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Pythagorean fuzzy VIKOR-based approach for safety risk assessment in mine industry

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A B S T R A C T

Introduction: Underground mining is considered one of the most hazardous industries and is often associated with serious work-related fatalities; this paper addresses job-related hazards and associated risks. *Method:* A risk assessment approach is proposed (Pythagorean fuzzy environment) and a case study is carried out in an underground copper and zinc mine. *Results:* Results of the study demonstrate that hazards can be categorized into different risk levels via compromised solutions of the fuzzy approach. *Conclusion:* The study provides a theoretical contribution by suggesting a Pythagorean fuzzy numbers-based VlseKriterijumska Optimizacija I Kompromisno Resenje (PFVIKOR) approach. Moreover, it contributes to improving overall safety levels of underground mining by considering and advising on the potential hazards of risk management. *Practical applications:* The proposed approach will improve the existing safety risk assessment mechanism in underground copper and zinc mining.

1. Introduction

Underground mining is considered one of the most hazard prone industries worldwide if one considers occupational accidents linked to death and injury risks (Samantra, Datta, & Mahapatra, 2017a; Vingård & Elgstrand, 2013). Mining is typically classified as surface or underground mining (Donoghue, 2004). Another categorization of metalliferous mining relates to the commodity being mined. A significant amount of mining occurs in developing countries such as Turkey. Turkey is ranked third in the world in terms of occurrence of coal mining accidents (Demiral & Erturk, 2013). On May 13, 2014, an explosion at a coal mine in Soma, Turkey caused a catastrophic event and 301 fatalities (Badri, 2015; Duzgun & Leveson, 2018; Spada & Burgherr, 2016). The Soma mine disaster was the most-deadly mining accident in Turkey's and OECD's history (Spada & Burgherr, 2016). In the report compiled by Demiral and Erturk (2013), several issues are dealt with as priority (divided into two main levels: at the policy and at the workshop practices level) for the improvement of Occupational Health and Safety (OHS) in mining in Turkey. The priorities have encouraged stakeholders to implement a proper risk assessment tool to use in future occupational accidents.

Although copper and zinc mines are considered to provide safer conditions than coal mines, both have difficult working condition hazards due to mining underground. Working at great depth, inrushing flood water from underground reservoirs, carbon monoxide poisoning, humidity, lack of ventilation, heatstroke from working on rock faces, shaft failure, various illnesses, falling loose rock from the sides and roof of development faces, fires in heavy machinery, noise, accidents occurred on loading, hoisting, hauling, or pushing, spontaneous combustion, and explosions are some of the hazards faced when working underground (Mahdevari, Shahriar, & Esfahanipour, 2014). According to a report on the Soma accident by The Union of Turkish Bar Associations (TBB) Human Rights Centre (2014), the general cause of mining accidents in Turkey, from the outset, is stemmed from the deficiency of any detailed and adequate risk assessment. Therefore, to have a certain picture of the practice and compliance of the OHS policy in underground mining industry in Turkey, without considering the number of employees, one needs to look at the industries obligatory legal requirement of risk assessment under the OHS Law No. 6331 (Gul, Ak, & Guneri, 2017).

The OHS risk assessment is used for estimating health risks from exposure to various levels of a workplace hazard (Mahdevari et al., 2014). Considerable amount of hybrid, qualitative, and quantitative risk assessment methods are proposed. L-matrix method, the Fine-Kinney, the failure mode and effect analysis (FMEA), the fault tree analysis (FTA), and the event tree analysis (ETA) are the most practiced classical OHS risk assessment methods (Gul, Ak, & Guneri, 2017; Guneri, Gul, & Ozgurler, 2015; Marhavilas, Koulouriotis, & Gemeni, 2011; Tixier, Dusserre, Salvi, & Gaston, 2002). Quantitative risk assessment methods can be improved by multi criteria decision-making (MCDM)-based approaches with their strength to overcome existing real-world problems

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with multiple, implicit or explicit, conflicting and incompatible criteria (Ak & Gul, 2018; Aminbakhsh, Gunduz, & Sonmez, 2013; Gul, Ak, & Guneri, 2017; Gul, Celik, & Akyuz, 2017; Gul & Guneri, 2016; Gul & Guneri, 2018; Gul, Guneri, & Baskan, 2018; Gul, Guneri, & Nasirli, 2018; Gul, Guven, & Guneri, 2018; Mete, 2018; Oz, Mete, Serin, & Gul, 2018; Ozdemir, Gul, & Celik, 2017; Yucesan & Kahraman, 2019). With traditional methods, decision-makers often face difficulties in evaluating hazards by giving a precise rating. Therefore, the fuzzy sets integrated methods are proposed to overcome this difficulty. For the current study, a recent version of fuzzy sets theory "Pythagorean fuzzy sets" is combined with VIKOR method. As a generalized set, Pythagorean fuzzy sets have a close relationship with intuitionistic fuzzy. They supply more flexibility to experts in clarifying their idea about the ambiguity and unpredictability of the considered risk assessment problem. Also, it has more capability in conducting contemporaneous consideration of the compromised solutions, straightforward computation, and relevant concept.

The rest of this paper continues as follows: Section 2 presents a related review of literature and reveals the research gap that this study addresses. Section 3 presents the research methods. In Section 4 and Section 5, the application case study and its results and discussion are presented. The final section includes some concluding remarks and discusses future recommendations.

2. Review of literature

Several risk assessment studies have been conducted in the knowledge. Table 1 shows a comparative summary for the recent studies on mining OHS risk management. AHP/FAHP is mostly used in risk assessment studies to prioritize the precautions or improvement actions of risky operations, to rank safety risks or failures caused by controllable hazards, and to determine safety/risk scores/weights in a hierarchical risk assessment process. Badri, Nadeau, and Gbodossou (2013) developed the integration of a novel concept called hazard concentration and AHP. All hazards and associated risks in gold mines throughout Quebec, Canada were dealt with. In another study, Lang and Fu-Bao (2010) determined influential factors that lead to the spontaneous combustion of coal seams and proposed a framework including a holistic scoring method and an AHP for evaluating the hazard of spontaneous combustion. To validate the applicability of the proposed framework, it was applied to Chinese coal mines. FAHP is the most widely applied MCDM methodology, which combines fuzzy logic with AHP. Since traditional AHP cannot present a subjective thinking manner, FAHP was proposed in order to solve hierarchical problems under fuzziness and uncertainty in mining. As in AHP-based risk assessment studies, FAHP is applied in order to determine weights of risk factors and sub-factors in imprecise hierarchical structures or to find the precedence of risk factors. Wang, Wang, and Qi (2016) used FAHP to estimate and rank the risk factors that involve managerial, environmental, operational, and individual criteria to develop a management model and to guide safety managers in the mining process. They also used the LFPP method to analyze risk data. While Ozfırat (2014) integrated FAHP with FMEA, Verma and Chaudhri (2014) used FRA to evaluate the risk levels associated with identified hazard factors weighted by FAHP. Mahdevari et al. (2014) proposed a FTOPSIS based approach to assess the risks associated with human health in order to manage control measures and support decision- making in underground coal mines in Iran. 86 hazards were investigated and classified under the categories of geo-mechanical, geochemical, electrical, mechanical, chemical, environmental, personal, social, cultural, and managerial risks. After applying the FTOPSIS model, 12 groups with different risks were obtained. Control measures for each group were taken into consideration. In a recent study by Samantra et al. (2017a), 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 measuring parameters were considered as a consequence of exposure,

Table 1
Comparison of the previous studies for OHS risk assessment in mining.

Study	Objective	Application area	Method(s) used	Approach used
Gul and Ak (2018)	Propose a outline for OHS risk assessment in mining industry with comparison	Underground copper and zinc mine	PFAHP, FTOPSIS, Circumcenter of Centroids	Used PFAHP to weight risk parameters and FTOPSIS and Circumcenter of Centroids to rank hazards
Amirshenava and Osanloo (2018)	Mine closure risk assessment using a three-dimensional risk matrix AHP, TOPSIS, PROMETHEE	Iron ore mine	AHP, TOPSIS, PROMETHEE	Used AHP to weight risk parameters and TOPSIS, PROMETHEE to select optimal post-mining land use
Wang et al. (2016)	Use of nonlinear FAHP in safety evaluation of coal mine	Underground coal mine	FAHP, LFPP	Used FAHP to calculate and rank risk factors which involves different specific group and individual criteria and LFPP to analyze the data
Samantra et al. (2017a)	Analysis of hazards and their related risks in an Indian mine	Underground coal mine	Fuzzy aggregation rules	Used fuzzy sets-based rules for categorizing health hazards into different risk levels
Mahdevari et al. (2014)	Investigate risks associated with OHS in underground coal mines	Underground coal mine	FTOPSIS	Used FTOPSIS method for arranging hazards in the mines in Iran
Özfırat (2014)	Integration of FMEA and FAHP for risk assessment of a Turkish underground coal mine	Underground coal mine	FAHP, FMEA	Used FAHP for prioritization of hazards with respect to three parameters of FMEA
Verma and Chaudhri (2014)	Propose a robust hybrid risk assessment approach for mining industry	Mine (Branch not specified)	FAHP, FRA	Used FRA to evaluate the risk levels and FAHP to obtain priority weights for the hazard factors
Petrovic et al. (2014)	Perform a risk analysis in Serbian coal mine industry	Underground coal mine	Fuzzy sets, FMEA	Used fuzzy sets to analyze parameters of FMEA as linguistic variables
Badri et al. (2013)	Contribute to risk management in mining projects	Underground gold mine	AHP	Used AHP for prioritization of hazards throughout goldmines in Quebec, Canada
Lang and Fu-Bao (2010)	Propose a hazard evaluation for combustion of coal in underground mining	Underground coal mine	AHP	Used AHP for classification of indicators of coal spontaneous combustion hazard
Current study	OHS risk assessment of an underground copper and zinc mine	Underground copper and zinc mine	PFVIKOR	Used PFVIKOR to prioritize hazards

Abbreviations - PFAHP: Pythagorean fuzzy analytic hierarchy process; FTOPSIS: Fuzzy technique for order preference by similarity to ideal solution; AHP: Analytic hierarchy process; TOPSIS: Technique for order preference by similarity to ideal solution; PROMETHEE: Preference ranking organization method for enrichment of evaluations; FAHP: Fuzzy analytic hierarchy process; LFPP: Logarithmic fuzzy preference programming; FRA: Fuzzy reasoning approach.

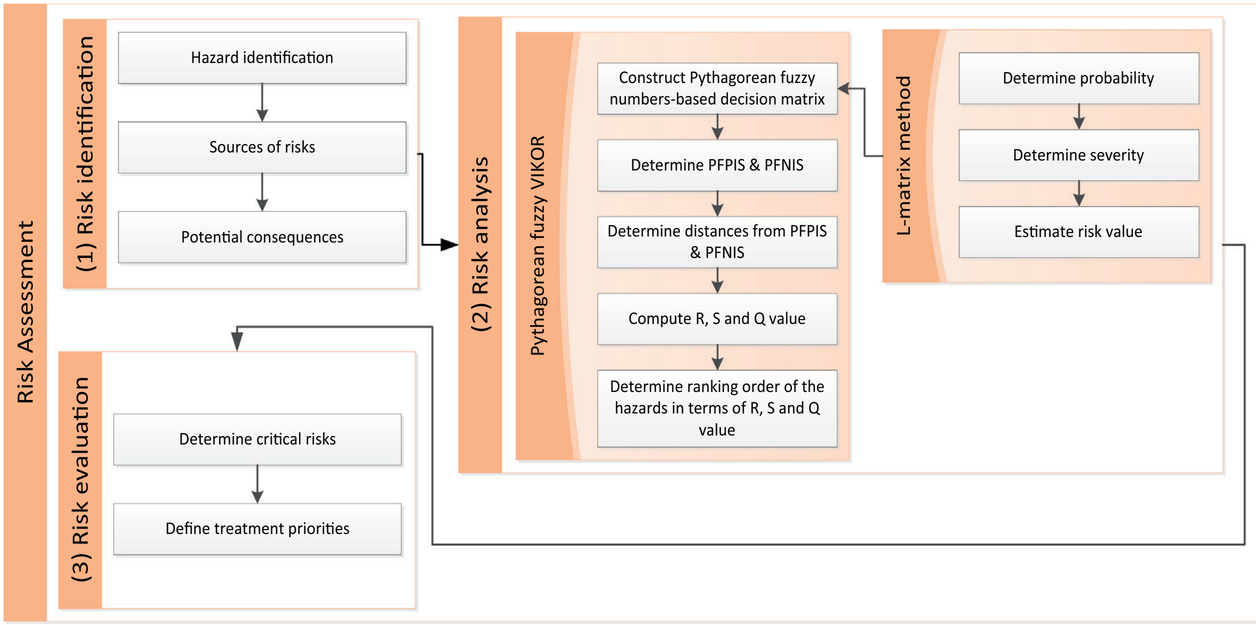


Fig. 1. The flowchart of the proposed fuzzy-based approach for risk assessment.

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. 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. The proposed model was applied for assessing the risk level of a conveyor belt elements failure, which is used for severe conditions in a coal mine.

From an overview of the previous studies, contributions of the current study are triplet: (1) A new OHS risk assessment approach based on PFVIKOR is applied for the assessment of occupational risks in an underground copper and zinc mine. Utilizing Pythagorean fuzzy sets appropriately managed the ambiguity and unpredictability of the OHS expert realization during the risk assessment process. (2) It is the first time in the literature. None of the above-mentioned studies has assigned a priority weights for the experts. In this study, OHS experts' priority weights are assigned in accordance with years of experience in mining domain in the OHS risk assessment process is taken into consideration. (3) A sensitivity analysis is attached to the outline of the study. Moreover, a risk evaluation that includes suggested preventive action plans is provided.

3. Material and methods

This section gives the procedural details of suggested methods and approach. In the first and second sub-sections, L-matrix and the PFVIKOR methods are provided, respectively. At the end, a brief summary of the proposed fuzzy-based risk model is showed.

3.1. L-matrix method

The L-matrix method, in other words *5 × 5 risk matrix*, is the simplest and systematic approach that is broadly used in OHS risk assessment. Probability and severity are two parameters of method that incorporate measuring and categorization of risks on an informed judgment basis (Amirshenava & Osanloo, 2018; Ceylan & Bashelvaci, 2011; Gul, 2018a, 2018b; Gul & Ak, 2018; Gul & Guneri, 2016; Onder et al., 2011; Samantra, Datta, & Mahapatra, 2017b; Yazdi, 2018a). Risk value can be easily obtained by multiplying probability and severity. It is important to define consequences properly with respect to obtained risk score.

3.2. Pythagorean fuzzy VIKOR

Firstly, some preliminaries of Pythagorean fuzzy sets are reviewed. Then, the algorithm of PFVIKOR method is presented in detail. Pythagorean fuzzy sets were first proposed by Yager (2014) and have been used by many researchers in different fields to address uncertainty like

Table 2
Details about experts' titles and years of experience.

Mine DM	Title	Years of experience
Expert-1	Mine planning engineer	12
Expert-2	Geological engineer	24
Expert-3	OHS expert	22
Expert-4	Manager of underground mining operations	18
Expert-5	Occupational physician	7
Expert-6	Drilling and blasting engineer	19
Expert-7	Rock mechanic engineer	11
Expert-8	Chemical safety expert	10

Table 3
Hazards emerged in the explosive storage area.

Hazard code	Hazard description	Who Effected
PN1	Explosion	All persons in the location, Gas danger, Pressure effect, Seismic effects, Spiritual effects, Damage to vehicles
PN2	Vehicle accident	All persons in the location, Damage to vehicles
PN3	Fire	All persons in the location, Damage to vehicles
PN4	Dropping of the explosives from the vehicle	All persons in the location
PN5	Electrical short circuit in the equipment	All persons in the location
PN6	Sabotage	All persons in the location
PN7	Stolen explosive material	All persons in the location
PN8	Static electricity	All persons in the location
PN9	Stroke of lightning	All persons in the location

Table 4
Seven-point Pythagorean fuzzy linguistic scale for assessing hazards with respect to L-matrix parameters (Cui et al., 2018).

Linguistic expression	Corresponding Pythagorean fuzzy number (u,v)
Very low (VL)	(0.15,0.85)
Low (L)	(0.25,0.75)
Moderately low (ML)	(0.35,0.65)
Medium (M)	(0.50,0.45)
Moderately high (MH)	(0.65,0.35)
High (H)	(0.75,0.25)
Very high (VH)	(0.85,0.15)

intuitionistic fuzzy sets. Both sets can be expressed in terms of membership function, non-membership function and hesitancy degree. However, in some cases intuitionistic fuzzy sets fail to fulfill the condition when there are times the degrees of membership and non-membership are bigger than 1. Obviously, they are unable to capture the situation. As a result, Yager (2014) developed Pythagorean fuzzy sets. Pythagorean fuzzy sets seem more powerful and flexible to solve problems involving uncertainty (Gul, 2018b; Gul & Ak, 2018; Ilbahar, Karasan, Cebi, & Kahraman, 2018; Karasan, Ilbahar, Cebi, & Kahraman, 2018; Mohd & Abdullah, 2017).

In Pythagorean fuzzy sets, the sum of squares cannot exceed 1 while the sum of membership and non-membership degrees can (Gul, 2018b; Gul & Ak, 2018; Ilbahar et al., 2018; Karasan et al., 2018; Zeng, Chen, & Li, 2016; Zhang & Xu, 2014). This situation is explained in Definition (1).

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

$$P = \{\langle x, P(\mu_P(x), v_P(x))\rangle | x \in X\} \tag{1}$$

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

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

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

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

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

Table 6
Aggregated Pythagorean fuzzy decision matrix.

Hazards	Probability	Severity
PN1	(0.150,0.850)	(0.850,0.150)
PN2	(0.216,0.789)	(0.793,0.208)
PN3	(0.165,0.837)	(0.850,0.150)
PN4	(0.150,0.850)	(0.797,0.204)
PN5	(0.165,0.837)	(0.695,0.306)
PN6	(0.193,0.813)	(0.755,0.248)
PN7	(0.170,0.833)	(0.740,0.260)
PN8	(0.205,0.800)	(0.809,0.192)
PN9	(0.150,0.850)	(0.850,0.150)

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

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

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

Definition 3. Let $\beta_1 = P(\mu_{\beta_1}, v_{\beta_1})$ and $\beta_2 = P(\mu_{\beta_2}, v_{\beta_2})$ be two Pythagorean fuzzy numbers, a nature quasi-ordering on the Pythagorean fuzzy numbers is defined as follows (Zhang & Xu, 2014):

$\beta_1 \ge \beta_2$ if and only if $\mu_{\beta_1} \ge \mu_{\beta_2}$ and $v_{\beta_1} \le v_{\beta_2}$

To compare magnitude of two Pythagorean fuzzy numbers, a score function is developed by (Zhang & Xu, 2014) as follows:

$$s(\beta_1) = \left(\mu_{\beta_1}\right)^2 - \left(v_{\beta_1}\right)^2 \tag{7}$$

Definition 4. Depending on the proposed score functions of Pythagorean fuzzy numbers as demonstrated above, the following laws are defined to compare two Pythagorean fuzzy numbers (Zhang & Xu, 2014):

i) If $s(\beta_1) < s(\beta_2)$, then $\beta_1 \prec \beta_2$
ii) If $s(\beta_1) > s(\beta_2)$, then $\beta_1 \succ \beta_2$
iii) If $s(\beta_1) = s(\beta_2)$, then $\beta_1 \sim \beta_2$

The OHS risk assessment problem in this paper has t OHS experts E_m $(m = 1,2,\ldots,t)$, f hazards H_a $(a = 1,2,\ldots,f)$, and s risk parameters RP_z $(z = 1,2,\ldots,s)$. Each OHS expert E_m has an importance weight $(w_m > 0$

Table 5
Linguistic assessed information of the hazards regarding *Explosive transport.*

Hazard code	Probability								Severity							
	Exp-1	Exp-2	Exp-3	Exp-4	Exp-5	Exp-6	Exp-7	Exp-8	Exp-1	Exp-2	Exp-3	Exp-4	Exp-5	Exp-6	Exp-7	Exp-8
PN1	VL	VL	VL	VL	VL	VL	VL	VL	VH	VH	VH	VH	VH	VH	VH	VH
PN2	L	VL	L	VL	L	L	VL	L	H	VH	H	H	VH	H	VH	H
PN3	VL	VL	VL	VL	VL	VL	L	VL	VH	VH	VH	VH	VH	VH	VH	VH
PN4	VL	VL	VL	VL	VL	VL	VL	VL	VH	VH	H	H	H	H	VH	H
PN5	VL	VL	VL	L	VL	VL	VL	VL	MH	H	MH	H	MH	MH	MH	H
PN6	VL	L	VL	VL	L	VL	L	VL	H	MH	VH	MH	H	H	MH	VH
PN7	VL	L	VL	VL	VL	VL	VL	VL	MH	H	H	H	H	H	H	H
PN8	VL	VL	L	VL	L	VL	L	L	H	VH	H	VH	H	VH	H	VH
PN9	VL	VL	VL	VL	VL	VL	VL	VL	VH	VH	VH	VH	VH	VH	VH	VH

Note: “Exp” refers to “Expert”

Table 7
S, R, and Q values and ranking orders for each hazard related to *Explosive transport*.

Hazard	S_a value	Ranking	R_a value	Ranking	Q_a value	Ranking
PN1	0.400	4	0.400	5	0.389	4
PN2	0.235	1	0.235	2	0.076	2
PN3	0.315	3	0.315	3	0.227	3
PN4	0.619	6	0.400	5	0.549	6
PN5	0.915	8	0.600	7	1.000	8
PN6	0.536	5	0.383	4	0.469	5
PN7	0.726	7	0.438	6	0.673	7
PN8	0.245	2	0.170	1	0.007	1
PN9	0.400	4	0.400	5	0.389	4

and $\sum_{m=1}^{t} w_m = 1$). Based on the given definitions and notations above, the procedural steps of PFVIKOR are detailed as follows:

Step 1. The first step is related to the construction of a Pythagorean fuzzy decision matrix considering OHS experts' opinions. In the OHS risk assessment process, each expert's opinion is merged into a group consensus to construct the Pythagorean fuzzy decision matrix. Let $\tilde{r}^{k}_{az} = (\mu^k_{az}, v^k_{az})$ be the Pythagorean fuzzy values provided by E_m on the assessment of H_a in relation to RP_z. Hereafter, the Pythagorean fuzzy ratings of hazards ($\tilde{r}^{k}_{az}$) with respect to each risk parameter are calculated by using a Pythagorean fuzzy weighted averaging (PFWA) operator as in Cui, You, Shi, and Liu (2018).

$$\tilde{r}_{az} = \mathrm{PFWA}\left(\tilde{r}^1_{az}, \tilde{r}^2_{az}, \ldots, \tilde{r}^t_{az}\right) = \oplus^t_{m=1} \lambda_m \tilde{r}^m_{az} = \left(\sqrt{1-\prod_{m=1}^{t}\left(1-\left(\mu^m_{az}\right)^2\right)^{w_m}}, \prod_{m=1}^{t}\left(v^m_{az}\right)^{w_m}\right) \quad a = 1, 2, \ldots, f, z = 1, 2, \ldots, s \tag{8}$$

After these calculations, the problem can be demonstrated in a matrix form as follows:

$$\tilde{R} = \begin{bmatrix} \tilde{r}_{11} & \cdots & \tilde{r}_{1s} \\ \vdots & \ddots & \vdots \\ \tilde{r}_{f1} & \cdots & \tilde{r}_{fs} \end{bmatrix} \tag{9}$$

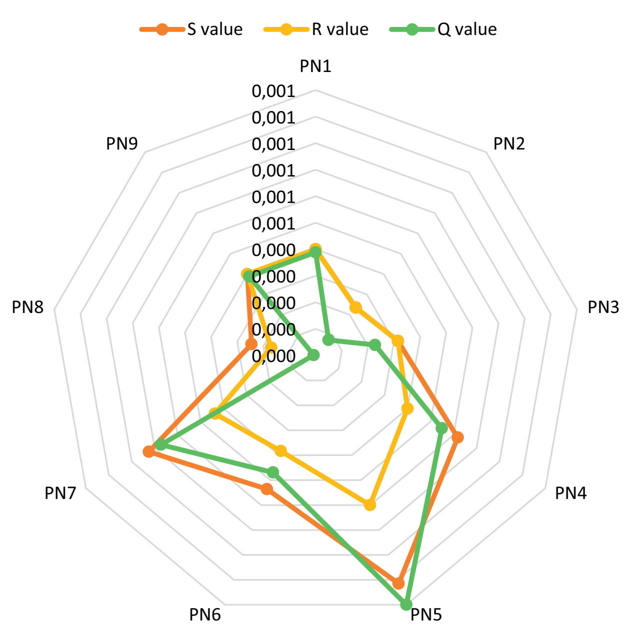


Fig. 2. VIKOR-specific values for *Explosive transport*.

where $\tilde{r}_{az} = (\mu_{az}, v_{az})$ is an element of the aggregated Pythagorean fuzzy decision matrix $\tilde{R}$.

Step 2. The second step is regarding the determination of Pythagorean fuzzy positive ideal solution (PFPIS) $\tilde{p}^*_z = (\mu^*_z, v^*_z)$ and Pythagorean fuzzy negative ideal solution (PFNIS) $\tilde{p}^-_z = (\mu^-_z, v^-_z)$.

$$\tilde{p}^*_z = \begin{cases} \max\limits_a \tilde{r}_{az} \; \textit{for benefit criteria} \\ \min\limits_a \tilde{r}_{az} \; \textit{for cost criteria} \end{cases} \quad z = 1, 2, \ldots, s \tag{10}$$

$$\tilde{p}^-_z = \begin{cases} \min\limits_a \tilde{r}_{az} \; \textit{for benefit criteria} \\ \max\limits_a \tilde{r}_{az} \; \textit{for cost criteria} \end{cases} \quad z = 1, 2, \ldots, s \tag{11}$$

Step 3. The third step is about the calculation of VIKOR-specific S_a and R_a values as formulated with the aid of generalized Pythagorean fuzzy ordered weighted standardized distance operator (GPFOWSD) in the following (Cui et al., 2018):

$$S_a = GPFOWSD\left(\langle \tilde{p}^*_1, \tilde{p}^-_1, \tilde{r}_{a1}\rangle, \ldots, \langle \tilde{p}^*_1, \tilde{p}^-_1, \tilde{r}_{as}\rangle\right) = \left(\sum_{m=1}^{s} w_m \overline{d}^{\lambda}_m\right)^{1/\lambda}, a = 1, 2, \ldots, f \tag{12}$$

$$R_a = \left(\max_m\left(w_m \overline{d}^{\lambda}_m\right)\right)^{1/\lambda}, a = 1, 2, \ldots, f \tag{13}$$

where w_m are the ordered weights of criteria (risk parameters) demonstrating the relative importance of their ordered positions.

Step 4. This step concerns with the computation of the third of the three VIKOR-specific indexes "$Q_a$value". Q_a value is calculated as follows:

$$Q_a = v\frac{S_a - S^*}{S^- - S^*} + (1-v)\frac{R_a - R^*}{R^- - R^*} \quad a = 1, 2, \ldots, f \tag{14}$$

where $S^* = \min\limits_a S_a, S^- = \max\limits_a S_a, R^* = \min\limits_a R_a, R^- = \max\limits_a R_a$ v is a weight of the maximum group utility, whereas (1-v) is the weight of individual regret. In this paper, v is considered as 0.5.

Step 5. This step gives the ranking of the hazards in terms of S_a, R_a and Q_a values in increasing order.

Step 6. The last step is to propose a compromise solution. As a compromise solution the alternative ($A^{(1)}$) which was the best ranked by the measure Q_a was proposed if the conditions in Awasthi and Kannan (2016) were satisfied.

3.3. Proposed fuzzy-based approach for mine risk assessment

The flowchart of the proposed fuzzy-based risk model is shown in Fig. 1. The process consists of three steps. Risk identification is in the first step. The second step is about risk analysis. In this step, the magnitude of risk is calculated via PFVIKOR considering risk parameters of a L-

Table 8
Cases and corresponding weight vectors.

Parameters	Current case	Case-1: weight vector of Yazdi (2018b)	Case-2: weight vector of Gul and Guneri (2016)	Case-3	Case-4
Probability	0.400	0.416	0.361	0.500	0.600
Severity	0.600	0.584	0.639	0.500	0.400

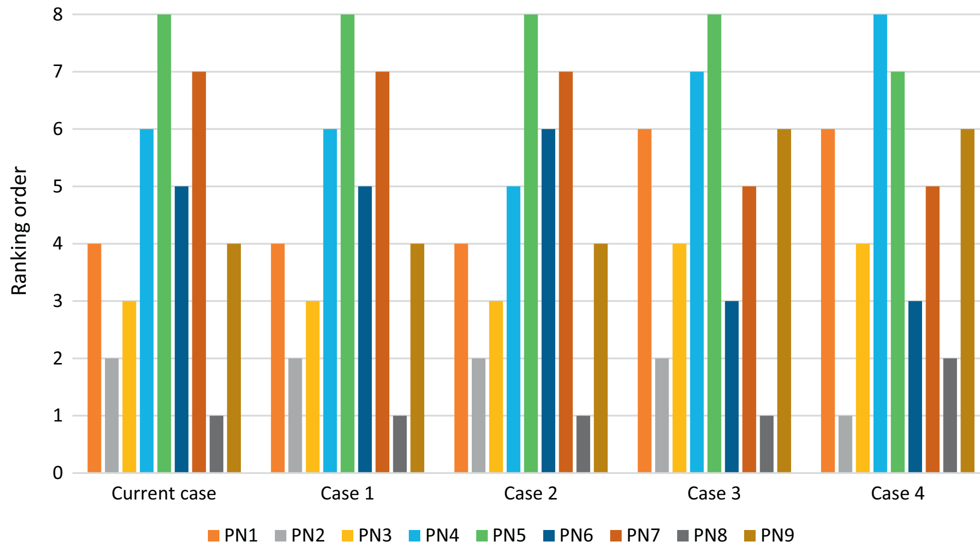


Fig. 3. Results of the sensitivity analysis.

matrix method (probability and severity) and accordingly the risk priority is determined. At the end, results of risk analysis are evaluated to point out unacceptable risks and suggest precautions.

4. Application of the proposed approach

4.1. Risk identification

In order to indicate the applicability of the above-mentioned proposed approach, a case study was carried out in an underground copper and zinc mine in Turkey. In the current study, eight experts participated in rating and analyzing occupational hazard risks in relation to the mine. In Table 2, the gathered detailed information about the expert team and corresponding working experience is shown. Different importance (priority weight) is given for each expert in analyzing risk assessment data. The identities of the experts are not revealed here to maintain anonymity. Therefore, it has denoted them as Expert-1, Expert-2, Expert-3, Expert-4, Expert-5, Expert-6, Expert-7, and Expert-8. The priority weights of experts are ranked using the methodology that considers the job experience in Kabir, Yazdi, Aizpurua, and Papadopoulos (2018) and Yazdi (2018b). If the years of experience are more than 30 years, a score of 5 is assigned. When the classifications are 20–29 years, 10–19 years, 6–9 years, and ≤5 years, the scores are 4, 3, 2, and 1, respectively (Kabir et al., 2018; Yazdi, 2018a). The weights are calculated as follows: $3/25 = 0.12$, $4/25 = 0.16$, $4/25 = 0.16$, $3/25 = 0.12$, $2/25 = 0.08$, $3/25 = 0.12$, $3/25 = 0.12$, and $3/25 = 0.12$.

333 different hazards that are influencing the mine's stakeholders were determined in the observed mine company. The hazard list is set out in Appendix A. The summarized and coded hazards emerged in 38 different activity areas of the mine. As an example, hazards in the explosive storage activity is set out in Table 3.

4.2. Risk analysis

The next step in the proposed fuzzy-based risk model is risk analysis. Risk analysis using the proposed PFVIKOR-based approach includes two main stages. First stage concerned with the weight assignment for probability and severity of the L-matrix method. The weights of probability and severity parameters are given by the expert group as $W = (0.40, 0.60)$, respectively. In the second stage, by using these risk parameters' weights, and the evaluations of hazards with respect to each risk parameter, the PFVIKOR was applied. In the paper, the evaluations of the experts in linguistic expressions for the risk parameters with respect to 333 different hazards were first obtained for each activity area. Due to space limitation, calculations with details were not given for each activity area. Instead, analysis results of, for example, the activity "*Explosive transport*" were given in the details instead.

The expert group evaluated nine hazards regarding "*Explosive transport*" using linguistic expressions and corresponding Pythagorean fuzzy numbers as shown in Table 4. At the end of this evaluation, the linguistic assessed information of the hazards and Pythagorean fuzzy decision matrix utilizing Eq. (8) is constructed as in Tables 5 and 6.

A small example that explains how the values in Table 6 are obtained is as follows: Experts assess the hazard "PN1" with respect to probability parameter by giving the linguistic terms of (VL, VL, VL, VL, VL, VL, VL, VL). According to the scale in Table 4, VL is corresponded to the Pythagorean fuzzy number of (0.15,0.85). The Pythagorean fuzzy rating of PN1 with respect to probability parameter is calculated by utilizing Eq. (8) as follows:

$$\tilde{r}_{11} = PFWA\left(\tilde{r}^1_{11}, \tilde{r}^2_{11}, \ldots, \tilde{r}^8_{11}\right) = \oplus^8_{m=1}\lambda_m \tilde{r}^m_{11}$$
$$= \left(\sqrt{1-\prod_{m=1}^{8}\left(1-\left(\mu^8_{11}\right)^2\right)^{w_m}}, \prod_{m=1}^{8}\left(v^8_{11}\right)^{w_m}\right), (a = 1, 2, \ldots, 9, z = 1, 2)$$

Here, the weights of eight experts $w_m = (0.12, 0.16, 0.16, 0.12, 0.08, 0.12, 0.12, 0.12)$. First, the degree of membership of Pythagorean fuzzy rating of PN1 with respect to probability parameter is calculated. Secondly, the degree of non-membership is computed.

Table 9
Correlation coefficients of four cases in sensitivity analysis.

	Current case	Case-1	Case-2	Case-3	Case-4
Current case	1.000	–	–	–	–
Case-1	0.997	1.000	–	–	–
Case-2	0.986	0.971	1.000	–	–
Case-3	0.880	0.912	0.789	1.000	–
Case-4	0.748	0.795	0.630	0.969	1.000

Table 10
Q values for each hazard in terms of v value change.

Hazard	$v = 0$	$v = 0.1$	$v = 0.2$	$v = 0.3$	$v = 0.4$	$v = 0.5$	$v = 0.6$	$v = 0.7$	$v = 0.8$	$v = 0.9$	$v = 1$
PN1	0.535	0.506	0.476	0.447	0.418	0.389	0.359	0.330	0.301	0.271	0.242
PN2	0.152	0.137	0.122	0.106	0.091	0.076	0.061	0.046	0.030	0.015	0.000
PN3	0.338	0.316	0.294	0.272	0.249	0.227	0.205	0.183	0.161	0.139	0.117
PN4	0.535	0.538	0.541	0.544	0.546	0.549	0.552	0.555	0.558	0.561	0.564
PN5	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
PN6	0.496	0.491	0.485	0.480	0.475	0.469	0.464	0.459	0.453	0.448	0.442
PN7	0.624	0.634	0.644	0.653	0.663	0.673	0.682	0.692	0.702	0.712	0.721
PN8	0.000	0.001	0.003	0.004	0.006	0.007	0.009	0.010	0.012	0.013	0.014
PN9	0.535	0.506	0.476	0.447	0.418	0.389	0.359	0.330	0.301	0.271	0.242

$$\mu_{11} = \sqrt{\left(1-\left(1-0.15^2\right)^{0.12*}\left(1-0.15^2\right)^{0.16*}\left(1-0.15^2\right)^{0.16*}\left(1-0.15^2\right)^{0.12*}\left(1-0.15^2\right)^{0.08*}\left(1-0.15^2\right)^{0.12*}\left(1-0.15^2\right)^{0.12*}\left(1-0.15^2\right)^{0.12}\right)} = 0.150$$
$$v_{11} = 0.85^{0.12*}0.85^{0.16*}0.85^{0.16*}0.85^{0.12*}0.85^{0.08*}0.85^{0.12*}0.85^{0.12*}0.85^{0.12} = 0.850$$

Then, using Eqs. (10–11), PFPIS and PFNIS values are determined. The obtained results are as follows:

$\tilde{p}_z^* = \{(0.216, 0.789), (0.850, 0.150)\}$

$\tilde{p}_z^- = \{(0.150, 0.850), (0.695, 0.306)\}$

Then, employing Eqs. (12–14), S_a, R_a and Q_a values are determined as shown in Table 7. Like the calculations above, a small example is provided on how the values in Table 7 are obtained. The S_a value of PN1 hazard (S_1) is calculated using Eq. (12) as follows:

$S_1 = GPFOWSD(\langle\tilde{p}_1^*, \tilde{p}_1^-, \tilde{r}_{11}\rangle, \ldots, \langle\tilde{p}_1^*, \tilde{p}_1^-, \tilde{r}_{12}\rangle) = \left(\sum_{m=1}^{2} w_m \overline{d}_m^{\lambda}\right)^{1/\lambda}$. Here, λ is set to 1. Then, the GPFOWD operator is reduced to Pythagorean fuzzy ordered weighted Hamming standardized distance operator (PFOWHSD). The $\overline{d}_1$ represents 1th largest (probability parameter) of the standardized Pythagorean fuzzy distance $d(\tilde{p}_1^*, \tilde{r}_{11})/d(\tilde{p}_1^*, \tilde{p}_1^-)$. $d(\tilde{p}_1^*, \tilde{p}_1^-)$ is computed by $\frac{1}{2} * (|(\mu_{p_1^*})^2 - (\mu_{p_1^-})^2| + |(v_{p_1^*})^2 - (v_{p_1^-})^2| + |(\pi_{p_1^*})^2 - (\pi_{p_1^-})^2|)$. The $d(\tilde{p}_1^*, \tilde{r}_{11})$ and $d(\tilde{p}_1^*, \tilde{p}_1^-)$ are calculated as follows: $1/2 * (|0.216^2 - 0.150^2| + |0.789^2 - 0.850^2| + |0.576^2 - 0.505^2|) = 0.101$, $1/2 * (|0.216^2 - 0.150^2| + |0.789^2 - 0.850^2| + |0.576^2 - 0.505^2|) = 0.101$.

Thus, $\overline{d}_1$ is obtained as $0.101/0.101 = 1$. Similarly, $\overline{d}_2$ is computed as $0/0.239 = 0$. Finally, S_1 is obtained as $0.4*1 + 0.6*0 = 0.400$. Here, the weights of two risk parameters are set to w = (0.40,0.60) for probability and severity, respectively. Following computation of S_1, R_1 is obtained using maximum values of (0.4*1) and (0.6*0) as 0.400. Regarding Q_1 value, it is required to find the values of S^*, S^-, R^*, R^- *and* v. These values are obtained as follows: $S^* = 0.235$, $S^- = 0.915$, $R^* = 0.170$, $R^- = 0.600$ *and* $v = 0.5$. Then, Q_1 is calculated as $0.5 * (0.400 - 0.235)/(0.915 - 0.235) + (1 - 0.5) * (0.400 - 0.170)/(0.600 - 0.170) = 0.389$

Fig. 2 also shows the values of S, R, and Q for the Explosive Transport activity. The minimum values were ranked as being the highest risk, while risks having S, R, and Q values nearest to 1 were ranked as being the lowest risk. Results showed that the most hazardous explosive transport activity in the mine stemmed from PN8, PN2, and PN3.

Results of PFVIKOR including VIKOR-specific values for each hazard in the observed copper and zinc mine are provided in Appendix-B.

4.3. Risk evaluation

Hazards with highest and lowest risk(s) for each activity in the observed mine are determined and potential control measures are suggested within the context of the last step of the risk assessment. For example, in relation to barricade construction case, B10 (referring to the compressed air and other pressure systems) and B5 (describing chemical hazard) represent the risk priority value closest to the ideal solution, which means it has the most serious risk compared to others, and similarly B7 (regarding sound) represents the hazard which has the least risk associated with it. For instance, in order to prevent the whole system against the hazard that has the highest risk score value, these are some of control measures that can be applied to supervise system properly and control hazards and associated risks: appropriate controls and cleaning of miss-fires; providing proper fortification standards; giving an advanced training before works; preferring qualified, certificated and experienced mine operators; planned and regular maintenance of equipment; providing of suitable PPE; design of technical surveillance; filling individual identification number; providing safety barricading procedure; building barricade start-up checklist; building hot work permit form; regulations for ventilation and air conditioned equipment; providing control for rope system; control of hazardous energy with procedure; providing leakage circuit breakers; application of job safety analysis; and preparation for compressed air and pressurized waters. The detailed control measures for each activity area are found in Appendix-C.

Risk assessments are valid for a long time unless there has been a significant change and there is reason to suspect validity. The 6331 OHS law of Turkey indicates that risk assessment must be renewed according to the hazard class. There are three different hazard classes for the workplace: very hazardous, hazardous, and less hazardous. These workplaces should renew their risk assessments in two-year, four-year, and six-year periods, respectively. Since the minimum period is 2 years to renew risk assessment there is a certain requirement for detailed, comprehensive, and effective analysis. Our proposed approach has more benefits over simple L-matrix or FMEA methods. That is, the observed mine authorities have also applied the L-matrix method to categorize the risks into different levels based on crisp risk ratings. To differentiate reliability of the proposed approach, the opinions of authorities were consulted. By the review of the executives, whether or not the ranking was achieved reasonably and realistically was investigated. This can be proved with the use of the Pythagorean fuzzy set-based approach, which is useful mining safety risk assessment consulted when making expert opinions. As follow-up work to the proposed approach, risk categories adapted from Samantra et al. (2017a) are considered in Gul and Ak (2018). In this categorization, a lower PFVIKOR Q value corresponds to a higher risk class. 333 different risks have been categorized under five different risk levels (very high risk, high risk, sustainable risk, possible risk, and no action requiring risk). Following this categorization, a preventive action plan was suggested by mine experts and executives to effectively control different risks placed at different levels (see Appendix C for more details of control

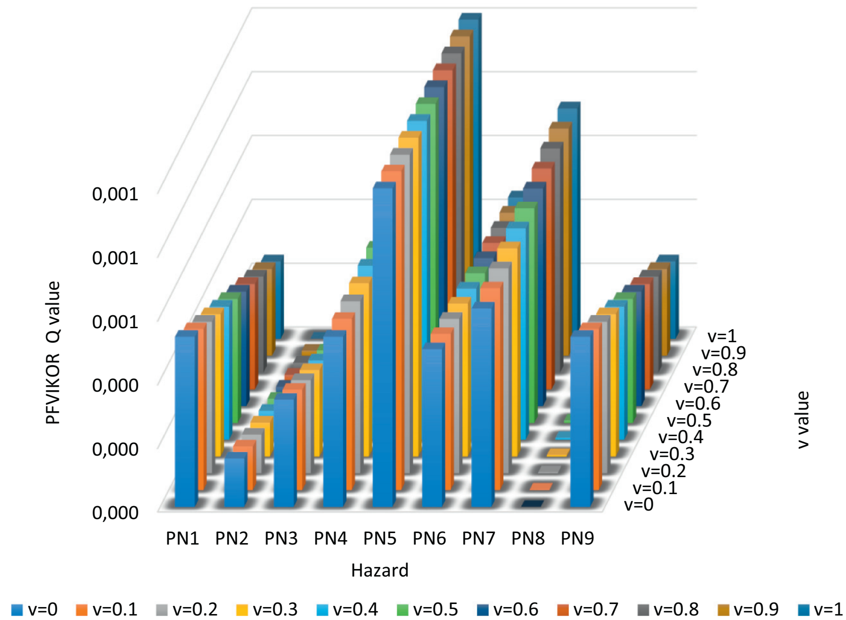


Fig. 4. PFVIKOR Q values according to different *v* values.

measures). Various risks at each level and their corresponding control action plan will enhance successful management and mitigation of risks.

4.4. Sensitivity analysis

A sensitivity analysis was carried out to investigate the validity of the proposed approach. The assigned weights given by the expert group are changed to test the accuracy of the results performance of the suggested PFVIKOR-based model. Four cases are performed during the sensitivity analysis as in Table 8. Thus, changes in the results of the proposed approach can be seen, and this supplies opportunity for the decision maker to determine the priorities and make the risk assessment process more accurate. The results of the sensitivity analysis can be seen from Fig. 3.

From the sensitivity analysis it can be observed that the ranking among the hazards is quite sensitive to the changes. In the first three cases including current case, the first four most serious hazards have not been changed. In case-3, PN8 is in the first place while it has placed in the second place for case-4. On the other hand, the last least important hazard is PN5 except case-4. In addition, a correlation coefficient is applied to measure the correlation between the ranking orders in current case and the other four cases. The correlation coefficients obtained are nearly 99.7%, 98.6%, 88%, and 74.8%, respectively (Table 9). It shows that the relationships between ranking results are very strong. The correlation coefficients between current case and the remaining cases are all positive and high. Analysis results prove that the PFVIKOR-based approach can yield appropriate results and provide suitable information to assist the risk assessment process.

Another sensitivity analysis is applied by varying amount of *v*, which in this study is considered as 0.5. Ten different values are tried from 0.00 to 1.00 increasing by 0.1 to analyze the result of the problem. The results

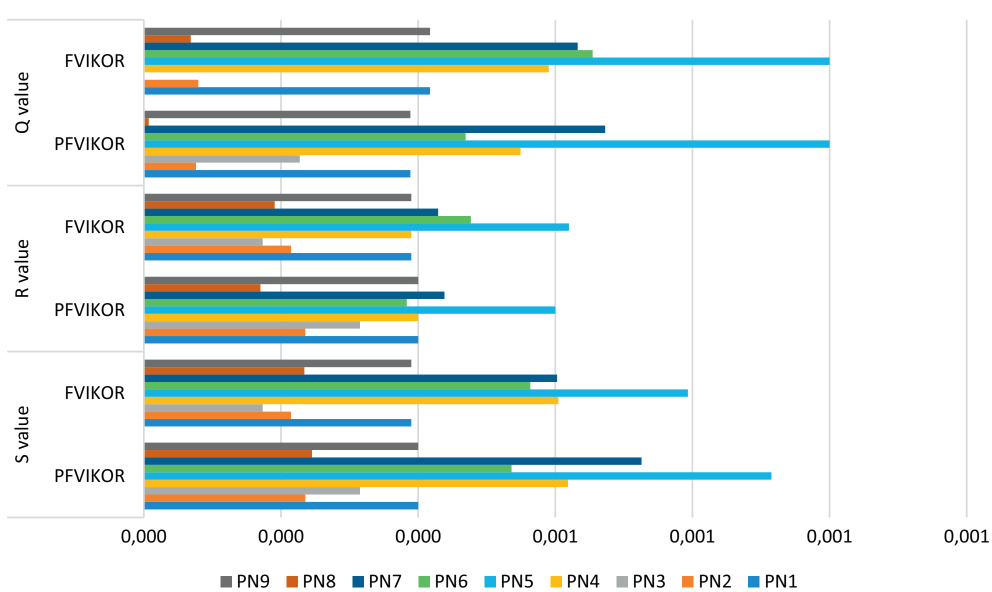


Fig. 5. Comparison of PFVIKOR and FVIKOR results for explosive transport hazards.

of this second sensitivity analysis are presented in Table 10 and graphically in Fig. 4. The PN8 has the best rankings in all case. This type of sensitivity analysis confirms that the results of the ranking orders are consistent. According to the results, this study finds that the proposed approach yields reasonable results and presents suitable outcomes to support stakeholders in OHS decision making.

A comparison is also performed with the results of PFVIKOR with fuzzy VlseKriterijumska Optimizacija I Kompromisno Resenje (FVIKOR) method (Gul, 2018b; Gul, Guneri, & Baskan, 2018; Gul, Guneri, & Nasirli, 2018). It is one of the multi-criteria analysis methods for multi-criteria optimization problems and compromise solutions under fuzzy sets. It ranks alternatives and determines the compromise solution that is the closest to the "ideal" solution. It includes fuzzy assessments of criteria and alternatives. Fig. 4 shows the ranking of hazards by Qi values in *Explosive transport* process. According to Fig. 5, the similar ranking results were obtained from both methods (PFVIKOR and FVIKOR). A Pearson correlation coefficient to measure the correlation between two methods is calculated. It is obtained as 96% & 91% and 95% in terms of S_i, R_i and Q_i values. Therefore, the relationships between ranking results are strong. According to this analysis, it can be proved that the PFVIKOR is consistent with the other methods in risk assessment like FVIKOR.

5. Conclusion

This paper suggests an occupational health and safety risk assessment process including Pythagorean fuzzy sets, the L-matrix method and VIKOR. Occupational hazards and associated risks in a mine company were analyzed as a case study. In this analysis, the opinions and feedback of eight experts of the observed mine were employed to determine the practicability of the suggested approach. By applying PFVIKOR, its aim was prioritizing the hazards that emerged. Since there is a high level of uncertainty and ambiguity involved in the OHS risk assessment data, Pythagorean fuzzy numbers were adapted for evaluating risk score. Results of the study determined risk priorities and corresponding control measures should be included risk assessment process.

Contributions of the study from a methodological and application perspective are as follows:

(1) The first contribution is to propose a novel OHS risk assessment approach in determining the risk rankings. The PFVIKOR, which is a commonly used MCDM method under Pythagorean fuzzy sets, is applied to the assessment of occupational risks for the first time in the literature. Usage of Pythagorean fuzzy sets reflect the uncertainty and vagueness of the OHS expert perceptions during the subjective judgment process.
(2) The second contribution deals with consideration of experts' priority weights in accordance with years of experience in mining domain in the OHS risk assessment process.
(3) Thirdly, assessing the hazards of an underground mining environment by performing a case study in a copper and zinc mine and utilizing PFVIKOR provides a novel area of study and methodology due to the literature gap.
(4) The fourth contribution concerns the inclusion of a sensitivity analysis and a comparison with FVIKOR to the outline of the study. Results of this analysis proved that all cases result in similar ranking orders of hazards. Moreover, a risk evaluation that includes suggested preventive action plans are provided.

The limitation of the study can be observed in the proposed risk assessment approach under fuzzy environment. Only hazards like construction, chemical, physical, electrical, mechanical, and ergonomic risk factors were considered. Hazard risk was subjectively stated in terms of probability and severity parameters of the L-matrix. However, in practice, there are other parameters like sensitivity to maintenance non-execution and sensitivity to PPE non-utilization, very seldom used for occupational risk assessment. The latter risk parameters were not taking into account in this study. A more comprehensive quantitative OHS risk assessment on mine hazards may include these perspectives in future work.

Appendix A. Hazard list

Worksite/Activities	ID	Hazard
Oxygen works	O1	Fire
	O2	Pressurized gas
	O3	Poisonous gas
	O4	Spark formation
	O5	Eye deterioration
Barricade construction	B1	Dent
	B2	Fire
	B3	Fall of scale
	B4	Unexploded hole
	B5	Chemicals
	B6	Ambient temperature
	B7	Sound
	B8	Dust
	B9	Electricity
	B10	Compressed air and other pressure systems
	B11	Moving parts
	B12	Operator competence
Scaling	KA1	Rubber rims and vehicle window
	KA2	Sound
	KA3	Land rock structure
	KA4	Sash or metal protrusions on the wall
	KA5	Operator competence
	KA6	Cubicle stick
Fan assembly	FM1	Determination of fan location: Being not appropriate in terms of ground support
	FM2	Determination of fan location: Unsuitability of drift section
	FM3	Determination of fan location: Water tunnel
	FM4	Nailing bolts to install fan: Do not nail a suitable bolt
	FM5	Nailing bolts to install fan: Do not nail bolts in appropriate pattern
	FM6	Loading and unloading of fans for transport: Suspended fan
	FM7	Loading and unloading of fans for transport: Falling of fan from height
	FM8	Loading and unloading of fans for transport: Wrong bearing element selection
	FM9	Loading and unloading of fans for transport: Lifting equipment
	FM10	Loading and unloading of fans for transport: Authorization
	FM11	Transport of fans: Transporter
	FM12	Transport of fans: Fixing the fan
	FM13	Transport of fans: Inappropriate loading of the fan
	FM14	Assembly and disassembly of fans: Working at height
	FM15	Assembly and disassembly of fans: Load lifting
	FM16	Assembly and disassembly of fans: Suspension
	FM17	Assembly and disassembly of fans: Working at narrow area
	FM18	Assembly and disassembly of fans: Assembly elements
	FM19	Assembly and disassembly of fans: Ventilation
	FM20	Assembly and disassembly of fans: Uncontrolled movement of fan
	FM21	Assembly and disassembly of fans: Hot works
	FM22	Engaging the fan: Diffuser and adapter

(continued on next page)

(*continued*)

Worksite/Activities	ID	Hazard
		selection
	FM23	Engaging the fan: Electricity
	FM24	Engaging the fan: Working at height
	FM25	Engaging the fan: Working at narrow area
	FM26	Periodic maintenance and control of fans: Corrosion
Sputnik	S1	Transport of explosive material
	S2	Preparation of sputnik
	S3	Placement of sputnik in the ore pass
	S4	Ignition
	S5	Post-ignition control
	S6	Blasting in shift
	S7	Compressed air
Installation with remote control	UKY1	Dent
	UKY2	Scaling
	UKY3	Ventilation-Temperature
	UKY4	Unexploded hole
	UKY5	Fall from height
	UKY6	Working alone
	UKY7	Ladle
	UKY8	Ladle
	UKY9	Ladle
	UKY10	Ladle
	UKY11	Ladle
	UKY12	Worksite
Personnel transport with shaft	ŞPT1	Power cut
	ŞPT2	Communication disruption
	ŞPT3	Rope breakage
	ŞPT4	Sudden brake lock on the move
	ŞPT5	Mechanical Problems: Rope release, peeling and breaking at rope connection pins
	ŞPT6	Opening the elevator door on the move and removing the limb out of the elevator
	ŞPT7	Fall of material onto the elevator
	ŞPT8	Obstacles on the movement path
	ŞPT9	Misalignment in the shaft
	ŞPT10	Movement of the elevator while getting on and off
	ŞPT11	Fire in the shaft
	ŞPT12	Loose materials inside the elevator
	ŞPT13	Being of the elevator between two outlets
	ŞPT14	Working at height
Emplacement of steel timbering	ÇİY1	Scaling
	ÇİY2	Hot works
	ÇİY3	Transport
	ÇİY4	Jamming
	ÇİY5	Bucket piece
	ÇİY6	Working at height
	ÇİY7	Bad first aid and medical treatment support
	ÇİY8	Lifting and loading
	ÇİY9	Noise
	ÇİY10	Working environment
	ÇİY11	Ventilation
Mirror drilling	ADE1	Ventilation
	ADE2	Scaling
	ADE3	Compressed air
	ADE4	Pressure water
	ADE5	Electricity
	ADE6	Pressure hydraulic hoses
	ADE7	Fire
	ADE8	Incorrect drill
	ADE9	No authoritative operator
	ADE10	Working alone
	ADE11	Booms of drilling machine
	ADE12	Moving parts of drilling machine
	ADE13	Misfire

(*continued*)

Worksite/Activities	ID	Hazard
Filling the stope	KAD1	Ventilation
	KAD2	Scaling
	KAD3	Compressed air
	KAD4	Pressure hydraulic hoses
	KAD5	Fire
	KAD6	Working at height
	KAD7	Explosive material
	KAD8	Wrong explosive choice
Filling the mirror	ADO1	Ventilation
	ADO2	Scaling
	ADO3	Compressed air
	ADO4	Pressure hydraulic hoses
	ADO5	Fire
	ADO6	Working at height
	ADO7	Explosive
	ADO8	Wrong explosive choice
Continuous Paste Fill	SPF1	Blasting
	SPF2	Barricade construction
	SPF3	Dent
	SPF4	Flush operation
	SPF5	Sensor
	SPF6	Camera
	SPF7	No authoritative operator
	SPF8	Mine type (mineral type)
	SPF9	Amount of cement
Unplanned power cut	PEK1	Paste Fill pipeline clogging
	PEK2	Being stuck in an elevator
	PEK3	Stopping of the pumps
	PEK4	Stopping of compressors
	PEK5	Rescue chamber energy and air cut-off
	PEK6	Cement working equipment
	PEK7	Stopping of the fans
Work under hanging materials	AMÇ1	Fall of electrical material
	AMÇ2	Fall of electrical material
	AMÇ3	Falling of fans
	AMÇ4	Falling of fans
	AMÇ5	Falling of service pipes
	AMÇ6	Falling of service pipes
	AMÇ7	Falling of cranes
Pass through ventilation doors	HKG1	Hitting of ventilation doors to people
	HKG2	Compression of pistons
	HKG3	Blowing of employees working through the doorway by ventilation air
	HKG4	Hitting of vehicles to ventilation doors
	HKG5	Electric shock
Piping to Cubex brand hole	CBS1	Strapping and bumping of the pipe of operator's hand
	CBS2	Crashing of crane boom
	CBS3	Worker's foot pinched and jammed
	CBS4	Falling of pipes into downstairs
	CBS5	Burrs in the pipe
	CBS6	Manual removal of pipes
	CBS7	Contact with grease
	CBS8	Fall of material through the hole
	CBS9	Disconnection of anchor points or chain
	CBS10	Breaking of the platform and breakage of the used wooden wedge
Sheet pipe placement to V30 shaft	SBY1	Fall of material through the hole
	SBY2	Disconnection of anchor points or chain
	SBY3	Breaking of the platform and breakage of the used wooden wedge
	SBY4	Manual removal of pipes
	SBY5	Strapping and bumping of the pipe of operator's hand
	SBY6	Fire
Piston pump cleaning	GPT1	Poisoning
	GPT2	Rotating components
	GPT3	Muscle strain
	GPT4	Waste water
	GPT5	Falling of hanging material
	GPT6	Crane bucket cover crash

(*continued*)

Worksite/Activities	ID	Hazard
	GPT7	Flow of drainage waters
	GPT8	Pressurized water (Service)
	GPT9	Temperature
Explosive transport	PN1	Explosion
	PN2	Vehicle accident
	PN3	Fire
	PN4	Dropping of the explosives from the vehicle
	PN5	Electrical short circuit in the equipment
	PN6	Sabotage
	PN7	Stolen explosive material
	PN8	Static electricity
	PN9	Stroke of lightning
Vehicle and pedestrian traffic	AYT1	Vehicle crashing to the pedestrian
	AYT2	Crash
	AYT3	Road conditions
	AYT4	Falling of hanging materials
	AYT5	Quality of visibility
	AYT6	Rule violation
Material handling	MT1	Manual loading and handling
	MT2	Lifting and transporting by crane
	MT3	Working at height
	MT4	Overload or overflow out
	MT5	Fall and spillage of material from vehicle
	MT6	Vehicle docking or parking
	MT7	Emptying of materials
	MT8	Road conditions
	MT9	Competence
	MT10	Sort order
Opening of clogged drainage	TDA1	Compressed air
	TDA2	Dirty water
	TDA3	Muddy environment
	TDA4	Obtaining materials while digging with wire rope or C bolt hoses
	TDA5	Splitting the pipe
Bringing of sulfurous tallow to the side of concrete plant	BSG1	Fall of the vehicle
	BSG2	Damage to the impermeable layer on the subsoil
	BSG3	Sound
	BSG4	Bogging of vehicle
Explosive storage	PMD1	Spreading of acidic water around
	PMD2	High slope
	PMD3	Contact with acidic water in or around the sulfurous tallow
	PMD4	Vehicle crash
	PMD5	Damper tipping
	PMD6	Spilling of sulfur material on the way of transport
	PMD7	Uncovering working environment
Vehicle fueling and lubrication	AYAY1	Operator competence
	AYAY2	Ventilation
	AYAY3	Chemicals
	AYAY4	Fire
	AYAY5	Sound and noise
	AYAY6	Compressed air and other pressure systems
	AYAY7	Fall of scales
	AYAY8	Electricity
	AYAY9	Moving parts
	AYAY10	Jamming
	AYAY11	Working at height
	AYAY12	Bad first aid and medical treatment support
	AYAY13	Working environment
	AYAY14	Working alone
	AYAY15	Maintenance in different processes
620 Ore pass new ladle usage	YKK1	Fall of materials onto the ladle
	YKK2	Hitting or falling of materials to the operator
	YKK3	Dustiness of the environment
	YKK4	Not working of level detection sensors and traffic light system
	YKK5	Illumination problem
	YKK6	Thermal factors
Dust	TOZ1	Occupational disease
	TOZ2	Quality of visibility

(*continued*)

Worksite/Activities	ID	Hazard
	TOZ3	Breakdown of vehicles
	TOZ4	Dust explosion
Sledging materials/vehicles	KMÇ1	Unsuitable towing vehicles and equipment
	KMÇ2	Competence
	KMÇ3	Planning
	KMÇ4	Loading of materials or vehicles to the sled
	KMÇ5	Crash
	KMÇ6	Rollover
	KMÇ7	Rope breakage
	KMÇ8	Breaking up of vehicle or equipment
	KMÇ9	Road conditions
	KMÇ10	Traffic management
	KMÇ11	Crushing or employee jamming
	KMÇ12	Launch of equipment or supplies
SO2 formation and working in SO2 environment	SO21	SO_2 gas
	SO22	Temperature
	SO23	Quality of visibility
	SO24	Acidic environment
	SO25	SO_2 formation
Placement of reinforcing cage	HYHÇ1	Loading and moving of the reinforcing cage
	HYHÇ2	Improper stacking of the reinforcing cage underground
	HYHÇ3	Loading and moving of the reinforcing cage to the platform
	HYHÇ4	Uneven ground
	HYHÇ5	Unbalanced lifting
	HYHÇ6	Falling of reinforcing cage
	HYHÇ7	Limb compression
	HYHÇ8	Material launch
	HYHÇ9	Improper use of the pistol
	HYHÇ10	Hand tool usage
	HYHÇ11	Burnt materials
	HYHÇ12	Trip and fall
Drilling stope	KATD1	Unexploded explosives
	KATD2	Fall from height
	KATD3	Hand jamming
	KATD4	Electric shock
	KATD5	Hose burst
	KATD6	Penetration of energy line
	KATD7	Damages of rot
Transport of ore and tallow	ACPT1	Misfire
	ACPT2	Fall of scales
	ACPT3	Energy
	ACPT4	Ventilation
	ACPT5	Tire explosion
	ACPT6	Traffic
	ACPT7	Fire
	ACPT8	Bulge materials
	ACPT9	Fall down the stope or ore pass cavity
Shotcrete	SH1	Plug accelerator
	SH2	Hose burst
	SH3	Compressed air and concrete launch
	SH4	Traffic
	SH5	Fall of scales
	SH6	Boom crash
	SH7	Inadequate ventilation
	SH8	Misfire
	SH9	Bulk material
	SH10	Energy
	SH11	Fire
	SH12	Poor quality of visibility
Bolting	BOL1	Heavy load
	BOL2	Road conditions
	BOL3	Fall of scales
	BOL4	Traffic
	BOL5	Misfire
	BOL6	Energy
	BOL7	Ventilation
	BOL8	Hose burst
	BOL9	Boom crash
	BOL10	Fire
Tallow filling	PASD1	Dent

(*continued on next page*)

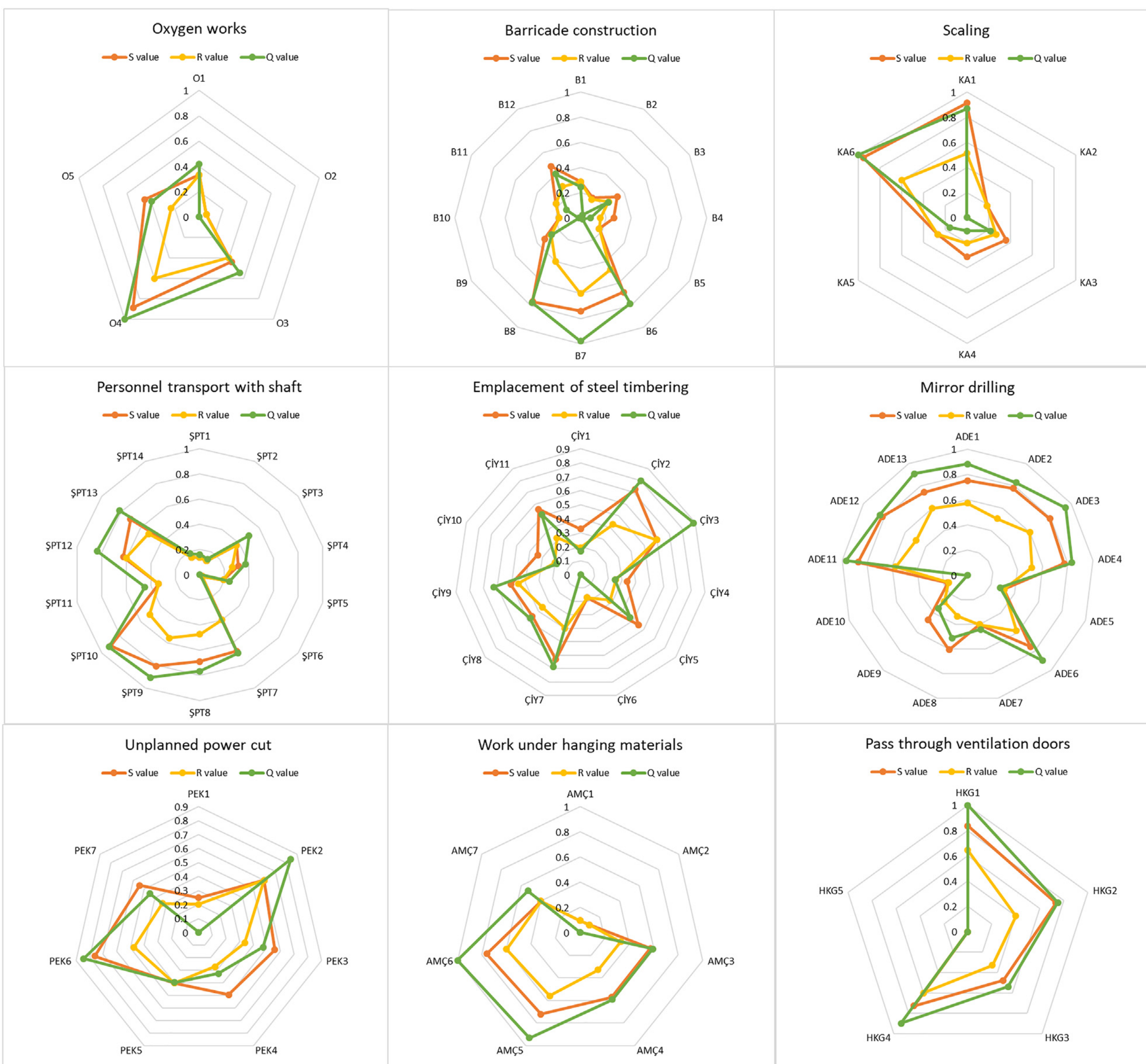
(*continued*)

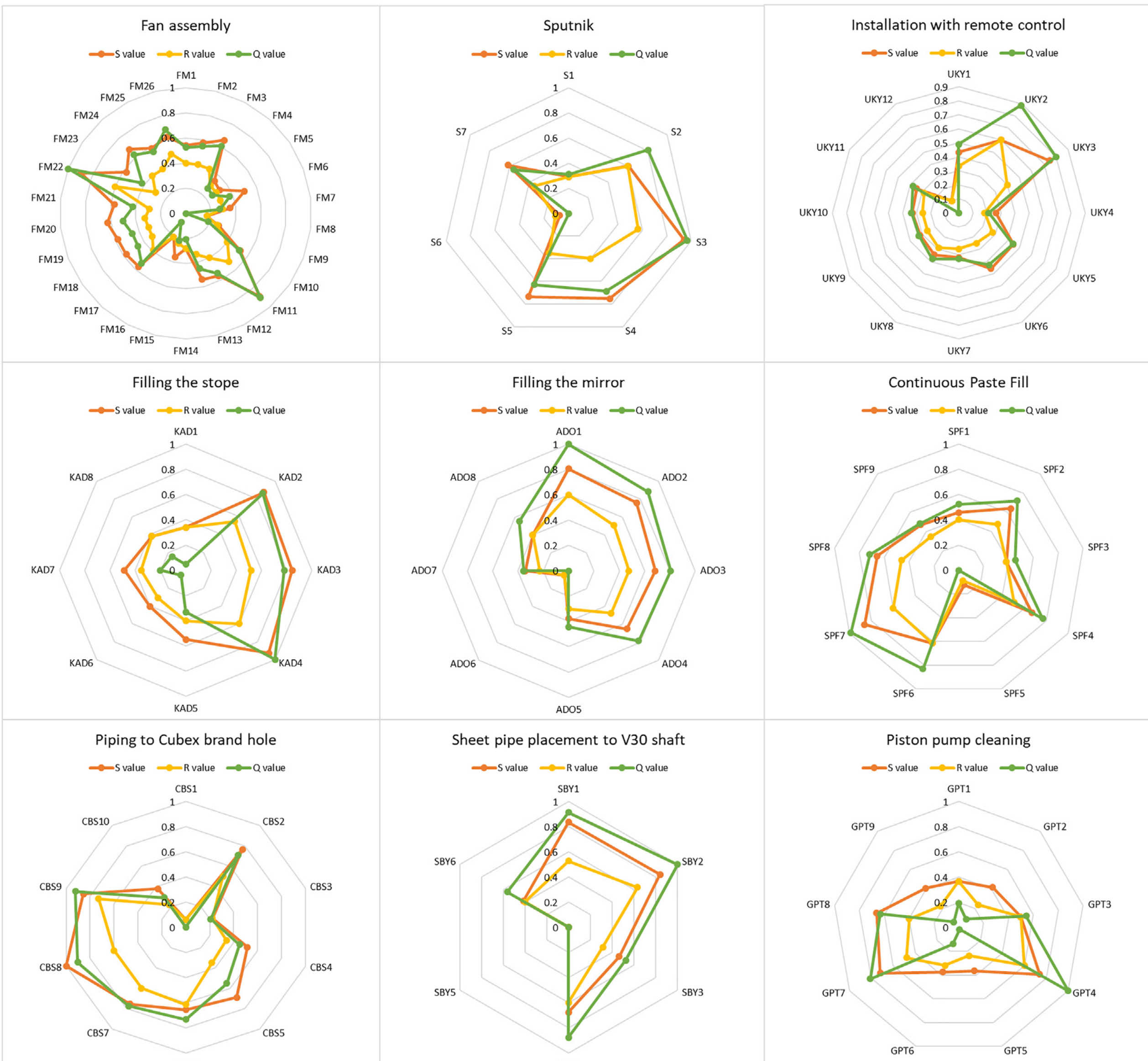
Worksite/Activities	ID	Hazard
	PASD2	Fall down the stope cavity
	PASD3	Fall of scales
	PASD4	Barricade
Cement filling	MACD1	Barricade
	MACD2	Pushing speed
	MACD3	Pressure
	MACD4	Lack of communication
	MACD5	Cutting of air flow
	MACD6	Disconnection of lines
	MACD7	Quality of visibility
	MACD8	Injecting continuous PF
Cement filling assembly line	MDHM1	Loading of the pipes
	MDHM2	Carrying of the pipes

(*continued*)

Worksite/Activities	ID	Hazard
	MDHM3	Compressed air
	MDHM4	Rotating components
	MDHM5	Fall from height
	MDHM6	Falling of the pipes or crashing
	MDHM7	Paste Fill pressure
	MDHM8	Pulling the pipes out of handcuff
	MDHM9	Scaling
Others	TAK1	Explosion of the capsule or explosives
	PAT1	Sudden material unloading
	PG1	Hazardous gases
	PG2	Dust

Appendix B. Results of PFVIKOR for each hazard in the observed copper and zinc mine

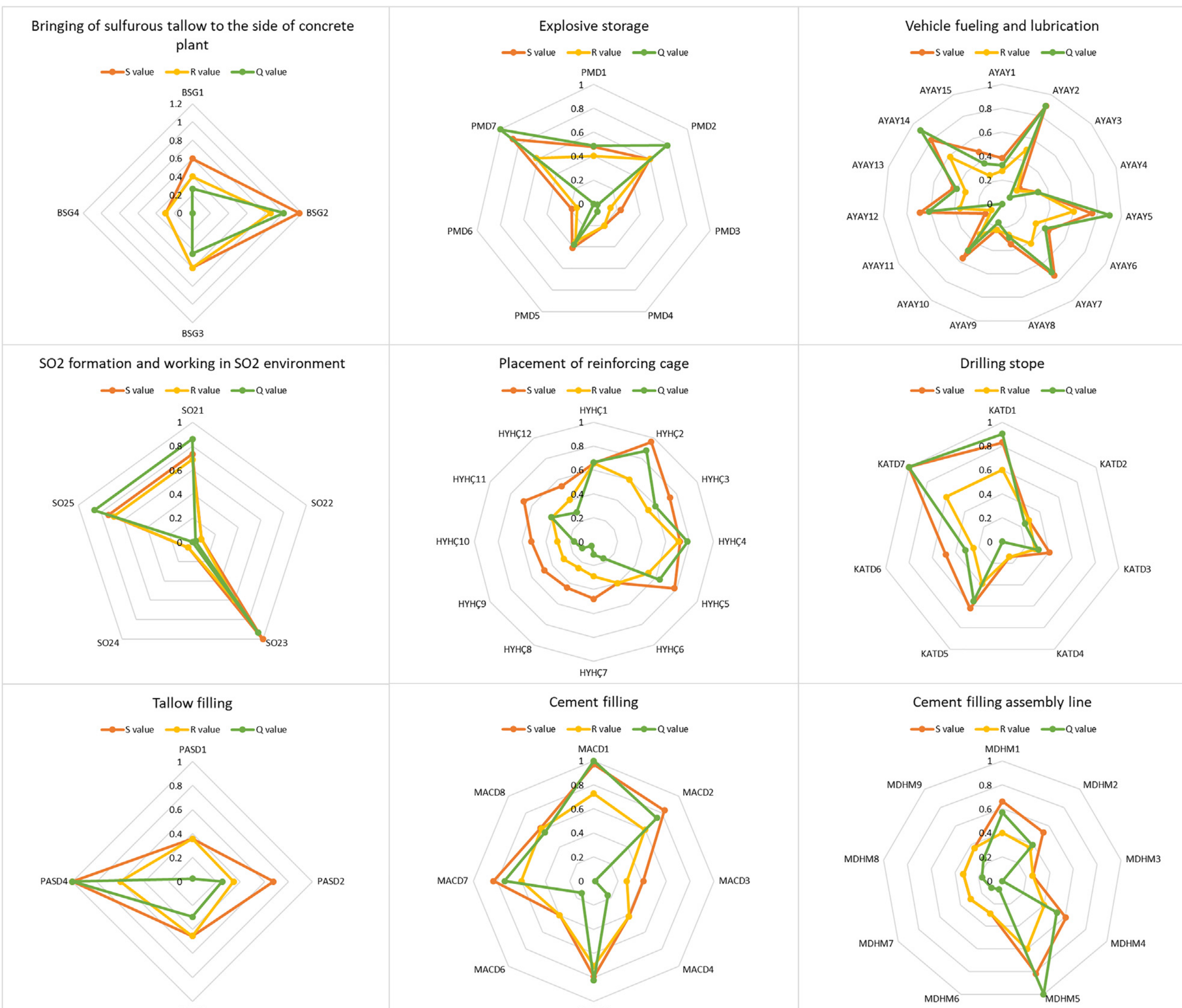



Fan assembly
S value
R value
Q value
FM1
FM2
FM3
FM4
FM5
FM6
FM7
FM8
FM9
FM10
FM11
FM12
FM13
FM14
FM15
FM16
FM17
FM18
FM19
FM20
FM21
FM22
FM23
FM24
FM25
FM26
Sputnik
S value
R value
Q value
S1
S2
S3
S4
S5
S6
S7
Installation with remote control
S value
R value
Q value
UKY1
UKY2
UKY3
UKY4
UKY5
UKY6
UKY7
UKY8
UKY9
UKY10
UKY11
UKY12
Filling the stope
S value
R value
Q value
KAD1
KAD2
KAD3
KAD4
KAD5
KAD6
KAD7
KAD8
Filling the mirror
S value
R value
Q value
ADO1
ADO2
ADO3
ADO4
ADO5
ADO6
ADO7
ADO8
Continuous Paste Fill
S value
R value
Q value
SPF1
SPF2
SPF3
SPF4
SPF5
SPF6
SPF7
SPF8
SPF9
Piping to Cubex brand hole
S value
R value
Q value
CBS1
CBS2
CBS3
CBS4
CBS5
CBS6
CBS7
CBS8
CBS9
CBS10
Sheet pipe placement to V30 shaft
S value
R value
Q value
SBY1
SBY2
SBY3
SBY4
SBY5
SBY6
Piston pump cleaning
S value
R value
Q value
GPT1
GPT2
GPT3
GPT4
GPT5
GPT6
GPT7
GPT8
GPT9

(*continued*).


Vehicle and pedestrian traffic
S value
R value
Q value
AYT1
AYT2
AYT3
AYT4
AYT5
AYT6
Material handling
MT1
MT2
MT3
MT4
MT5
MT6
MT7
MT8
MT9
MT10
Opening of clogged drainage
TDA1
TDA2
TDA3
TDA4
TDA5
New ladle usage
YKK1
YKK2
YKK3
YKK4
YKK5
YKK6
Dust
TOZ1
TOZ2
TOZ3
TOZ4
Sledging materials/vehicles
KMÇ1
KMÇ2
KMÇ3
KMÇ4
KMÇ5
KMÇ6
KMÇ7
KMÇ8
KMÇ9
KMÇ10
KMÇ11
KMÇ12
Transport of ore and tallow
ACPT1
ACPT2
ACPT3
ACPT4
ACPT5
ACPT6
ACPT7
ACPT8
ACPT9
Shotcrete
SH1
SH2
SH3
SH4
SH5
SH6
SH7
SH8
SH9
SH10
SH11
SH12
Bolting
BOL1
BOL2
BOL3
BOL4
BOL5
BOL6
BOL7
BOL8
BOL9
BOL10

(*continued*).


Bringing of sulfurous tallow to the side of concrete plant
S value
R value
Q value
BSG1
BSG2
BSG3
BSG4
Explosive storage
PMD1
PMD2
PMD3
PMD4
PMD5
PMD6
PMD7
Vehicle fueling and lubrication
AYAY1
AYAY2
AYAY3
AYAY4
AYAY5
AYAY6
AYAY7
AYAY8
AYAY9
AYAY10
AYAY11
AYAY12
AYAY13
AYAY14
AYAY15
SO2 formation and working in SO2 environment
SO21
SO22
SO23
SO24
SO25
Placement of reinforcing cage
HYHÇ1
HYHÇ2
HYHÇ3
HYHÇ4
HYHÇ5
HYHÇ6
HYHÇ7
HYHÇ8
HYHÇ9
HYHÇ10
HYHÇ11
HYHÇ12
Drilling stope
KATD1
KATD2
KATD3
KATD4
KATD5
KATD6
KATD7
Tallow filling
PASD1
PASD2
PASD3
PASD4
Cement filling
MACD1
MACD2
MACD3
MACD4
MACD5
MACD6
MACD7
MACD8
Cement filling assembly line
MDHM1
MDHM2
MDHM3
MDHM4
MDHM5
MDHM6
MDHM7
MDHM8
MDHM9

(*continued*).

Appendix C. Control measures

For the oxygen works: general checklists that OHS experts can use to do an inspection of the workplace, preparing initial mine rescue team training and procedures, giving an advanced skills training for mine rescue team, work permit and its form before initiating hot work, partial or temporary closures on lane roads using traffic signs and traffic signals, building rules and instructions covering the operation and maintenance of oxy acetylene shielding, providing of appropriate personal protective equipment (PPE), periodic checks of load and pressure limits with the aims of maximum safety level and optimum performance, preferring qualified, certificated and experienced mine operators, periodic checks of pressure tubes, proper vehicle maintenance and fixing, filling an individual identification number, providing suitable equipment for oxy acetylene sets, providing proper flame safety lamps, periodic control of valves are major control measures and essentials with respect to OHS. *For the barricade construction*: for the barricade construction, appropriate controls and cleaning of miss-fires, providing proper fortification standards, giving an advanced training before works, preferring qualified, certificated and experienced mine operators, planned and regular maintenance of equipment, providing of suitable PPE, design of technical surveillance, filling individual identification number, providing safety barricading procedure, building barricade start-up checklist, building hot work permit form, regulations for ventilation and air conditioned equipment, providing control for rope system, control of hazardous energy with procedure, providing leakage circuit breakers, application of job safety analysis, preparation for compressed air and pressurized waters are necessities to control hazards and associated risks.

For the scaling activity: investigation of the geological structure of the area before scaling, providing and following scaling procedure, providing suitable equipment, scaling in high and low headings, regular check scaling of main access ways, ensuring that the workplace ventilation is operating adequately, arranging specific staff for operation, filling individual identification number, providing spare parts, continuous observation of scaling, providing of suitable PPE, follow-up seismic events, regular and periodic controls of scaling area, ensuring that controlled drilling and blasting practices are control measures. *The Fan assembly activity requires following control measures*: preparing proper procedures for fortification, lifting and suspension, determination of suitable location, providing well-qualified experienced personal, providing appropriate PPE, choosing appropriate transportation vehicles and providing effective vehicle procurement, providing initial work education and prior authorization process, providing air velocity testing devices, building a system for immobilization of equipment and materials during transportation, preparing initial mine rescue team training and procedures, periodically transportation vehicles inspection and examination, follow-up ventilation standards, work permit and its form before initiating hot work, proper locking procedure, providing safety signs and proper procedure for working high up. *Sputnik requires the following control measures*: providing safety zone with signs before blasting by mine control and notification of all participants in the system, providing appropriate PPE and requirement procedure for transporting explosives, providing anthropometric-based ergonomic design of sputnik window, providing warning signs not to use cords in explosion, preferring qualified, certificated and experienced personal, providing a minimum requirement installation list for power structure, providing control checklist for all valves before activities, preparation sputnik for process, follow-up the legislation, controlling all valves before starting of activity, providing night vision camera and mobile falling prevention system, choosing appropriate vehicles, periodic checks of work area. Authorization and advanced education before works, procedure for non-blasting holes, remote distance control system, providing suitable PPE, regulations for ventilation, regular and periodic controls, using specific *check-list are major measures for installation with remote control*. Advanced battery and brake system and periodic maintenance, Speed limit enforcement (3.8 m/s), authorization and advanced education before works, weekly advanced control for whole components of shaft, checklist for battery voltage control panel, control system for rope clamps, follow-up legislation, well and bucket controls, surface topography measurements, providing suitable PPE, signal system for key points, set-up radio and camera communication system, avoiding flammable materials in transportation, providing elevator maintenance system, emergency staircase on shaft are control measures *for personnel transport with shaft activity*. Follow-up and providing barricading procedure, providing proper fortification standards, building hot work permit form, authorization and advanced education before works, providing and follow-up an air pollution system, providing suitable PPE are major control measures *for emplacement of steel timbering*. Providing mine control and multi-channel *radio* communication technology, providing automatic fire suppression system, providing methodical mine rescue fire training, periodic health checks, giving an advanced education and authorization before works, energy insulation and locking procedure, providing drilling and blasting standards, regular and periodic checks, providing suitable PPE are basic control measures *for mirror drilling/filling activities*. *Following-up the legislation and scaling procedure, providing personal escape mask,* regulations for ventilation, using mobile devices and ergonomic equipment, maximize system energy efficiency with proper energy insulation system, providing suitable PPE, regular and periodic controls, giving an advanced education and authorization before works are basic control measures *for filling the stope*. Providing an *explosives management plan and micro seismic monitoring system, pre-work controls, obligation for vocational education, providing rock mechanics testing equipment,* providing proper fortification standards are control measures *for continuous paste fill activity*. Providing backup power lines, natural ventilation gas conversion and radio communication system, mine rescue chamber, set up proper and effective air distribution, availability of opened roof of the elevator from inside, providing clean air outlets, giving an advanced education and authorization before works are control measures for *unplanned power cut*. *For the work under hanging materials activity:* procedure of assembly, regular and periodic controls and maintenance of *rock mechanics, cables, panels* (weekly/monthly/yearly), filling individual identification number, follow-up ventilation and corrosion effect, blasting checks, training of driving to avoid crashes, fortification standards, periodic supervisory checks, pipe &fitting procedure, the checklist for use of crane, adequate number of safety switches. Usage of the isolated cable and earth leakage circuit, grounding system, working under low voltage (24-Volts), grounding of electrical panels properly, usage of safety hazard warning signs, gate transition procedure, energy insulation and locking procedure, the use of double door system and one of them should permanently closed, preference of concave curved doors and transparent window, set-up proper pneumatic system, regular and periodic controls and maintenance (monthly/yearly), providing suitable PPE, filling individual identification number are control measures *for pass through ventilation doors activity*. *For the piping to cubex brand hole activity:* filling individual identification number, selection and use of gloves procedure, occupational hazard analysis periodically, chemical spill procedure, periodic pull test, authorization and advanced education before works are major control measures. Preference of cut resistant gloves, material handling training, filling individual identification number, preference of cut resistant gloves, providing automatic fire suppression system, occupational hazard analysis periodically, authorization and advanced education before works, using specific check-list (oxygen set), periodic pull test, building hot work permit form are proposals for sheet pipe placement to V30 shaft activity. *For the piston pump cleaning activity:* abundant fluid consumption, providing proper ventilation line for pools, improvement on material output, filling individual identification number, providing suitable PPE, providing appropriate energy insulation system, high quality training on climactic conditions, indoor permit form, authorization and advanced education before works, material handling training, preference of suitable dress, regular and periodic controls are basic control measures. Portable fire extinguisher, anti-static work clothes, gloves and products, use fire extinguisher, separate transport of explosives and capsules, follow-up legislation and international *lightning protection* codes and standards, giving an advanced training and authorization before works regular and periodic controls, using specific check-list, filling individual identification number, providing suitable PPE, providing appropriate energy insulation system *for explosive transport activity*. *For the vehicle and pedestrian traffic activity:* procedures for vehicles and pedestrians' safety in workplace, providing required number of camera and headlights, preference of reflective dress, improvement of vehicle visibility, periodic supervisory checks, washing equipment and vehicles periodically, follow-up legislation, giving an advanced education and authorization before works are basic control measures. Providing suitable PPE procedure for transporting, follow-up standard operating procedure (SOP), usage of stop-look-assess-manage tool (SLAM), preference of ergonomic equipment, periodic supervisory checks, proper and certificated loading equipment, filling individual identification number, occupational hazard analysis periodically, giving an advanced training and authorization before works regular and periodic controls are fundamental preventions *for material handling activity. For opening of clogged drainage activity:* regular and periodic controls of work area, follow-up the legislation, filling individual identification number, giving an advanced education and authorization before works, providing suitable PPE procedure, operation and maintenance of *wastewater collection* systems should be done as control measures. Building a gravel road and 1.5 m high wall to avoid fall down, the material is taken from the top without approaching more than 3 m, follow-up standard working hours 8 am–17 pm, noise reduction technology for installing of trucks, *for bringing of sulfurous tallow to the side of concrete plant activity*. *For explosive storage activity:* avoiding sulfurized materials in rainy weather and work area abandoned, follow-up traffic regulations, regular and periodic controls of work area, the vehicle operator checks field before damping, periodic and regular cleaning on truck roads with broom and bucket, working area will closed with safety line after work is finished, providing suitable PPE procedure, periodic supervisory checks, selection and use of gloves procedure, occupational hazard analysis periodically are considered as preventions. Temporary lane closures with signs for workplace, regulations for ventilation and air conditioned equipment, building safety and health regulations and periodic checks, authorization and advanced education before works, providing automatic fire suppression system, providing suitable PPE procedure, noise exposure will not exceed the action level (85 dB), follow-up SOP, usage of SLAM tool, energy insulation and locking procedure, providing proper fortification standards, giving an advanced training before works, ensuring that the workplace ventilation is operating adequately, preferring qualified, certificated and experienced mine operators, planned and regular maintenance of equipment are basic control measures *for vehicle fueling and lubrication activity.* 620 *Ore pass new ladle usage activity*, procedure and improvement on current system, sensors for level measurement, traffic lights and signs, providing suitable PPE procedure, filling individual identification number, ensuring ORP throat remain closed, giving an advanced training before works, follow-up SOP, usage of SLAM tool are major control measures. *Providing suitable and ergonomic PPE, regular cleaning of dusty areas* and dust suppression system, periodic supervisory checks, usage of powder vacuum tool and main fan filter system, ambient and particular dust measurements, proper vehicle lightings, authorization and advanced education before works, changing and improving vehicle exhaust system periodically, cleaning mirrors and stopes are major control measures for dust activity. *For the sledging materials/vehicles activity:* authorization and advanced education before works (G class driving license), providing suitable and ergonomic PPE, standardized materials and equipment, filling individual identification number, using specific check-list, risk assessment tools (SLAM), providing required number of communication equipment, heavy lift coordinator assignments, follow-up legislation are basic control measures. *SO_2 formation and working in SO_2 environment activity requires following control measures:* fixed and mobile emission measurements, natural gas replacement system, follow-up legislation and emission allowances, providing suitable and ergonomic PPE, advanced registration system, flexible operational system, emergency procedure, ventilation standards, providing proper fortification standards. Lifting procedure, providing suitable and ergonomic PPE, standardized materials and equipment, filling individual identification number, using specific check-list, manual transportation training, authorization and advanced education before works, recognition of right to refuse work, regular and periodic controls, *using specific check-list are control measures for placement of reinforcing cage activity*. *Drilling stope activity requires following control measures:* recognition of right to refuse work, safety hazard warning signs, providing appropriate energy insulation system, mine sight applications, periodic supervisory checks, filling individual identification number, using specific check-list, authorization and advanced education before works, regular and periodic cable and equipment controls. Providing vehicle camera system, control of jumbo boxes and fireman, authorization and advanced education before works, recognition of right to refuse work, providing appropriate energy insulation system, periodic supervisory checks, preferring certified and experienced mine operators, filling individual identification number, vehicle safety cabinets, required number of fans and buckets, regular metal collection, use of wedge kit follow-up traffic regulations, regular and periodic checks of work area *using specific check-list, major control measures for transport of ore and tallow activity*. *Shotcrete activity requires following control measures:* follow-up legislation and emission allowances, recognition of right to refuse work, filling individual identification number, providing appropriate energy insulation system providing suitable and ergonomic PPE, advanced registration system, periodic supervisory checks, preferring certified personal, authorization and advanced education before works, standardized materials and equipment, periodic cleaning with buckets, ensuring that the workplace ventilation is operating adequately, arranging specific staff for operation. Firefighting equipment, technology procedure, providing automatic fire suppression system, providing methodical mine rescue fire training, periodic health checks, occupational hazard analysis periodically, authorization and advanced education before works, using specific check-list, practice with fire drills, emergency procedure and updated plans, providing appropriate energy insulation system providing suitable and ergonomic PPE, filling individual identification number, required number of fans and buckets basic control measures for bolting activity. *Tallow filling activity requires following control measures:* use of tallow and wedge kit set, vehicle safety cabinets, periodic supervisory checks, filling individual identification number, energy insulation system providing suitable and ergonomic PPE, recognition of right to refuse work, using specific check-list, authorization and advanced education before works, standardized materials and equipment, follow-up the legislation, regular and periodic checks of work area. *Cement filling and assembly line activities requires following control measures:* separation of lines, bonding and fixing of pipes, carefully engineered modification and replacement, clearly labeled warning alarms, automatic shut-off systems, lookout personal, set-up radio and camera communication, advanced underground ventilation system, follow-up regulations, preferences of experienced employee, authorization and advanced education before works, regular and periodic controls of work area, providing suitable and ergonomic PPE, filling individual identification number, energy insulation system, recognition of right to refuse work, periodic supervisory checks, providing required number of sensors.

For the other activities: manual gas measurements and checks, standard gas measurement systems, providing suitable and ergonomic PPE, detailed emergency plan, explosion alarm and control system, follow-up legal regulations, usage of thermal camera, environmental cleaning due to dust, regulations for proper ventilation system are common control measures.

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