28, H29, H30, H32, H40, H41, H44, H46, H48, H49, H50, H51, H60, H62, H68, H69, H70, H73, H74, H80, H81, H82, H83, H86, H87, H88, H92, H98, H103, H112, H120, H124, H126, H127, H128, H150, H151, H153, H156, H157, H159, H160, H162, H164, H165, H169, H170, H172, H176, H188, H190, H192, H197, H198, H199, H200, H201, H206, H210, H213, H214, H217, H219, H221, H223, H226, H233, H235, H236, H238, H239, H240, H241, H247, H251, H252, H255, H256, H257, H258, H259, H260, H261, H262, H263, H265, H266, H267, H270, H272, H273, H274, H277, H278, H283, H284, H285, H286, H287, H288, H290, H291, H294, H295, H296, H297, H300, H301, H304, H305, H306, H309, H311, H312, H313, H314, H315, H316, H318, H320, H321, H323, H324, H325, H326, H327, H330, H331, H333	● The risk committee shall inform the General Manager of the measures to be used to eliminate the risk, or the risk reduction plans. ● The Operations Manager will decide whether to continue the operation, or to operate the plant. ● These risks should be actively managed by the relevant Chief Engineer or Mine Captains using the relevant parts of the following possible controls: o Relevant Serious high protocol guidelines o Use case-specific Secure Work Procedures o Regular workplace inspections and security discussions o Other specific instructions as needed
Category 1 (Rating 0.2238–0.4305)	H3, H4, H11, H12, H13, H18, H22, H23, H24, H25, H26, H33, H34, H35, H36, H42, H43, H45, H47, H52, H53, H54, H56, H57, H58, H59, H61, H63, H64, H65, H66, H67, H71, H72, H75, H76, H77, H78, H79, H84, H85, H89, H90, H91, H93, H94, H95, H96, H97, H99, H100, H101, H102, H104, H105, H106, H108, H109, H110, H111, H113, H114, H115, H116, H117, H118, H119, H121, H122, H123, H125, H129, H130, H131, H132, H133, H134, H135, H136, H137, H138, H139, H140, H141, H142, H143, H144, H145, H146, H147, H148, H149, H152, H154, H155, H158, H161, H163, H166, H167, H168, H171, H173, H174, H175, H177, H178, H179, H180, H181, H182, H183, H184, H185, H186, H187, H189, H191, H195, H196, H202, H203, H204, H205, H207, H208, H209, H211, H212, H215, H216, H218, H220, H222, H224, H225, H228, H230, H231, H232, H234, H237, H242, H243, H244, H245, H248, H249, H250, H254, H264, H268, H269, H271, H275, H276, H279, H280, H281, H282, H289, H292, H293, H298, H299, H302, H303, H307, H308, H310, H317, H319, H322, H328, H329, H332	● Risk committee will ensure that preventive controls and oversight plans are created and maintained, and that these risks are reassessed at appropriate intervals. ● These risks should be actively managed by the relevant team leader using the relevant parts of the following possible controls: o Use of relevant Safe Operating Procedures o Workplace inspections and safety discussions
Category 0 (Rating 0.0000–0.2237)	Not available	● No action is required and operational management should be confident that risk control measures are in place. Employees and contractors are aware of the hazards and follow established Watch Lists. ● These risks are managed by the employee performing the task using the standard Control Hierarchy.

5. Conclusions

This paper proposes a novel OHS risk assessment approach using the 5×5 risk matrix method, AHP with Pythagorean fuzzy sets, and TOPSIS with trapezoidal fuzzy sets. A case study on the assessment of risks and their control measures was carried out in an underground copper and zinc mine. The current study assessed risk by considering two important parameters of a classical 5×5 risk matrix method (likelihood and severity) and 333 potential hazards (as well as their associated risks). It also suggested preventive action plans for controlling the risks. It was clearly seen that effective risk management necessitates a systematic practice loop that includes risk identification, risk assessment, risk control, and risk review. A total of 333 potential hazards were identified by considering critique by OHS experts.

The first contribution of the current study is the proposal of a novel iterative fuzzy MCDM-based OHS risk assessment approach in quantifying the risk ratings of each identified risk. The PFAHP, which is a commonly used MCDM method with interval-valued Pythagorean fuzzy sets, is applied to the assessment of risk parameters *likelihood* and *severity* using a classical 5×5 risk matrix method. In the second step of the assessment, the trapezoidal fuzzy TOPSIS method is used for the prioritization of hazards. Additionally, an improved MCDM-based risk assessment approach using linguistic terms with Pythagorean and trapezoidal fuzzy set theory was implemented. The OHS experts' linguistic data were transformed to numeric risk ratings. Use of interval-valued Pythagorean and trapezoidal fuzzy sets successfully managed the uncertainty and vagueness of the OHS expert perceptions during the subjective judgment process. The second contribution concerns the comparative outline of the study. Results of this study were compared with the circumcenter of centroids method and the fuzzy AHP-fuzzy VIKOR integrated method in the quantification of risk ratings. Taking advantage of the comparable ranking results of the two other methods, hazards were handled. On conclusion of this comparison, all three approaches resulted in similar ranking orders of hazards. Moreover, a risk categorization according to the circumcenter of centroids method and suggested preventive action plans according to the compared approaches were provided. These suggestions are expected to represent a basis for decisions and policies that must be made by mining authorities as part of their review control measures process.

In addition to its methodological contributions, this study has many benefits for the mining industry. Advanced manufacturing methods in underground mines in Turkey have increasingly been employed due to today's technological developments in the mining industry and will probably be applied in many underground mines in the near future. Due to the risk in the mining sector, comprehensive and effective risk assessment approaches are required for system safety. There is a certain necessity for appropriate monitoring of changing conditions and assessment of every risk element in mining. In order to maintain a safer underground working environment for copper and zinc mines, it is necessary to detect and analyze the existing risks. Therefore, a risk assessment system has been developed, and it has been used to evaluate the potential risks of underground copper and zinc mines in Turkey. This risk assessment study directly considers comprehensiveness and sustainability of MCDM-based risk assessment methods in the mining sector by comparison. It further encourages mine authorities to determine national and macro-scale risk control policies. In addition, other mining companies may use this method and adapt the case study to their plants for safety management in the future. This approach can be viewed as a first step for mining executives in establishing suitable ways to identify and analyze risks. Further research is needed to develop more models in this area.

The current study has some limitations, as follows. (1) This study proposed an OHS risk assessment approach in a fuzzy environment. Hazards and associated risks were subjectively assessed in terms of severity and likelihood parameters of the 5×5 risk matrix using linguistic variables. Linguistic information was transformed to interval-valued Pythagorean and trapezoidal fuzzy numbers in reference to fuzzy linguistic scales from the literature in order to quantify risk ratings. However, the sensitivity of fuzzy linguistic scales and the different fuzzy membership functions were not tested. (2) In practice, there are additional risk parameters, which are very rarely used for OHS risk assessment. A more comprehensive hybrid OHS risk assessment on mining hazards may incorporate these aspects in future work. (3) One potential difficulty is in representing an expert's judgment with respect to the risk parameters using a single set of fuzzy linguistic terms. The application of various versions of fuzzy set theories can be taken into consideration to resolve the issue.

Appendix A. Supplementary data

Supplementary data related to this article can be found at https://doi.org/10.1016/j.jclepro.2018.06.106.

References

Amirshenava, S., Osanloo, M., 2018. Mine closure risk management: an integration of 3D risk model and MCDM techniques. J. Clean. Prod. 184, 389–401.

Atanassov, K.T., 1986. Intuitionistic fuzzy sets. Fuzzy Set Syst. 20 (1), 87–96.

Aven, T., 2008. Risk Analysis: Assessing Uncertainties beyond Expected Values and Probabilities. Wiley, Chichester, UKT doi, 10, 9780470694435.

Badri, A., Nadeau, S., Gbodossou, A., 2013. A new practical approach to risk management for underground mining project in Quebec. J. Loss Prev. Process. Ind. 26 (6), 1145–1158.

Carpitella, S., Certa, A., Izquierdo, J., La Fata, C.M., 2018. A combined multi-criteria approach to support FMECA analyses: a real-world case. Reliab. Eng. Syst. Saf. 169, 394–402.

Celik, E., Gul, M., Gumus, A.T., Guneri, A.F., 2012. A fuzzy TOPSIS approach based on trapezoidal numbers to material selection problem. J. Inf. Technol. Appl. Manag. 19 (3), 19–30.

Ceylan, H., Başhelvacı, V.S., 2011. Risk analysis with risk assessment matrix method: an application. Int. J. Eng. Res. Dev. 3 (2), 25–33 (In Turkish).

Chen, C., 2000. Extensions of the TOPSIS for group decision-making under fuzzy environment. Fuzzy Set Syst. 114, 1–9.

Demiral, Y., Ertürk, A., 2013. Safety and health in mining in Turkey. In: Elgstrand, Kaj, Vingård, Eva (Eds.), Occupational Safety and Health in Mining Anthology on the Situation in 16 Mining Countries, vol. 47, pp. 87–93 no. 2.

Donoghue, A.M., 2001. The design of hazard risk assessment matrices for ranking occupational health risks and their application in mining and minerals processing. Occup. Med. 51 (2), 118–123.

Donoghue, A.M., 2004. Occupational health hazards in mining: an overview. Occup. Med. 54 (5), 283–289.

Gul, M., 2018. A review of occupational health and safety risk assessment approaches based on multi-criteria decision-making methods and their fuzzy versions. Hum. Ecol. Risk Assess. Int. J. https://doi.org/10.1080/10807039.2018.1424531.

Gul, M., Guneri, A.F., 2016. A fuzzy multi criteria risk assessment based on decision matrix technique: a case study for aluminum industry. J. Loss Prev. Process. Ind. 40, 89–100.

Gul, M., Guneri, A.F., 2018. Use of FAHP for occupational safety risk assessment: an application in the aluminum extrusion industry. In: Emrouznejad, Ali, Ho, William (Eds.), Fuzzy Analytic Hierarchy Process. Chapman and Hall/CRC, New York, pp. 249–271.

Gul, M., Ak, M.F., Guneri, A.F., 2017a. Occupational health and safety risk assessment in hospitals: a case study using two-stage fuzzy multi criteria approach. Hum. Ecol. Risk Assess. Int. J. 23 (2), 187–202.

Gul, M., Celik, E., Akyuz, E., 2017b. A hybrid risk-based approach for maritime applications: the case of ballast tank maintenance. Hum. Ecol. Risk Assess. Int. J. 23 (6), 1389–1403.

Gul, M., Guven, B., Guneri, A.F., 2018. A new Fine-Kinney-based risk assessment framework using FAHP-FVIKOR incorporation. J. Loss Prev. Process. Ind. 53, 3–16.

Guneri, A.F., Gul, M., Ozgurler, S., 2015. A fuzzy AHP methodology for selection of risk assessment methods in occupational safety. Int. J. Risk Assess. Manag. 18 (3–4), 319–335.

Health and Safety Authority, (HSA), 2006. Guidelines on Risk Assessments and Safety Statements, Dublin. http://www.hsa.ie/eng/Publications_and_Forms/Publications/Safety_and_Health_Management/Guidelines_on_Risk_Assessments_and_Safety_Statements.pdf.

Hermanus, M.A., 2007. Occupational health and safety in mining-status, new developments, and concerns. J. S. Afr. Inst. Min. Metall 107 (8), 531–538.

Hwang, C.L., Yoon, K., 1981. Multiple Attribute Decision Making: Methods and Applications, a State of the Art Survey. Springer-Verlag, New York, NY.

Ilbahar, E., Karaşan, A., Cebi, S., Kahraman, C., 2018. A novel approach to risk assessment for occupational health and safety using Pythagorean fuzzy AHP & fuzzy inference system. Saf. Sci. 103, 124–136.

ISO 31000, 2018. Risk Management - Principles and Guidelines, second ed. International Organization for Standardization, Geneva https://www.iso.org/iso-31000-risk-management.html. (Accessed 25 April 2018).

ISO 45001, 2018. Occupational Health and Safety Management Systems - Requirements with Guidance for Use. International Organization for Standardization, Geneva. https://www.iso.org/iso-45001-occupational-health-and-safety.html. (Accessed 25 April 2018).

ISO/IEC 31010, 2009. Risk Management—Risk Assessment Technique, first ed. International Organization for Standardization, Geneva https://www.iso.org/obp/ui/#iso:std:51073:en. (Accessed 25 April 2018).

Joy, J., 2004. Occupational safety risk management in Australian mining. Occup. Med. 54 (5), 311–315.

Kutlu, A.C., Ekmekçioğlu, M., 2012. Fuzzy failure modes and effects analysis by using fuzzy TOPSIS-based fuzzy AHP. Expert Syst. Appl. 39 (1), 61–67.

Lang, L., Fu-Bao, Z., 2010. A comprehensive hazard evaluation system for spontaneous combustion of coal in underground mining. Int. J. Coal Geol. 82 (1–2), 27–36.

Mahdevari, S., Shahriar, K., Esfahanipour, A., 2014. Human health and safety risks management in underground coal mines using fuzzy TOPSIS. Sci. Total Environ. 488, 85–99.

Marhavilas, P.K., Koulouriotis, D.E., 2008. A risk-estimation methodological framework using quantitative assessment techniques and real accidents' data: application in an aluminum extrusion industry. J. Loss Prev. Process. Ind. 21 (6), 596–603.

Marhavilas, P.K., Koulouriotis, D., Gemeni, V., 2011. Risk analysis and assessment methodologies in the work sites: on a review, classification and comparative study of the scientific literature of the period 2000–2009. J. Loss Prev. Process. Ind. 24 (5), 477–523.

Mohd, W.R.W., Abdullah, L., 2017. Pythagorean fuzzy analytic hierarchy process to multi-criteria decision making. In: AIP Conference Proceedings, vol. 1905. AIP Publishing. No. 1, p. 040020.

Önder, S., Suner, N., Önder, M., 2011. Investigation of occupational accident occurred at mining sector by using risk assessment decision matrix. In: 22nd International Mining Congress and Exhibition of Turkey, 11–13 May 2011, Ankara, pp. 399–406.
Ozdemir, Y., Gul, M., Celik, E., 2017. Assessment of occupational hazards and associated risks in fuzzy environment: a case study of a university chemical laboratory. Hum. Ecol. Risk Assess. Int. J. 23 (4), 895–924.
Özfırat, P.M., 2014. Bulanık önceliklendirme metodu ve hata türü ve etkileri analizini birleştiren yeni bir risk analizi yöntemi (A new risk analysis methodology integrating fuzzy prioritization method and failure modes and effects analysis). J. Faculty Eng. Arch. Gazi Univ. 29 (4), 755–768 (In Turkish).
Petrović, D.V., Tanasijević, M., Milić, V., Lilić, N., Stojadinović, S., Svrkota, I., 2014. Risk assessment model of mining equipment failure based on fuzzy logic. Expert Syst. Appl. 41 (18), 8157–8164.
Qiaoxiu, W., Hong, W., Zuoqiu, Q., 2016. An application of nonlinear fuzzy analytic hierarchy process in safety evaluation of coal mine. Saf. Sci. 86, 78–87.
Samantra, C., Datta, S., Mahapatra, S.S., 2017. Analysis of occupational health hazards and associated risks in fuzzy environment: a case research in an Indian underground coal mine. Int. J. Inj. Contr. Saf. Promot. 24 (3), 311–327.
Sari, M., Selcuk, A.S., Karpuz, C., Duzgun, H.S.B., 2009. Stochastic modeling of accident risks associated with an underground coal mine in Turkey. Saf. Sci. 47 (1), 78–87.
Spada, M., Burgherr, P., 2016. An aftermath analysis of the 2014 coal mine accident in Soma, Turkey: use of risk performance indicators based on historical experience. Accid. Anal. Prev. 87, 134–140.
The Union of Turkish Bar Associations (TBB) Human Rights Centre, 2014. Soma Incident Report,Turkey. https://www.barobirlik.org.tr/dosyalar/duyurular/20141112_somamadenfaciasipdf.pdf.
Tixier, J., Dusserre, G., Salvi, O., Gaston, D., 2002. Review of 62 risk analysis methodologies of industrial plants. J. Loss Prev. Process. Ind. 15 (4), 291–303.
Tzeng, G.H., Huang, J.J., 2011. Multiple Attribute Decision Making: Methods and Applications. CRC Press.
Verma, S., Chaudhri, S., 2014. Integration of fuzzy reasoning approach (FRA) and fuzzy analytic hierarchy process (FAHP) for risk assessment in mining industry. J. Ind. Eng. Manag. 7 (5), 1347.
Vingard, E., Elgstrand, K., 2013. Safety and health in mining (Anthology on the situation in 16 mining countries). Gothenburg: Occup. Environ. Med. Sahlgrenska Acad. 9–10.
Yager, R.R., 2014. Pythagorean membership grades in multicriteria decision making. IEEE Trans. Fuzzy Syst. 22 (4), 958–965.
Zeng, S., Chen, J., Li, X., 2016. A hybrid method for pythagorean fuzzy multiple-criteria decision making. Int. J. Inf. Technol. Decis. Making 15 (02), 403–422.
Zhang, X., Xu, Z., 2014. Extension of TOPSIS to multiple criteria decision making with Pythagorean fuzzy sets. Int. J. Intell. Syst. 29 (12), 1061–1078.