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Fuzzy Approach for the Safety Risk Assessment in Dimension Stone Mining

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ABSTRACT

Mining activities are liable to injuries and different types of diseases. The occurrence of an accident threatens safety in dimension stone mines. Therefore, the safety risk assessment in such mines is an important issue that needs special consideration. In this paper, the safety risk of incidents in dimension stone mines in Iran is evaluated using the fuzzy inference system. The fuzzy analytical hierarchy process is used to identify the importance degree of each incidence and then, the overall risk priority number is calculated based on the fuzzy inference process. The results of this study show that vehicle traffic and wire rupture are the most hazardous incidents.

Keywords: Dimension stone mines; safety risk assessment; risk priority number; fuzzy inference process

Acercamiento difuso para la evaluación del riesgo de seguridad en minas de rocas de dimensión

RESUMEN

Las actividades mineras son responsables de lesiones y diferentes tipos de enfermedades. La ocurrencia de un accidente amenaza la seguridad de la minería de rocas de dimensión. Además, la evaluación de riesgos de seguridad en estas minas es un tema importante que necesita consideración especial. Este artículo evalúa el riesgo de seguridad en incidentes de minería de rocas de dimensión en Irán. El proceso analítico jerárquico difuso se usa en este trabajo para identificar el grado de importancia de cada incidente y, luego, se calculó el valor de prioridad de riesgo general con base en la inferencia difusa del proceso. Los resultados de este estudio muestran que el tráfico de vehículos y la ruptura de cables son los incidentes más peligrosos.

Palabras Clave: Minas de rocas de dimensión; evaluación del riesgo de seguridad; valor de prioridad del riesgo; proceso analítico jerárquico difuso

1. Introduction

Risk assessment, as a primary part of occupational health and safety management, is a critical state in industrial activities. Dimension stone mining using diamond wire cutting is one of the most hazardous mining activities. Accidents in this type of rock exploitation cause serious injuries, even fatalities, and have a considerable effect on financial losses. Regarding the National Statistical Center of Iran (NSCI) in 2020, more than 12% of total mines in Iran are in the category of dimension stone mines (NSCI, 2020). There are more than 10,000 workers in the dimension stone mines of Iran, and therefore, the safety risk assessment in this type of mine is necessary.

Over the last few years, numerous studies have been done in the field of safety risk analysis in quarries. Sanmiquel et al. (2014) studied occupational safety management and its effect on the incidence rate of occupational accidents in dimension stone mines in Spain from 2004 to 2008. In this research to evaluate the quality of occupational safety management in each mine, a questionnaire with four main categories was used. The main categories included preventive organization, treatment plants, workshops, storages, dimension stone mine-related items, and other general questions. Results of the mentioned study showed that, in the dimension stone mine-related items, the signs for entries and tracks, electrical facilities, and operating slopes had the worst condition. Sanmiquel et al. (2015) studied the accidents in Spanish mines from 2003 to 2012. They expressed that the leading causes of accidents were collisions with a moving object and physical effort. They concluded that most accidents were because of the previous causes before the accidents which were the electric problem, collapse, loss of the machinery control, fall of a person, body movement with or without physical effort, prevention organization, experience, and age of the injured worker. Khalilabad et al. (2018) provided a model to analyze the safety risk of dimension stone mines. In the mentioned study, fault tree analysis under the fuzzy environment was used to analyze hazards related to the wire-cutting machine in a quarry mine in Iran. Results of the reviewed study showed that the dangers of the rupture of wire, diversion of wire, and the existence of mud inside the stone blocks were basic events that had the highest occurrence probability. Marras and Careddu (2018) studied occupational injuries in the dimension stone mines of Italy industry. In the mentioned study, the work-related injuries and fatal accidents caused for quarrying of stone, sand, and clay mines were analyzed from 2012 to 2019. Regarding the results of the reviewed study, the role of human behavioral factors on safety is decisive and the competence of safety measures and identification of unambiguous regulations are necessary to prevent quarry accidents. Melodi et al. (2020) studied the risk management analysis for labor and equipment in quarry mines in three states of Nigeria. In this study, the level of risks and likelihood of occurrence of potential hazards were identified and analyzed. Results of the mentioned study showed that slips and trips, noise pollution, and dust impact were the most potential safety hazards. Bogoly and Fuzesi (2021) studied the slope stability of a dolomite quarry in Hungary by using deterministic and probabilistic methods. In this study, the factor of safety was obtained from the deterministic approaches and then, compared to the results of probabilistic methods. Results of the mentioned study showed that probabilistic methods are more flexible to design the slope properties. Hazard identification skills of workers in dimension stone mines were studied by Bae et al. (2021). In the mentioned study safety behaviors of workers in a quarry mine in the Mid-Atlantic region of the United States were explored by using interviews and field notes collection. Results of the reviewed study indicate that the quarry workers identified hazards and improved their safety knowledge from their interaction with other workers, hands-on experience, and sharing their responsibilities among the team members. Esmaeilzadeh et al. (2022) used the failure modes and effect analysis (FMEA) method for the safety risk assessment of quarry mines. In this research, the main causes of risks in the West-Azerbaijan quarry mines of Iran were identified and studied. Results of the reviewed study showed that the diamond cutting wire breaking, rock-fall, and car accidents had the highest risk priority number. Moreover, some preventive activities such as the planned cutting wire replacement, application of an intelligent system to control cutting tools, and training workers to mitigate the safety hazards.

Reviewing the papers, mentioned above, shows that the safety risk of quarry mines has been studied by researchers. Some of these studies have usually focused on the frequency of accidents without considering their hazardous consequences. These studies didn't take into account some factors such as weather-related or delivering services of the Health, Safety, and Environment (HSE) unit, which might be the leading cause of some serious incidents. Moreover, all safety incidents have no same importance degree and then, considering the importance measure of them during is essential. Furthermore, obtaining the risk evaluation factors using the crisp values may bring a different level of uncertainty and ambiguity in the form of doubt and hesitancy. In such cases, using the fuzzy set theory could reduce these uncertainties. In this paper, to overcome these scarcities, the importance degree of the most frequent incidents in Iran's dimension stone mining is considered and then the safety risk is evaluated under the fuzzy environment. To achieve this, in the first step, the fuzzy analytical hierarchy process (FAHP) is used to find the importance degree of each incidence. There have been many successful applications of this method for vague and uncertain decision-making problems (Karimnia and Bagloo, 2015; Alizadeh et al., 2016; Modak et al., 2017). Then the risk priority numbers (*RPN*s) for each incidence is computed under the fuzzy environment by applying the fuzzy inference system (FIS). Finally, the overall *RPN* is calculated for each safety incident.

The result of this study defines the most hazardous incidents during dimension stone mining in Iran. These results are helpful for the mine engineers and directors to predict the most hazardous incidents during dimension stone mining, create a safe working place for the employees and accordingly prevent the occupational incidents.

This paper is organized as follows. In section 2, the research methodology is introduced. In this section, first, the fuzzy AHP is presented, and then and fuzzy inference process is introduced. In section 3, the safety risk of the most frequent incidents during the dimension stone mining is evaluated and discussed.

2. Theoretical Foundation

In this section, first, the fuzzy AHP is presented. Then, the risk level assessment by using the fuzzy inference system is explained.

2.1. Fuzzy analytical hierarchy process

The AHP is based on the innate human ability to make judgments about small problems. AHP is one of the well-known multi-criteria decision-making methods which was first presented by Saaty (1980). This method is a simple, flexible, and practical approach that is widely used to obtain the importance degree of the decision criteria. In the application of AHP, both quantifiable and nonquantifiable information can be evaluated, any level of detail about the main goal of the problem can be structured, and scientific judgment can be combined with personal judgment in the evaluation process (Hakan and Kanik, 2012; Qureshi and Harrison, 2017). The methodology of conventional AHP is based on comparisons of objectives and alternatives in a natural and pairwise manner to evaluate the customer's needs using the point scales. In conventional AHP, the decision-makers are only able to focus on a limited number of items at the same time. Zadeh (1965) proposed a new method as the theory of fuzzy sets based on the generalization of the classical methods. The crisp set allows full membership or no membership at all for an element, while a fuzzy set is an extension of a crisp set that allows partial membership. The range of values of membership from zero to one was suggested by Zadeh to show the object's membership in a fuzzy set. The complete membership and non-membership are represented by one and zero, respectively and values between one and zero indicate the intermediate membership degrees. The fuzzy set is characterized by a membership (or characteristic) function which assigns to each object a grade of membership between zero and one (Rahimdel and Ghodrati, 2021).

In this paper, triangular fuzzy numbers (TFNs) are used because TFNs have the characteristics of being constructive and easy to calculate in comparison to trapezoid and Gaussian fuzzy numbers (Rahim, 2017; Tsai et al., 2022). TFNs expressed with $\tilde{M} = (l,m,u)$, where $l \leq m \leq u$, in which the parameter l indicates the smallest possible value and m and u, respectively, represent the most promising and the largest possible value with the membership function as (Rahimdel and Ghodrati, 2021):

$$\mu_{\tilde{M}} = \begin{cases} 0 & x < l \\ \frac{x-l}{m-l} & l \leq x \leq m \\ \frac{u-x}{u-m} & m \leq x \leq u \\ 0 & x > u \end{cases} \tag{1}$$

In using real crisp numbers, the ratio of the pairwise comparison is linguistic and vague and the human assessments cannot reflect the human thinking style. Therefore, the AHP method seems inadequate to determine the customers' importance measures, accurately. To overcome these kinds of shortcomings, the fuzzy sets were used with the pairwise comparison to extend conventional AHP, named fuzzy AHP (FAHP), to handle the linguistic variables. On the other hand, reflecting the uncertain preferences of the decision-making group using crisp values is impossible. Therefore, the AHP under the fuzzy environment is used. In the last decades, fuzzy AHP has been successfully applied in various mining and mineral-related fields such as risk assessment in coal mines (Li et al., 2020; Rahimdel et al., 2022), carrying capacity prediction of the water resource (Chi et al., 2019), selection of the process mining technology (Dogan, 2021), mining method selection (Bajić et al., 2020), mine reclamation (Yu et al., 2020), and mining equipment selection (Patyk and Bodziony, 2022).

Different approaches have been proposed to drive the priorities in FAHP from the fuzzy pairwise comparison matrices that the logarithmic least squares method (Van Laarhoven and Pedrycz, 1983), the geometric mean method (Buckley, 1985), the fuzzy modification of the logarithmic least squares method (Boender et al., 1989), synthetic extent analysis (Chang, 1996), the fuzzy least square method (Xu, 2000), Lambda-max method (Csutora and Buckley, 2001), fuzzy preference programming and two-stage logarithmic programming (Wang et al., 2005) are some of them. Among these approaches, the extent analysis method was found to be the most commonly applied method because of its computational simplicity. This approach was proposed to handle the pair-wise comparison scale using the TFNs for the synthetic extent value of the pairwise comparison. In this method, first, the TFNs are used for pairwise comparison, and then, the extent analysis method is applied to obtain the weight vector by using synthetic extent values. The steps of the fuzzy AHP method, introduced by Chang (1996), are summarized as follows:

Step 1: Constructing the triangular Fuzzy Judgment Matrix

The pair-wise comparison matrix is constructed by using TFNs via pairwise comparison as follows:

$$\tilde{A} = \begin{bmatrix} 1 & \tilde{a}_{12} & \cdots & \tilde{a}_{1n} \\ \tilde{a}_{21} & 1 & \cdots & \tilde{a}_{2n} \\ \vdots & \vdots & 1 & \vdots \\ \tilde{a}_{n1} & \tilde{a}_{n2} & \cdots & 1 \end{bmatrix} \tag{2}$$

where, $\tilde{A}$ is an $n \times n$ fuzzy matrix containing the TFNs $\tilde{a}_{ij}$ in which the $\tilde{a}_{ji}$ equals $1/\tilde{a}_{ij}$. The fuzzy numbers in the corresponding of each linguistic variable are defined regarding the uncertain linguistic variables of the human judgments as Table 1.

Table 1. Linguistic variable terms and their corresponding TFN

Linguistic scale	TFN $\tilde{a}_{ij}$	Reciprocal TFN ($1/\tilde{a}_{ij}$)
Just equal	(1,1,1)	(1/1,1/1,1/1)
Equal preferred	(1,1,3)	(1/3,1/1,1/1)
Weak preferred	(1,3,5)	(1/5,1/3,1/1)
Moderately preferred	(3,5,7)	(1/7,1/5,1/3)
Strongly preferred	(5,7,9)	(1/9,1/7,1/5)
Very strongly preferred	(7,9,10)	(1/10,1/9,1/7)
Extremely preferred	(9,10,10)	(1/10,1/10,1/9)

Let the object set $X = \{x_1, x_2, x_3 \dots x_n\}$ and the goal set $G = \{g_1, g_2, g_3 \dots g_n\}$. Each object is considered and the extent analysis for each goal is performed. Therefore, m extent analysis values for each object can be obtained as:

$$M_{gi}^1, M_{gi}^2, \dots, M_{gi}^m \qquad\qquad i = 1,2,\dots,n$$

where all of the M_{gi}^1, ($j = 1,2,\dots,n$) are TFNs representing the performance of object x_i with regard to each goal u_j.

Step 2: Calculating the fuzzy synthetic extent values

The value of fuzzy synthetic extent with respect to ith criterion can be obtained as:

$$s_i = \sum_{j=1}^{m} M_{gi}^j \otimes \left[\sum_{i=1}^{n} \sum_{j=1}^{m} M_{gi}^j \right]^{-1} = \left(\sum_{j=1}^{m} l_j, \sum_{j=1}^{m} m_j, \sum_{j=1}^{m} u_j \right) \otimes \left(\frac{1}{\sum_{j=1}^{m} u_j}, \frac{1}{\sum_{j=1}^{m} m_j}, \frac{1}{\sum_{j=1}^{m} l_j} \right) \tag{3}$$

, where S_i is the fuzzy synthetic extent and $\otimes$ is the fuzzy multiplication operator.

Step 3: Calculating the possibility degree of decision matrices

In this step, synthetic extent is compared to other synthetic extent values of decision matrices. The degree of possibility is assumed to be $M_1 \geq M_2$, where $M_1 = (l_1, m_1, u_1)$ and $M_2 = (l_2, m_2, u_2)$. The degree of possibility is obtained by using the following equation:

$$V(M_2 \geq M_1) = \begin{cases} 1, & \text{if } m_2 > u_2 \\ 0 & \text{if } l_1 < u_2 \\ \dfrac{l_1 - u_2}{(m_2 - u_2) - (m_1 - u_1)} & otherwise \end{cases} \tag{4}$$

, where $V(M_1 \geq M_2)$ is degree of possibility for M_1 and M_2, d is the highest intersection point between μM_1 and μM_2 as shown in Figure 1. To compare M_1 and M_2, both values $V(M_1 \geq M_2)$ and $V(M_2 \geq M_1)$ are needed. It is worth noting that the degree of possibility is an index to compare two TFNs and cannot be used to represent their relative importance.
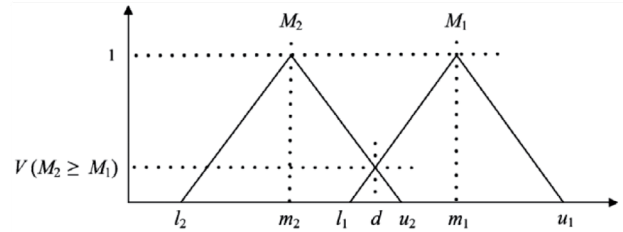
Figure 1. Intersection point d between two fuzzy number M_1 and M_2

Step 4: Calculating the weight vector

The possibility degree for a convex fuzzy number to be greater than k convex fuzzy numbers $M_i = (i = 1,2,\dots,k)$ is given by the following equation:

$$V(M \geq M_1, M_2, \dots, M_k) = \min V(M \geq M_i), i = 1, 2, \dots, k \tag{5}$$

Letting $d'(A_i) = \min V(S_i \geq S_k)$ for $k = 1, 2, \dots, n; k \neq i$, then the vector of weight (W') is obtained as:

$$W' = (d'(A_1), d'(A_2), \dots, d'(A_n))^T \tag{6}$$

, where $A_i = (i = 1, 2, \dots, n)$ are n elements.
The normalized weight vector is calculated as follows:

$$W = (d(A_1), d(A_2), \dots, d(A_n))^T \tag{7}$$

, where W is not a fuzzy weight number.

Step 5: Checking the degree of inconsistency of the judgements

To assure a certain quality level of a decision, the consistency of evaluation is analyzed. According to Saaty (1980), the consistency ratio is used to verify the consistency of the comparison matrix. The consistency ratio is computed using the consistency index and random index as follows.

$$CR = \frac{CI}{RI} \tag{8}$$

$$CI = \frac{\lambda_{max} - n}{n - 1} \qquad (9)$$

, where *CR* is the consistency ratio, *CI* is the consistency index, *RI* is the random index, λ_{max} is the maximum eigenvalue of the pair-wise comparison matrix, and *n* is the size of the comparison matrix.

The random index represents the consistency index of a randomly generated reciprocal matrix, is also calculated as follows:

$$RI = 1.98 \times [(n - 2)/n], \qquad (10)$$

If the consistency ratio is high, it means that the input judgments are not consistent and consequently are not reliable. Therefore, it requires that the consistency ratio smaller than 0.10 to avoid too much inconsistency. On the other hand, if the consistency ratio smaller than 0.1 it means the pair-wise comparisons are supposed consistent within acceptable random variations. If the consistency ratio is higher than 0.1, the judgments are not reliable, and a new comparison matrix needs to be solicited.

2.2. Risk level assessment based on the fuzzy logic theory

Risk is defined as the uncertainty and lack of awareness about the consequences which can lead to a loss or benefit of action or incident. The risk priority number has been the most widely used technique for analyzing the risk level of potential incidents. The risk priority number guides ranking the potential incidents and is calculated as (Zhang and Chu, 2011):

$$RPN = S \times O \times D \qquad (11)$$

where *RPN* is the risk priority number, *S* is the severity, which means the level of damage effects that occur, *O* is the occurrence, which represents the frequency of incident, and *D* is detectability, which indicates the ability to detect the potential incident.

In the traditional *RPN*, the *S*, *O*, and *D* values are defined by crisp point scales and some problems are made in interpreting the results of the conventional quantitative *RPN* method. Because in this way, the RPNs are calculated by only multiplying three crisp numbers. In some cases, the different level of risk evaluation factors leads to the same *RPN*. On the other hand, the real crisp numbers are linguistic, and vague and therefore analyzing the *RPN* in this way seems inadequate. In calculating the final *RPN* in the traditional approach, it is assumed that all incidents have equal importance. Therefore, fuzzy logic is applied to work with the linguistic terms directly. To prioritize the risk in the fuzzy environment, in comparison with the traditional method, fuzzy linguistic terms are used. In this approach, the linguistic term and corresponding fuzzy membership function of each incident are used as Table 2 (Zhang and Chu, 2011).

Table 2. Linguistic terms and the corresponding triangular fuzzy numbers (Zhang and Chu, 2011)

Fuzzy number	Linguistic terms	Fuzzy membership function
$\tilde{1}$	Equally important	(1,1,2)
$\tilde{2}$	Intermediate value	(1,2,3)
$\tilde{3}$	Weakly important	(2,3,4)
$\tilde{4}$	Intermediate value	(3,4,5)
$\tilde{5}$	Fairly important	(4,5,6)
$\tilde{6}$	Intermediate value	(5,6,7)
$\tilde{7}$	Strongly important	(6,7,8)
$\tilde{8}$	Intermediate value	(7,8,9)
$\tilde{9}$	Very strong importance	(8,9,10)

Concerning the scores of *RPN*s, the incidents can be ranked, and accordingly, suitable actions can be taken on the incidents with high-risk priority numbers.

The safety risk analysis in this paper is based on expert judgments. However, the evaluation of the same event by different experts is usually subjective and ambiguous. In such conditions dealing with imprecise and partial data information, a fuzzy inference system (FIS) is applied. Mamdani-type (Mamdani and Assilian, 1975), and Sugeno-type (Sugeno and Kang, 1988), are well-known fuzzy inference systems. The Mamdani fuzzy inference method, which is known as the Mamdani method, is the most common FIS method. The Mamdani-type method employs the defuzzification of a fuzzy output, while the Sugeno computes the crisp output. Mamdani's approach is not dependent on a data set, involves sufficient expertise in the system, and is a generalized model that can be applied for effective future predictions (Khalifa et al., 2015). Moreover, it has a more interpretable rule base and is well-suited to human input (Bobzin et al., 2022).

The rest of this section is devoted to explaining the Mamdani fuzzy inference method. The Mamdani method has three main steps including fuzzification, rule processing, and defuzzification as shown in Figure 2.
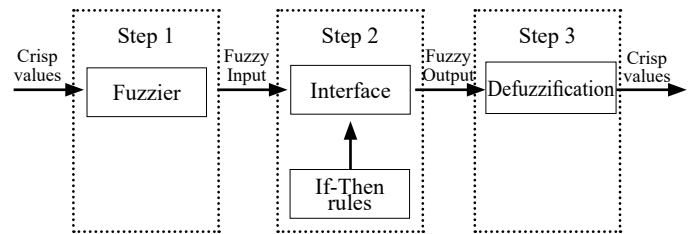
Figure 2. The fuzzy logic system

In the fuzzification step, all risk factors and risk priority levels are converted to fuzzy numbers regarding the expert's judgment. In this research, the triangular fuzzy numbers described in Table 3 are used to interpret the linguistic terms of experts.

Table 3. Linguistic variable and corresponding membership function for all risk factors and risk level

Severity (*S*)	Occurrence probability (*O*)	Probability of detection (*D*)	Risk level (*RPN*)	Membership function
None	Rarely	Very high	None	(1,1,2)
Very minor	Remote	High	Very low	(1,2,3)
Minor	Slight	Moderately high	Low	(2,3,4)
Very low	Low	Moderate	High low	(3,4,5)
Low	Moderately low	Low	Low moderate	(4,5,6)
Moderate	Moderate	Moderately low	Moderate	(5,6,7)
High	Moderately high	Very low	Moderate high	(6,7,8)
Very high	High	Remote	Low high	(7,8,9)
Serious	Very high	Very remote	High	(8,9,10)
Hazardous	Almost certain	Almost impossible	Very high	(9,10,10)

In the rule processing step, the relationships between all *O*, *S*, *D*, and risk levels were created and characterized by fuzzy "If–Then" rules obtained from experts' knowledge and opinions. Table 3 is used to achieve this. The "If-Then" rules, by using the Mamdani algorithm, can be presented in the following form (Kalogirou, 2009):

"If X_l is A_{il} and X_r is A_{ir} then *Y* is B_i," for *I* = 1, 2, . . ., *K*, where X_l and X_r are the input variables, A_{il}, A_{ir}, B_i are the linguistic terms (fuzzy sets), *Y* is the output variable, and *K* is the number of rules. After creating rules, the rule consequences are obtained by combining the results based on the system's input values. In this paper, the "min-max" composition, as the most commonly used

technique, is used. In this method, the truth value of the rule was defined as the minimum value. If the output of fuzzy sets were more than one rule, this subset was defined as the maximum real value.

The outputs of the fuzzy inference system are the fuzzy values. In the third step, the defuzzification process, all fuzzy conclusions were defuzzified. There are different algorithms such as the center of the area (COA), the bisector of area (BOA), the mean of maximum (MOM), smallest of maximum (SOM), and the largest of maximum (LOM) methods for defuzzification (Rahimdel et al., 2022). In this paper, the center of the area method, due to simplicity and ease of computation, is used. In the COA method the crisp value is obtained from the following equation:

$$x^* \frac{\int_a^b x \cdot \mu_a(x)dx}{\int_a^b \mu_a(x)dx} \tag{12}$$

Where, x^* is the defizzified value for x output and $\mu_A(x)$ is the aggregated output membership function for the interval a to b.

2.3. The overall risk priority numbers

After calculating RPN for each hazard, by using the above-mentioned procedure, importance degree of each incidence (derived from the Fuzzy AHP) is integrated with the RPN values (derived from the fuzzy inference process) to obtain the overall risk priority numbers as follows:

$$RPN_{Overall}^i = W_i \times RPN_I \tag{13}$$

, where, $RPN_{Overall}^i$ is the overall RPN for hazard i, Wi is the non-fuzzy weight for hazard i, and RPN is the risk priority number.

3. Results and Discussion

In this section, first, the safety risk of dimension stone mining in Iran is evaluated using the procedure mentioned in the previous sections. The hazardous incidents in the dimension stone mines of some other countries are also surveyed and discussed.

3.1. Safety Risk Assessment of Iran dimension stone mines

According to the reports of NSCI (2020) and also the experts' opinions on the dimension stone mines in Iran, the serious incidents were identified. Crucial incidents in the dimension stone mines of Iran are summarized in Table 4. The importance degree of the incidents is obtained using the fuzzy AHP, and then, considering the risk-evaluating values in the fuzzy environment, the overall RPN of each incident is calculated.

In the first step of the fuzzy AHP method, the linguistic variables, mentioned in Table 1, were used by the group of decision-makers to obtain the fuzzy judgment matrix. This matrix is given in Table 5.

In the next step, the fuzzy synthetic extent values (S_i) are calculated from the Equation 2 for each incident. Accordingly, the degree of possibility for each pairwise incident was calculated by using Equation 4 and given in Table 6.

Table 4. The crucial incidents in the dimension stone mines of Iran (NSCI, 2020)

Safety incident	Code	Description
Rupture of the diamond cutting wire	I_1	The diamond wire cutting rupture because of the wire exhaustion in incurrent or overtime usage.
Fall from the bench	I_2	Falling the workers/equipment/machinery from the height is one the most frequency incidents in Iran's quarries due to the slimy place or lack of caution.
Vehicles traffic	I_3	Vehicles accidents with other vehicles or employees.
Rockfall	I_4	Falling the rocks because of loose blocks or poor scaling.
Electrical shocks	I_5	Rupturing the worn-out cables and exposing people to the conductive materials.
Machine-related incidents	I_6	The incidents because of vehicles failures e.g., vehicle brake damage, poor maintenance, or working with more than the design capacity.
Operator-related incidents	I_7	The incidents due to the poor skill level of workers or tiredness and sleepiness because of the working overtime.
Weather-related incidents	I_8	The incidents because of adverse weather conditions such as raining, snowfall, high temperature.
Poor delivering the HSE unit services	I_9	The incidents due to the poor service of HSE unit in the installation of awareness signs in the needed places, persuading worker to consider the safety issue, weak training schedule.

Table 5. The fuzzy judgment matrix

	I_1	I_2	...	I_4	I_9
I_1	(1,1,1)	(1,3.67,7)	...	(5,8.5,9)	(3,6.333,9)
I_2	(0.143,0.227,1)	(1,1,1)		(3,5.5,7)	(1,2.333,5)
I_3	(0.333,0.040,1)	(1,1.67,3)		(5,8.5,9)	(0.3,0.57,1)
I_7	(0.333,1,1)	(1,1,1)	...	(5,8.5,10)	(7,9.5,10)
I_8	(0.111,0.118,0.2)	(0.143,0.182,0.333)		(1,1,1)	(1,3.68,5)
I_9	(0.111,0.158,0.3)	(0.2,0.429,1)		(0.2,0.27,1)	(1,1,1)

Table 6. The degrees of possibility for the fuzzy judgment matrix

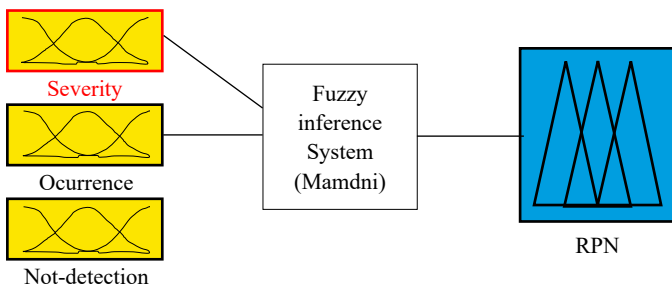|				
$V(I_1 \geq I_2) = 1$	$V(I_2 \geq I_1) = 0.684$	$V(I_3 \geq I_1) = 0.884$	$V(I_4 \geq I_1) = 0.346$	$V(I_5 \geq I_1) = 0.404$
$V(I_1 \geq I_3) = 1$	$V(I_2 \geq I3) = 0.779$	$V(I_3 \geq I_2) = 1$	$V(I_4 \geq I_2) = 0.702$	$V(I_5 \geq I_2) = 0.790$
$V(I_1 \geq I_4) = 1$	$V(I_2 \geq I_4) = 1$	$V(I_3 \geq I_4) = 1$	$V(I_4 \geq I_3) = 0.417$	$V(I_5 \geq I_3) = 0.488$
$V(I_1 \geq I_5) = 1$	$V(I_2 \geq I_5) = 1$	$V(I_3 \geq I_5) = 1$	$V(I_4 \geq I_5) = 0.898$	$V(I_5 \geq I_4) = 1$
$V(I_1 \geq I_6) = 1$	$V(I_2 \geq I_6) = 1$	$V(I_3 \geq I_6) = 1$	$V(I_4 \geq I_6) = 0.972$	$V(I_5 \geq I_5) = 1$
$V(I_1 \geq I_7) = 1$	$V(I_2 \geq I_7) = 1$	$V(I_3 \geq I_7) = 1$	$V(I_4 \geq I_7) = 0.441$	$V(I_5 \geq I_6) = 0.515$
$V(I_1 \geq I_8) = 1$	$V(I_2 \geq I_8) = 1$	$V(I_3 \geq I_8) = 1$	$V(I_4 \geq I_8) = 1$	$V(I_5 \geq I_7) = 1$
$V(I_1 \geq I_9) = 1$	$V(I_2 \geq I_9) = 1$	$V(I_3 \geq I_9) = 1$	$V(I_4 \geq I_9) = 1$	$V(I_5 \geq I_8) = 1$

$V(I_6 \geq I_1) = 0.286$	$V(I_7 \geq I_1) = 0.846$	$V(I_8 \geq I_1) = 0.019$	$V(I_9 \geq I_1) = 0.088$
$V(I_6 \geq I_2) = 0.670$	$V(I_7 \geq I_2) = 1$	$V(I_8 \geq I_2) = 0.298$	$V(I_9 \geq I_2) = 0.355$
$V(I_6 \geq I_3) = 0.350$	$V(I_7 \geq I_3) = 0.697$	$V(I_8 \geq I_3) = 0.010$	$V(I_9 \geq I_3) = 1.000$
$V(I_6 \geq I_4) = 1$	$V(I_7 \geq I_4) = 1$	$V(I_8 \geq I_4) = 0.667$	$V(I_9 \geq I_4) = 0.724$
$V(I_6 \geq I_5) = 1$	$V(I_7 \geq I_5) = 1$	$V(I_8 \geq I_5) = 0.534$	$V(I_9 \geq I_5) = 0.605$
$V(I_6 \geq I_7) = 0.375$	$V(I_7 \geq I_6) = 1$	$V(I_8 \geq I_6) = 0.652$	$V(I_9 \geq I_6) = 0.706$
$V(I_6 \geq I_8) = 1$	$V(I_7 \geq I_8) = 1$	$V(I_8 \geq I_7) = 0.016$	$V(I_9 \geq I_7) = 0.112$
$V(I_6 \geq I_9) = 1$	$V(I_7 \geq I_9) = 1$	$V(I_8 \geq I_9) = 1.006$	$V(I_9 \geq I_8) = 1.000$

Regarding Table 6, the normalized weight of each incident was calculated using Equations 6 and 7:

$W_{I1}=0.220$, $W_{I2}=0.150$, $W_{I3}=0.194$, $W_{I4}=0.076$, $W_{I5}=0.089$, $W_{I6}=0.063$, $W_{I7}=0.186$, $W_{I8}=0.002$, $W_{I9}=0.019$.

To calculate the consistency index, first, the fuzzy judgment matrix was defuzzified to a crisp number by using the center of gravity (CoG) method (Wang and Luoh, 2000). Based on our conclusions, the eigenvalue of the pair wise comparison matrix (λ_{max}) is calculated as 10.192. The dimension of the matrix is nine, and then the random index is 1.540 (=1.98 × ((9 - 2) / 9)). The consistency index is 0.149 (= 10.192 – 9) / (9 – 1)). Therefore, the consistency ratio of the matrix is calculated as 0.096 (=0.149/1.540)) < 0.1 which means the judgment in the comparison matrices is acceptable, and the judgment errors are tolerable.

In the rest of this section, the overall risk priority number is calculated for each incident by using the fuzzy inference system (FIS), as described in subsection 2.2. The membership functions corresponding to linguistic terms are considered for each safety incident. To define the severity, occurrence, and probability of detection for each incident, some questionnaires were prepared. These questionnaires were sent out to the experts and directors in the field of dimension stone mining to fill them out. In this way, the severity, occurrence, and detectability of each incident were defined by using fuzzy linguistic scales as described in Table 3. In this paper, the Mamdani fuzzy inference process was performed in MATLAB Software (Johanyák et al., 2006). The structure of the applied fuzzy inference model with attribute inputs and the corresponding output is shown in Figure 3. It notes that all risk factors were considered as inputs and the RPN was considered as output variables. Then, the fuzzy inference model was created by matching inputs to output variables against the "If-Then" rules. These rules were defined with the aims of the experts with enough experience in the field of dimension stone mining. Considering ten states for all three risk factors, a total (103=) 1000 rules were created. Some of these rules are given in Table 7.

Table 7. Creating rules in the fuzzy inference process

No. of rule	IF (inputs)			Then (output)
	Severity (S)	Occurrence (O)	Probability of Detection (D)	RPN
1	None	Rarely	Very high	None
2	None	Rarely	High	None
3	None	Rarely	Moderately high	Very low
4	None	Rarely	Moderate	Very low
5	None	Rarely	Low	Low
6	None	Rarely	Moderately low	Low
7	None	Rarely	Very low	High low
8	None	Rarely	Remote	Moderately low
1000	Hazardous	Almost certain	Almost impossible	Very high

In the next step of the fuzzy inference process, the RPN values were defuzzied from the fuzzy results set. To achieve this, the center of the area method was applied. Then, the overall RPNs are obtained from Equation 13 by multiplying the incidents' importance weight by the risk priority number obtained from the fuzzy inference process. The results are shown in Figure 4. In this way, the incidents can be prioritized.

Figure 3. Structure of the fuzzy inference model in the MATLAB software
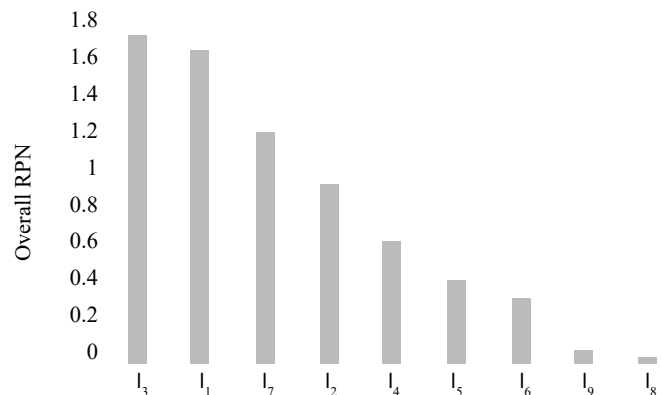
Figure 4. The overall RPNs for each safety incident

According to Figure 4, vehicle traffic (I_3), and rupture of the diamond cutting wire (I_1) are the most hazardous incidents during the dimension stone mining. Therefore, effective risk adjustment approaches need to be considered for occurrence preventing of them.

4.2. Hazardous incidents in the dimension stone mines of some other countries

Incident comparison of the other dimension stone-rich countries can provide helpful information to suggest suitable strategies experienced by more advanced countries in safety issues. Incidence rate in Spanish mining sector is much higher compared with other countries. In 2007, the incidence rate was 8.9 times higher than in the United States and 19.6 times higher than in the Australian state of Queensland. Occupational health and safety studies of quarries in Spain from 2007 to 2008 show that 2,452 accidents caused 60,194 days away from work. More than 200 non-fatal accidents caused at least 60 days of lost work. The incidence rate of quarries in Spain was also higher in treatment plants, workshops, and storage than the other workplaces. Physical over-exertion on the muscular-skeletal system and being hit by falling objects were the leading causes of accidents (Sanmiquel et al., 2014). Studying the occupational accidents in marble quarries in the Diyarbakir province of Turkey showed that about 42.9% of incidents occurred because of the cutting wires rupture and 17.8% and 3.6% were because of the blasting and falling from the bench, respectively. It is worth noting that 10.7% of these incidents resulted in death (Gumus and Akkyun, 2006). The main accidents which occurred in the marble quarries of Turkey were respectively because of the broken wires, slipping, and falling. More than 4% of accidents caused death or permanent disability, and more than 60% of accidents caused a harmful impact. Moreover, there was an extremely negative exponential relationship between the safety index and the accident index, which means the importance of safety measures in reducing accidents. It should be noted that 40% of incidents in these mines were so dangerous for workers (Ersoy, 2013). In the dimension stone mines of Australia, about 2600 deaths were reported from 2003 to 2012 (SWA, 2013). The quarries safety reports show that the vehicle accident was the cause of more than 50 present of incidents in quarries from 2013 to 2016 (DNRM, 2016). Regarding the incident analysis of Australian quarries, the accident rate (accident per one million hours worked) from 2015 to 2016 was about 2.7 while, in the other surface and underground mineral types was 0.2 and 0.7, respectively. Moreover, vehicle collision was the most dangerous hazard in more than one-third of high-potential incidents (DNRM, 2017).

The hazardous area of Italy's quarries is the overburden areas where the construction machines move the overburden. While the most hazardous area of Turkey's mine was the benches. In this area, falling pieces could injure the people who work in front of the bench, because of the weight of construction machines or vibrations. Regarding the mentioned study, the area of Italy's quarries is safer than turkey's quarries both in terms of working fields and observed issues (Ersoy and Yesilkaya, 2016).

Regarding the occupation and safety condition of different dimension stone-rich countries, mentioned above, the vehicle collision is the most hazardous incident of Iranian, Australian and Italian quarries. While, the rupture of diamond cutting wire is the leading cause of the incidents in dimension stone mines of Turkey. It is also worth noting that, the most frequent incident in the dimension stone mines of Spain caused by falling objects. Teaching the operators and persuading and encouraging them to consider the safety issues would have a considerable effect on reducing the operator-related dangers. Different actions such as proper maintenance of the installations in workplaces with unprotected moving parts, walkways and railings, materials in poor conditions, defective electrical installations and dust emissions or noises should be considered to avoid vehicle accidents. In terms of observed issues, using the diamond cutting wires, correctly, checking and inspecting the wires, periodically, avoiding to use the worn-out wires and also selecting the optimum length of diamond wires should be taken to account decrease the safety risk level.

5. Conclusions

This paper analyzed the safety risk of the most frequent incidents in dimension stone mines of Iran which exploited by using the diamond wire cutting method. The importance degree of each incident was obtained using the fuzzy AHP. Then, the overall risk priority numbers were calculated using the fuzzy inference system. The results of this study showed that the vehicle traffic, rupture of the diamond wires, falling from the bench, and human imprudence are the most critical incidents. While the weather-related incidents and the insufficient delivering services of the HSE unit are the lowest portion of unsafety conditions. The incidents dealing with traffic, rupturing the diamond wires, and falling from the bench have the highest level of severity and occurrence, while the low detectability level of them is the main reason for the high-risk priority. Therefore, considering the effective measures such as encouraging and persuading the vehicles' operators to observe the safety issues, trying to improve the skill levels of operators, regular checking and inspecting the wires, scaling and cleaning the benches from the loosed rocks and slimy materials are recommended.

The results of this study are helpful for the dimension stone mine directors and managers to improve the safety level. Although this study considered the most common incidents in dimension stone mines in Iran, there were some restrictions during the research. Dimension stone mines have different maintenance and inspection plans for equipment and vehicles. Therefore, the frequency of the vehicle-related incident can be different from one mine to others. Economic aspects of the safety measure were another limitation that should be taken into account in future studies.

Studying effects of the risk adjustment issues for reducing the safety risk level, ranking different types of dimension stone mines based on the safety risk levels, and economic analysis of the measures taken to ensure the safety mining in comparison with the production lost costs are also recommended for the future studies. Real-time safety risk assessment and applying artificial intelligence approaches to perform safety risk assessment are recommended, as well.

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