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Development a risk assessment method for dimensional stone quarries

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Over the last 20 years, the global production of dimension stones has grown rapidly. Today, seven countries—China, India, Turkey, Iran, Italy, Brazil, and Spain—account for around two-thirds of the world's output of dimension stones. Each one has annual production levels of nine to over twenty-two million tons. Mining operation in general is one of the most hazardous fields of engineering. A large amount of dimensional stone quarries require a special scheme of risk assessment. Risk Breakdown Structure is one of the major stages of risk assessment. In this paper, a detailed structure of risks of the dimension stone quarrying is formed, and divided into 17 main levels and 128 sublevels. The complexity of identifying different parameters made it requisite to use multi-attribute decision-making methods for prioritizing associated risks. As a case study, the main risks of the Ghasre Dasht marble mine are evaluated using the VIKOR method considering 10 major parameters under a Fuzzy environment. The results showed that the economic, Management, and Schedule risks are the most threatening risks of dimensional stone quarrying.

Keywords Dimensional stone, RBS, Risk assessment, Fuzzy-AHP, Fuzzy-VIKOR

Investment decisions in dimension stone projects are highly susceptible to risks, making effective risk management essential. As the Project Management Institute's (PMI) Guide to the Project Management Body of Knowledge (PMBOK) defines, risk is inherently uncertain, potentially leading to adverse impacts like safety hazards and financial losses¹. Additionally, risk encompasses any event or condition, positive or negative, that can affect project goals, including both threats and opportunities^{2,3}.

Therefore, robust risk management practices are crucial for maximizing the impact of positive events while minimizing the likelihood and severity of detrimental occurrences. Following the PMBOK standard, risk management involves six key steps: planning, identification, qualitative analysis, quantitative analysis, response planning, and monitoring⁴.

The global production of dimension stone, particularly for building projects, has witnessed significant growth over the past two decades. Architects increasingly leverage the diverse colors, textures, and finishes natural stone offers. Consequently, seven countries—China, India, Turkey, Iran, Italy, Brazil, and Spain—now contribute approximately two-thirds of global dimension stone output, with individual annual production exceeding 9 million and reaching up to 22 million tons. Mining operations, in general, represent some of the most risk-intensive engineering projects throughout both the design and implementation stages, demanding meticulous attention to risk management. The high volume of dimensional stone quarrying necessitates a specific risk analysis approach. Identifying risk factors, understanding their potential impact, and prioritizing them are fundamental steps. Doing so allows for timely decision-making, implementation of appropriate responses to potential risks, and ultimately, the reduction of negative consequences. Notably, various studies have explored risk assessment and

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management in the context of open-pit and underground mining operations^{5–17}. Machine learning algorithms have shown promising results in risk assessment modeling e.g.^{18–28}.

In 2011, Careddu and Siotto, by implementing 3-dimensional topographic models, analyzed environmental effects and consequent challenges of these factors such as noise, vibration, fumes, dust, and vehicle traffic on a Marble quarrying in Orosei industrial area²⁹.

Yarahmadi et al.³⁰ selected risks of dimensional quarries are considered for calculating safety risks in this field. Machinery or man falls from bench crest and rock falls were the most influential incidents reported by researchers.

Yari et al.³¹ presented a comprehensive method for evaluating 19 active mines of the Pyrtak Company in Lorestan province, Iran, considering safety parameters.

The efficiency of dimensional stone quarries was processed by Esmailzadeh et al.³². Based on this research selected factors of gross income, safety, desirability, reduction of environmental impacts, waste and reduction of extracting time are implemented for determining a suitable method to extract the dimensional stone to achieve a more efficiency. As a result, extraction of dimensional stone using diamond wire presented as more efficient method considering the mentioned factors.

Khalilabad et al.³³ 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.

Marras and Careddu³⁴ studied the work-related injuries and fatal accidents in the dimension stone mines of the Italian industry from 2012 to 2019. The role of human behavioral factors, the competence of safety measures, and the identification of unambiguous regulations are reported as the most important factors in preventing quarry accidents.

Yari et al.³⁵ determined and ranked the main hazards of decorative stone quarrying by implementing the 'Preference Ranking Organization Method for Enrichment Evaluation' (PROMETHEE) technique.

Melodi et al.³⁶ 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 the likelihood of occurrence of potential hazards were identified and analyzed.

Rasti et al.³⁷ investigated research for decreasing financial risk by considering all affecting factors on extraction direction. They recommended determining discontinuities and rock blocks and evaluating the typical geometry of a rock block, counting the shape and size, before mining the benches to maximize mining exploitation efficiency and minimize waste ore production.

The study was presented by Wangela and Shah³⁸ which processed quarrying operations in the Ndarugo area of Kiambu County and concluded that these activities both positive and negative impacts. This study indicates that quarrying companies should consider all environmental, health, and education safety factors to approach sustainable mining.

Esmailzadeh et al.³⁹ 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.

A user-friendly decision-making program was developed by Hazrathosseini⁴⁰ using a combination of the AHP and Folchi methods to select the most appropriate method for the identification and assessment of hazards. The suggested model was evaluated in two decorative quarries.

Mikaeil et al.⁴¹ identified the safety and economic hazards of 10 dimensional stone mines in West Azerbaijan province in Iran. Then, the risk severity, probability of occurrence, and probability of risk were assessed by completing a questionnaire. Finally, the risk scores of each risk were determined using the FMEA risk assessment method.

Rahimdel⁴², evaluated the safety risk of incidents in dimension stone mines in Iran 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 background of research in the field of the risks of the dimensional stone quarries is summarized in Table 1. As seen, there is extensive research on risk assessment and management in dimension stone quarrying, primarily focusing on safety but also addressing efficiency and environmental sustainability. Different methodologies are employed, with FMEA and fuzzy logic being popular choices. The previous research often employs comprehensive methods that fail to capture the full spectrum of potential risks. Typically, specific risks are addressed through case-by-case analyses, neglecting a holistic approach. Moreover, most studies rely solely on "consequence" and "probability" as key risk assessment factors, leading to concerns about the reliability of these methods^{17,43}. A critical limitation is the equal weighting given to risks with low probability but high consequence and those with high probability but low consequence⁴⁴.

A grading system for water inrush risk is developed based on the amount of simultaneous anomalous data instances found inside a borehole group⁴⁵. A study conducted by Xiao et al.⁴⁶ provides a theoretical foundation for policymakers and engineers to develop hot dry rock resources utilizing closed-loop geothermal systems. Guo et al.⁴⁷ developed mathematical model to provide theoretical direction for the investigation of stress wave energy transformation and fracture propagation during rock blasting and mineral mining. The influence of cyclic weak disturbance on the stress relaxation of rock under different confining pressures was studied by Yu et al.⁴⁸. For effective risk prioritization and ranking, the multi-attribute decision-making (MADM) method based on expert opinions offers a valuable approach^{49,50}. This method has been successfully implemented in previous studies about risk assessment for example in the tunnel projects, as demonstrated in Sayadi Anari, et al.¹⁷. There are many MADM methods; selecting the appropriate methods depend on matching methods with the problems.

This study aims to rank various risks associated with dimensional stone quarries based on their non-commensurable and conflicting nature. Given these characteristics, the VIKOR method emerges as the appropriate choice

Author name	Year	Subject	Methodology	Results
Careddu and Siotto ²⁹	2011	Environmental impacts	3D topographic models	Noise, vibration, fumes, dust, and traffic are key concerns
Yarahmadi et al. ³⁰	2014	Safety risks	Statistical survey	Machinery & man falls, rock falls are most concerning
Yari et al. ³¹	2016	Safety evaluation	Fuzzy logic	A comprehensive method for evaluating 19 mines in Iran
Esmailzadeh et al. ³²	2018	Efficiency	Fuzzy logic	Diamond wire extraction was found most efficient
Khalilabad et al. ³³	2018	Safety risk analysis	Fuzzy fault tree analysis	The model analyzes wire-cutting machine hazards
Marras and Careddu ³⁴	2018	health and safety	Statistical survey	Assessment the main safety risks linked with the Dimension Stone quarrying
Yari et al. ³⁵	2020	Hazard ranking	PROMETHEE	Technique for ranking hazards in decorative stone quarrying
Melodi et al. ³⁶	2020	Potential Hazards analysis	Statistical survey	Identifies and analyzes hazards in Nigerian quarry mines. Slips and trips was the most likely hazard
Rasti et al. ³⁷	2021	Reducing financial risk	3D numerical simulation	Recommends evaluating rock blocks before mining to maximize efficiency
Wangela and Shah ³⁸	2021	Sustainability	Statistical survey	Emphasizes environmental, health & safety considerations for sustainable mining
Esmailzadeh et al. ³⁹	2022	Safety risk assessment	FMEA	Identifies and studies the main causes of safety risks in Iranian mines
Hazrathosseini ⁴⁰	2022	Decision-making	AHP & Folchi methods	User-friendly program for hazard identification & assessment
Mikaeil et al. ⁴¹	2022	Safety & economic hazards	FMEA	Identifies and assesses safety & economic hazards in Iranian mines
Rahimdel ⁴²	2023	Safety risk evaluation	Fuzzy inference system	Fuzzy AHP & fuzzy inference system used to assess risk

Table 1. The background of research.

for this research. For this purpose, in the first stage, all influencing factors of risks are determined considering the published research on this topic and the authors' expertise in Risk Breakdown Structure (RBS) in Dimensional Stone Quarries in 17 major levels and 128 sublevels. In the next step, the weights of assessment factors are evaluated using Fuzzy-Analytical Hierarchy Processes (Fuzzy-AHP), Finally, all defined risks are prioritized using the Fuzzy-VIKOR method, and the most threatening risks are determined associated with the Ghasre Dasht Mine.

Methods

Risk breakdown structure

Since this definition of Risk Breakdown Structure (RBS) by Hillson⁵¹, this structure has been used as an efficient and effective tool for risk management in prominent standards such as PMBOK. The definition of RBS generally is similar to the Work Breakdown Structure (WBS). RBS is a hierarchy structure of potential risks that can help managers determine further risks of the project. In the sublevel of the risk breakdown structure, more detailed risk factors are presented.

A comprehensive RBS can be useful for the identification of risks of a Project but does not necessarily comprise all risks of every project. Therefore, an appropriate RBS should be prepared for each project according to its specific characteristics. The risks associated with mining projects generally divided into internal and external risks. Internal risks are about storage and mine conditions and external risks are caused by external conditions such as business and market conditions⁵².

Fuentes classifies risks in the mining industry as follows: geological risks, geotechnical risks, project risks, operational risks, environmental risks, marketing risks, macroeconomic risks, political risks, and transaction risks¹⁵. Critical risks of mining industry in Mongolia have been expressed by Chinbat and Takakuwa as follows⁵³: Owners' financial problems, Poor management, Technical problems, Government bureaucracy certificate, Wrong evaluation of reserve, Workers irresponsibility, Rail transport delays, Shortage of experts (skilled worker), Delivery delay of machines, Government inspectors' pressure, Changes in laws and regulations, Fuel shortage in the country, Unexpected environmental accidents, Insufficient investment, Organization/Human Resistance, Accidents during production operations.

Evaluating attributes for risk assessment

Due to the disadvantages of the conventional method mentioned in the introduction for risk assessment and ranking (using only two parameters: probability and consequence), in this research, after comprehensive analysis, 10 attributes were identified for risk assessment (Table 2).

Multi-attribute decision-making methods

Multi-Attribute Decision Making (MADM) presents a process for decision making such as evaluation, prioritization, and selection of the best available alternatives. In MADM problems, some alternatives should be ranked. Every problem has also several attributes that would specify alternatives and decision-making to define problems accurately⁵⁴. The attributes in a decision matrix are different from each other in terms of scale and units. Sometimes, attributes have a positive aspect and sometimes, they have negative features. Therefore, proper alternatives will provide the best state of each attribute⁵⁴.

Fuzzy-AHP method

Decision-making problems have several attributes with different degrees of importance. Therefore, each attribute is given weight, and the preference for each index over other attributes is determined using these "weights". There

Attribute	Description
Event probability	Expert opinion about the expected rate of event risk
Impact on project time	The negative effect of risk on the project time
Impact on project cost	The negative effect of risk on the project cost
Impact on project quality	The negative effect of risk on the project quality
Impact on project performance	The negative effect of risk on the project performance
Manageability	The ability to manage and respond to risk
Continually repeating	The repetition rate of risk-facing
Exposure	The ability to predict risk occurrence
Proximity	The proximity of time of the risk occurring
Confidence level	Confidence level of estimated risk values

Table 2. Important attributes in the risk assessment process for dimensional stone quarries.

are different methods for measuring the weights of the attributes. In this study, considering the broad application, the Fuzzy-AHP method has been used.

Fuzzy-AHP methods are applied in the calculation of attributes with comparative priority. Comparative priority is obtained from taking pairs of comparison matrices while overall priorities are the final rank of alternatives. Here, only the calculation of the weights of the attributes is the main goal of using the AHP method⁵⁵.

The Fuzzy-AHP technique can be viewed as an advanced analytical method developed from the traditional AHP. The process, depending on this hierarchy, using the method of Chang’s⁵⁶ analysis, consists of the following steps:

- Step 1.** Break down the complex problem into a hierarchical structure form.
- Step 2.** Form a pair of comparisons of matrices (with n rows and m columns):

$$\begin{bmatrix} \tilde{1} & \tilde{a}_{12} & \tilde{a}_{13} & \dots & \tilde{a}_{1n} \\ 1/\tilde{a}_{12} & \tilde{1} & \dots & \dots & \dots \\ 1/\tilde{a}_{13} & \dots & \tilde{1} & \dots & \dots \\ \dots & \dots & \dots & \dots & \dots \\ 1/\tilde{a}_{1n} & 1/\tilde{a}_{2n} & \dots & \dots & \tilde{1} \end{bmatrix} \tag{1}$$

where

$$\tilde{a}_{ij} = \begin{cases} 1 & i = j \\ 1, \tilde{3}, \tilde{5}, \tilde{7}, \tilde{9} \text{ or } \tilde{1}^{-1}, \tilde{3}^{-1}, \tilde{5}^{-1}, \tilde{7}^{-1}, \tilde{9}^{-1} & i \neq j \end{cases}$$

- Step 3.** Calculating fuzzy synthetic extent value S_i for rows of pair-wise comparison matrix as follows:

$$S_i = \sum_{j=1}^m M_{g_i}^j \otimes \left[\sum_{i=1}^n \sum_{j=1}^m M_{g_i}^j \right]^{-1} \tag{2}$$

where $M_{g_i}^j$ are Triangular Fuzzy Numbers (TFNs). To obtain $\sum_{j=1}^m M_{g_i}^j$ perform the “fuzzy addition operation” of m extent analysis values for a particular matrix given below:

$$\sum_{j=1}^m M_{g_i}^j = \left(\sum_{j=1}^m l_j, \sum_{j=1}^m m_j, \sum_{j=1}^m u_j \right) \tag{3}$$

where l is the lower limit value, m is the most promising value and u is the upper limit value. To obtain $\sum_{i=1}^n \sum_{j=1}^m M_{g_i}^j$ perform the “fuzzy addition operation” of $M_{g_i}^j$ ($j = 1, 2, \dots, m$) values give as:

$$\sum_{i=1}^n \sum_{j=1}^m M_{g_i}^j = \left(\sum_{i=1}^n l_i, \sum_{i=1}^n m_i, \sum_{i=1}^n u_i \right) \tag{4}$$

and then compute the inverse of the vector:

$$\left[\sum_{i=1}^n \sum_{j=1}^m M_{g_i}^j \right]^{-1} = \left(1 / \sum_{i=1}^n u_i, 1 / \sum_{i=1}^n m_i, 1 / \sum_{i=1}^n l_i \right) \tag{5}$$

- Step 4.** The degree of possibility of $M_2 = (l_2, m_2, u_2) \geq M_1 = (l_1, m_1, u_1)$ is defined as⁵⁷ (see Fig. 1):

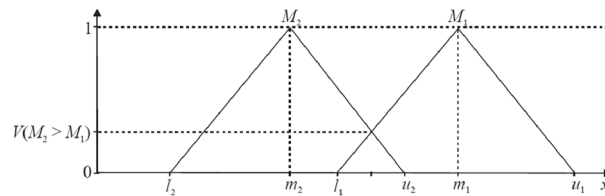


Figure 1. The degree of possibility of two fuzzy numbers.

$$V(M_2 \geq M_1) = \begin{cases} 1 & \text{if } m_2 \geq m_1 \\ 0 & \text{if } l_1 \geq u_2 \\ (l_1 - u_2) / (m_2 - u_2) - (m_1 - l_1) & \text{otherwise} \end{cases} \quad (6)$$

The degree of possibility for a convex fuzzy number to be greater than k convex fuzzy numbers M_i ($i = 1, 2, \dots, k$) can be defined as follows:

$$V(M \geq M_1, M_2, \dots, M_k) = V[(M \geq M_1) \text{ and } (M \geq M_2) \text{ and } (M \geq M_k)] = \min V(M \geq M_i) \quad (7)$$

$i = 1, 2, \dots, k$

Step 5. Calculating the weights of attributes in pair-wise comparisons matrix:

$$d'(A_i) = \min V(S_i \geq S_k), \quad k = 1, 2, \dots, n, \quad k \neq i \quad (8)$$

Then the weight vector is given by:

$$W' = (d'(A_1), d'(A_2), \dots, d'(A_n))^T \quad (9)$$

where A_i ($i = 1, 2, \dots, n$) are n attributes.

Step 6. Via normalization, the normalized weight vectors are given:

$$W = (d(A_1), d(A_2), \dots, d(A_n))^T \quad (10)$$

where W is a non-fuzzy number. To evaluate the risks, experts only select the related linguistic variable, then for calculations, they are converted into the scale including triangular fuzzy numbers developed⁵⁸ and are specified as given in Table 3.

Fuzzy VIKOR Method

VIKOR is an abbreviation of the Serbian name ‘Visekriterijumska Optimizacija I Kompromisno Resenje’, which means multi-criteria optimization and compromise solution. This method was developed by Opricovic in late 1998⁵⁹. The VIKOR method which is a multi-conflicting criteria decision-making method concentrates on ranking and selecting the best alternative from a set of alternatives, by finding the compromise solution (closest to the ideal) of a problem. The basic principle of VIKOR is defining the positive-ideal solution and the negative-ideal solution in the first step⁶⁰. The positive and negative-ideal solutions are respectively the best value and the worst value of alternatives under the measurement criteria. In the end, the alternatives are arranged based on the proximity to the calculated ideal value. Therefore, the VIKOR method is generally known as a multi-attribute decision-making method based on the ideal point technique⁶¹.

VIKOR uses the following adopted form of LP-metric aggregate function for compromise ranking of multi-criteria measurement⁶²:

$$L_{Pi} = \left\{ \sum_{j=1}^n \left[W_j \frac{(f_j^* - f_{ij})}{(f_j^* - f_j^-)} \right]^P \right\}^{\frac{1}{P}} \quad (11)$$

where, $1 \leq P \leq \infty$; $j = 1, \dots, n$, is the number of the attributes; $i = 1, \dots, m$, respect to alternatives such as A_1, A_2, \dots, A_m ; f_{ij} is the evaluated value of the j th criterion for the alternative A_i ; n is the number of criteria.

The measured L_{Pi} shows the distance between the alternative A_i and the positive-ideal solution. Within the VIKOR method L_{1i} (as S_i in Eq. 20) and $L_{\infty i}$ (as R_i in Eq. 21) have been used to formulate the ranking calculation.

Linguistic	Very high	High	Medium high	Medium	Medium low	Low	Very low
Fuzzy	(5,7,9)	(3,5,7)	(1,3,5)	(1,1,3)	(1/5,1/3,1)	(1/7,1/5,1/3)	(1/9,1/7,1/5)

Table 3. Fuzzy number of linguistic variables.

In this paper, the fuzzy-*VIKOR* method has been used to evaluate the most threatening risk under the group multi-criteria decision-making based on the concept of fuzzy set theory and *VIKOR* method. Generally, decision-making problems deal with some alternatives which can be ranked, concerning different criteria. Ratings of the alternatives and the weights of each criterion are the two most important factors that can affect the results of decision-making problems. Therefore, this methodology has been used in this research, to calculate the weights of criteria and prioritize the risks. In this paper, the important weights of various criteria and ratings of qualitative criteria are measured as linguistic variables. Linear triangular fuzzy numbers are considered for capturing the vagueness of these linguistic assessments because linguistic assessment can only have the capability to approximate the subjective judgment through a decision maker's opinion. It should be supposed, that there are k experts with different weights of opinions who are responsible for judging m alternatives ($A_i, i = 1, \dots, m$), regarding the importance of each of the n criteria, ($C_j, j = 1, \dots, n$)⁶³.

The compromise ranking algorithm of the fuzzy *VIKOR* method consists of the following steps⁶⁴:

Step 1. Defining appropriate linguistic variables and their positive triangular fuzzy numbers and forming Experts' opinions-criteria matrix:

$$\begin{matrix} & D_1 & D_2 & \cdots & D_k & \tilde{W}_j \\ C_1 & \tilde{x}_{11} & \tilde{x}_{12} & \cdots & \tilde{x}_{1k} & \tilde{W}_1 \\ C_2 & \tilde{x}_{21} & \tilde{x}_{22} & \cdots & \tilde{x}_{2k} & \tilde{W}_2 \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ C_n & \tilde{x}_{n1} & \tilde{x}_{n2} & \cdots & \tilde{x}_{nk} & \tilde{W}_n \end{matrix} \quad (12)$$

where, for example, \tilde{x}_{12} is a fuzzy number that shows the importance of 1th criterion with respect to 2th expert opinion and \tilde{W}_j is the average fuzzy weighted of each criterion. If $\omega_t \in [0, 1]$ be expert's opinion weights (where $\sum_{t=1}^k \omega_t = 1$), then \tilde{W}_j can be calculated as:

$$\begin{aligned} \tilde{W}_j &= (W_j^L, W_j^m, W_j^u) \\ &= \left(\min \{x_{j1}^L, x_{j2}^L, \dots, x_{jk}^L\}, \omega_1 x_{j1}^m + \omega_2 x_{j2}^m + \dots + \omega_k x_{jk}^m, \max \{x_{j1}^u, x_{j2}^u, \dots, x_{jk}^u\} \right) \end{aligned} \quad (13)$$

Linguistic variables are used to calculate the important weights of criteria and the ratings of the alternatives concerning criteria. In this paper, linguistic variables are defined by a triangular fuzzy number as presented in Table 2.

Step 2. Forming a fuzzy alternatives-criteria matrix for each decision maker:

$$D_t = \begin{matrix} & C_1 & C_2 & \cdots & C_n \\ A_1 & \tilde{y}_{11t} & \tilde{y}_{12t} & \cdots & \tilde{y}_{1nt} \\ A_2 & \tilde{y}_{21t} & \tilde{y}_{22t} & \cdots & \tilde{y}_{2nt} \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ A_m & \tilde{y}_{m1t} & \tilde{y}_{m2t} & \cdots & \tilde{y}_{mnt} \end{matrix} \quad t = 1, 2, \dots, k \quad (14)$$

Step 3. Forming a fuzzy decision matrix by pulling all of the experts' opinions.

$$FD = \begin{matrix} & C_1 & C_2 & \cdots & C_n \\ \tilde{W}_j & \tilde{W}_1 & \tilde{W}_2 & \cdots & \tilde{W}_n \\ A_1 & \tilde{z}_{11} & \tilde{z}_{12} & \cdots & \tilde{z}_{1n} \\ A_2 & \tilde{z}_{21} & \tilde{z}_{22} & \cdots & \tilde{z}_{2n} \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ A_m & \tilde{z}_{m1} & \tilde{z}_{m2} & \cdots & \tilde{z}_{mn} \end{matrix} \quad (15)$$

where \tilde{z}_{ij} is calculated by the following equation:

$$\tilde{z}_{ij} = (z_j^L, z_j^m, z_j^u) = \left(\min_{t=1,2,\dots,k} \tilde{y}_{ijt}^L, \sum_{t=1}^k \omega_t \tilde{y}_{ijt}^m, \max_{t=1,2,\dots,k} \tilde{y}_{ijt}^u \right) \quad (16)$$

Step 4. Defuzzification of the fuzzy decision matrix and fuzzy weight of each criterion:

$$D = \begin{matrix} & C_1 & C_2 & \cdots & C_n \\ W_j & \begin{bmatrix} W_1 & W_2 & \cdots & W_n \end{bmatrix} \\ A_1 & \begin{bmatrix} f_{11} & f_{12} & \cdots & f_{1n} \end{bmatrix} \\ A_2 & \begin{bmatrix} f_{21} & f_{22} & \cdots & f_{2n} \end{bmatrix} \\ \vdots & \begin{bmatrix} \vdots & \vdots & \vdots & \vdots \end{bmatrix} \\ A_m & \begin{bmatrix} f_{m1} & f_{m2} & \cdots & f_{mn} \end{bmatrix} \end{matrix} \tag{17}$$

Step 5. Computing the positive-ideal solutions value (f_j^*) and negative-ideal solutions value (f_j^-) for all criterion ratings:

$$f_j^* = \begin{cases} \max_{i=1,2,\dots,m} f_{ij}, & f_j \in C_1 \\ \min_{i=1,2,\dots,m} f_{ij}, & f_j \in C_2 \end{cases} \tag{18}$$

$$f_j^- = \begin{cases} \min_{i=1,2,\dots,m} f_{ij}, & f_j \in C_1 \\ \max_{i=1,2,\dots,m} f_{ij}, & f_j \in C_2 \end{cases} \tag{19}$$

where, $j = 1, \dots, n$ and C_1 is a benefit type criteria set, C_2 is a cost type criteria set.

Step 6. Computing the values of $S_i, R_i, (i = 1, 2, \dots, m)$, by using the relations:

$$S_i = \sum_{j=1}^n W_j (f_j^* - f_{ij}) / (f_j^* - f_j^-) \tag{20}$$

$$R_i = \max_{j=1,2,\dots,n} [W_j (f_j^* - f_{ij}) / (f_j^* - f_j^-)] \tag{21}$$

where, S_i is the aggregated value of i th alternatives with a maximum group utility, and R_i is the aggregated value of i th alternatives with a minimum individual regret of 'opponent'. W_j is the average weight of each criterion.

Step 7. Computing Q_i by using the following equation:

$$Q_i = \nu [(S_i - S^*) / (S^- - S^*)] + (1 - \nu) [(R_i - R^*) / (R^- - R^*)] \tag{22}$$

where, $S^* = \min_{i=1,2,\dots,m} S_i, S^- = \max_{i=1,2,\dots,m} S_i, R^* = \min_{i=1,2,\dots,m} R_i, R^- = \max_{i=1,2,\dots,m} R_i$ and ν is a weight for the strategy of maximum group utility, and $\nu = 0.5$ whereas $1 - \nu$ is the weight of individual regret. The compromise can be selected with 'voting by the majority' ($\nu > 0.5$), with 'consensus' ($\nu = 0.5$), with 'veto' ($\nu < 0.5$).

Step 8. Ranking of the alternatives by sorting each S, R and Q values in ascending order.

Step 9. Selecting the best alternative by choosing $Q(A^{(m)})$ as the best compromise solution with the minimum value of Q_i and must have to satisfy the below conditions⁶⁴:

Condition 1 The alternative $Q(A^{(1)})$ has an acceptable benefit; in other words,

$$Q(A^{(2)}) - Q(A^{(1)}) \geq 1 / (m - 1) \tag{23}$$

where $A^{(2)}$ is the alternative with the second position in the ranking list by and m is the number of alternatives.

Condition 2 The alternative $Q(A^{(1)})$ is stable within the decision-making process; in other words, it is also best ranked in S_i and R_i .

If condition 1 is not satisfied, that means $Q(A^{(m)}) - Q(A^{(1)}) \geq 1 / (m - 1)$, then alternatives $A^{(1)}, A^{(2)}, \dots, A^{(m)}$ all are the same compromise solution and there is no comparative advantage of $A^{(1)}$ from others. But for the case of maximum value, the corresponding alternative is the compromise (proximity) solution. If condition 2 is not satisfied, the stability in decision-making is deficient while it has $A^{(1)}$ a comparative advantage. Therefore, $A^{(1)}$ and $A^{(2)}$ has the same compromise solution.

Results and discussion

The mentioned studies indicate that the classifications of risk factors in mines have not enough integrity and only some of the risk factors are considered by authors. The large variety of risks that can occur in the mining process, without any systematic procedure for identifying and managing risks, makes quarrying projects more hazardous. RBS presents an effective and targeted tool for the identification and classification of risks^{17,65}. The present study provides a comprehensive structure of risks for Dimensional Stone Quarries in the two general categories of internal risks (11 main categories and 79 sublevels) and external risks (6 main categories and 49 sublevels).

Figures 2 and 3 show Risk Breakdown Structures for internal and external sources of risk in Dimensional stone quarries respectively.

Case study

The Ghasre Dasht Marble Quarry is a building stone quarry with a high production rate. This quarry is located in the northeast of Fars Province, Iran. The quarry primarily extracts marble, characterized by its northwest-southeast orientation and association with the Bangestan Group marls. Figure 4 provide a general overview of the Ghasre Dasht quarry.

This case study presents risk assessment at Ghasre Dasht, leveraging the insights of 18 experts. These 18 experts included 14 PhDs, 3 MSc holders, and 1 BSc graduate person spanning diverse fields of mining engineering and geology. The group of experts possesses an average of 15 years of academic experience as a teacher, and 10 years of industry expertise. Two questionnaires were distributed: The first questionnaire for determining the important weights of 10 attributes using Fuzzy-AHP; and another questionnaire to form a decision matrix to evaluate and rank the risks using the Fuzzy-VIKOR method. The decision matrix has 17 rows and 10 columns: the rows are risks, and the columns are attributes. In this research, in the first stage, the opinions of the 18 experts are collected as linguistic variables for the weight of attributes and risk scores in relation to each attribute. In the next stage, the weights of attributes are calculated using the Fuzzy-AHP method based on experts' opinions. Fuzzy weights of attributes are presented in Table 4 and fuzziness weights of them are shown in Fig. 5.

After evaluating the weight of attributes and applying all mentioned stages of the Fuzzy-VIKOR method, the ranking process of risks is conducted according to section "Conclusions". The hierarchical structure of the problem is shown in Fig. 6. The presented results in Table 5 showed that social risks fall as the lowest-threat



Figure 2. Risk Breakdown Structure for internal risks in dimensional stone quarries.

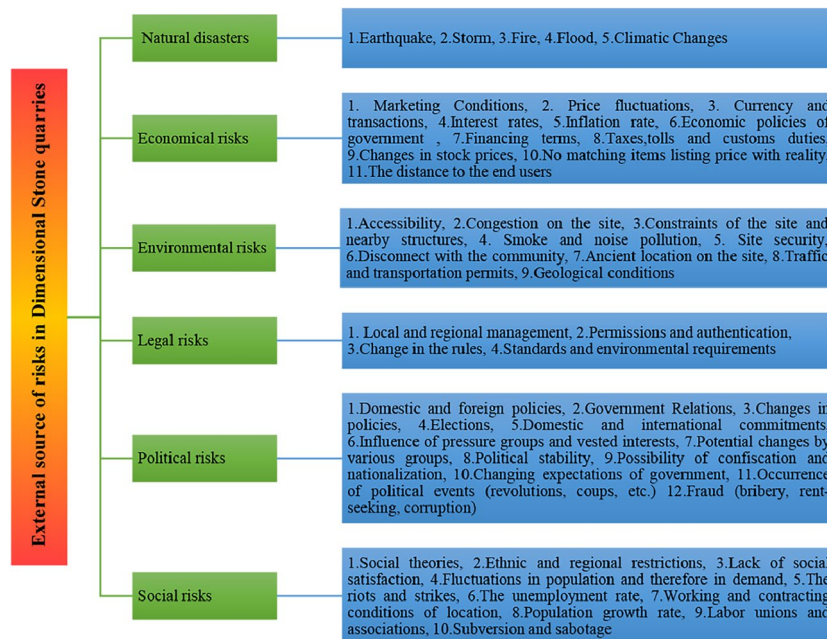


Figure 3. Risk Breakdown Structure for external risks in dimensional stone quarries.



Figure 4. The Ghasre Dasht quarry.

Attribute	Fuzzy weight			Attribute	Fuzzy weight		
Event probability	0.068923	0.107163	0.136036	Manageability	0.018053	0.098814	0.136036
Impact on project time	0.137051	0.166629	0.185032	Continually repeating	0.071529	0.099088	0.117775
Impact on project cost	0.026268	0.113709	0.182786	Exposure	0.060676	0.084728	0.120327
Impact on project quality	0.039645	0.110846	0.168434	Proximity	0.071027	0.068242	0.162172
Impact on project performance	0.031424	0.079585	0.124458	Confidence level	0.032251	0.071196	0.176124

Table 4. Fuzzy weights of attributes.

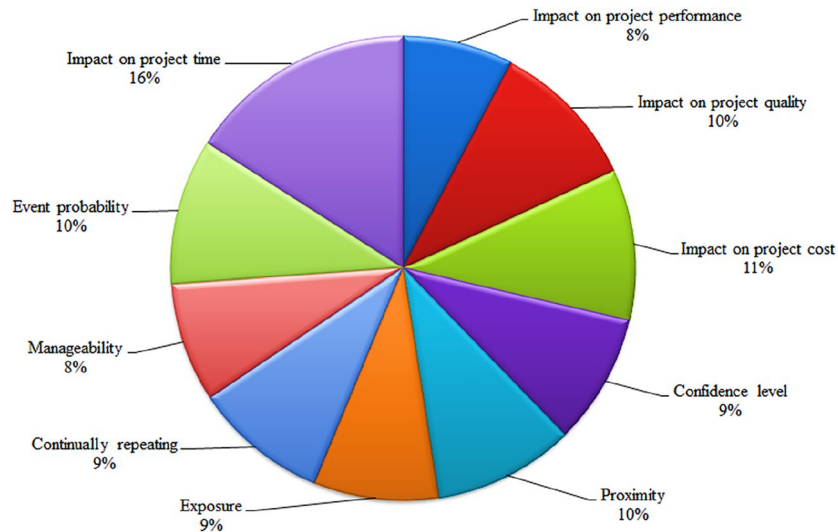


Figure 5. The fuzziness weights of attributes.

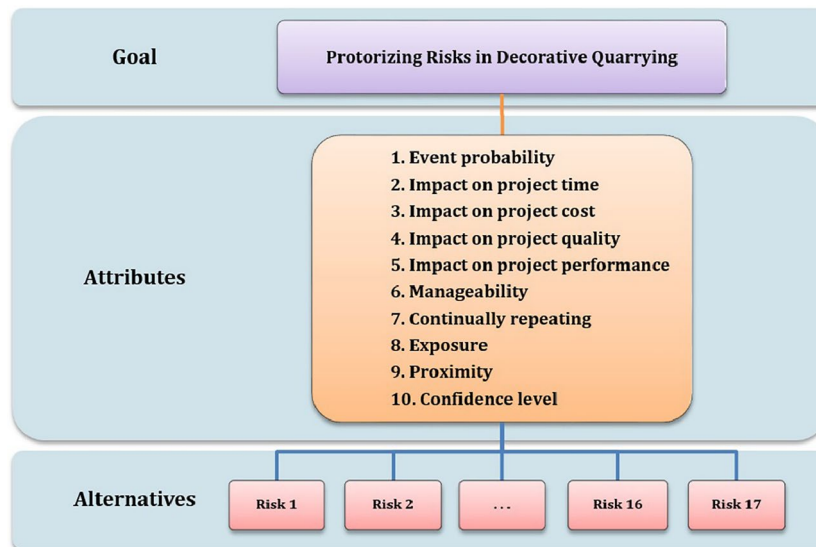


Figure 6. The hierarchical structure of the problem.

Risk	Rank	Risk	Rank	Risk	Rank
Natural disasters	6	Contracting risk	11	Material and Equipment risk	7
Economical risk	1	Financial risk	5	The employer involvement risk	9
Environmental risk	15	Guarantees risk	14	Planning risk	4
Legal risk	13	Personnel risk	8	Schedule risk	3
Political risk	10	Loss or damages risk	16	Technical risk	12
Social risk	17	Management risk	2		

Table 5. Ranking of risks using Fuzzy-VIKOR (most threatening risk is first).

risks. Located quarry far from the city, with limited community connection and a small workforce, social risks naturally rank lowest. Conversely, economic risk is the most threatening risk for the Ghasre Dasht quarry, and management and Schedule risks are ranked next.

Economic risks, identified in the RBS of external risks of the Ghasre Dasht quarry (Fig. 3), encompass more than ten sublevel risks, including Marketing Conditions, Price fluctuations, Interest rates, Inflation rate, Economic policies of the government, Financing terms, Taxes, tolls and customs duties, and more. These risks can significantly impact various project aspects, such as time, quality, cost, and overall performance.

Economic downturns, inflation, or currency fluctuations can lead to material shortages, resource limitations, and funding delays, potentially slowing down or stalling project activities and extending the timeline. Consequently, the economic risks negatively affect project time (with a relative weight of 16%). Furthermore, economic risks can significantly increase project costs due to inflation, higher material costs, and resource scarcity. Additionally, economic instability can drive up financing costs and interest rates. Economic fluctuations can lead to unpredictable costs, such as currency exchange rate variations or higher insurance premiums. Therefore, economic risks also negatively affect project costs (with a relative weight of 11%). In response to economic pressure, project managers may implement cost-cutting measures that compromise on materials, labor, or quality control. This can lead to reduced functionality, durability, or safety in the final product. Furthermore, project scope might be reduced to stay within budget, potentially sacrificing desired features or functionalities. The economic risks likewise have a negative effect on the project quality (with a relative weight of 10%). Project performance (with a relative weight of 8%) is also impacted by economic risks. Delays, reduced quality, and cost overruns lead to reduced stakeholder satisfaction. Failure to meet deadlines and budgets can damage the project's reputation and credibility, potentially affecting future funding opportunities.

On the other hand, the economic risks for the Ghasre Dasht quarry have high values in terms of probability of occurrence, proximity, and repeatability. The nature of these economic risks in the mentioned mine makes them difficult to manage and predict. Considering these factors, it is understandable why economic risks is ranked as the most threatening risk of the Ghasre Dasht quarry.

A more comprehensive analysis of risk classification results reveals a significant trend: 70% of the top ten most threatening risks plaguing Ghasre Dasht quarry stem from internal sources. While external risks present greater challenges in identification and management, mining experts prioritize controlling internal risks due to their greater influence. Many of these top internal risks are human-made and labor-related, such as management risks, Schedule risks, planning risks, that leading to operational problems causing low productivity, low efficiency, more delays and safety hazards. The results resembles the results presented in regard to the previous studies in the field of risks assessment of dimensional stone quarries as reported in^{34,35,38,39,41}. Considering the importance of personnel's role in these risks, owners of Ghasre Dasht quarry can control and limit the resulting risks by employing an experienced and skilled team for management and technical positions.

Conclusions

The mining process as one of the hazardous fields of engineering requires additional consideration of risk assessment. Risk Breakdown Structure as one of the major stages of risk assessment is formed for dimension stone quarrying and divided into 17 main levels and 128 sublevels. In the next, the main risks of the Ghasre Dasht marble quarry are evaluated using the 'VlseKriterijumska Optimizacija I Kompromisno Resenje' (VIKOR) method considering 10 major parameters under a fuzzy environment. Finally, after analyzing 18 experts' opinions and sorting the main risks, the economic, management, and schedule risks are presented as the most threatening risks of dimensional stone quarrying.

It should be noted that this research focuses on the initial steps of risk management, specifically the identification and qualitative analysis of risks associated with dimensional stone quarries, to uncover the most threatening risks. The next stages of the research will involve the quantitative analysis, management, and control of consequences, as well as the monitoring of risks associated with dimensional stone quarries. Additionally, the authors are currently developing the same procedure for identification, qualitative analysis, and ranking of risks of other types of mines, including coal mines, open-cast metallic mines, underground mines, and more.

Data availability

The datasets used and/or analyzed during the current study available from the corresponding author on reasonable request.

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Author contributions

Mojtaba Yari: Conceptualization, Methodology, Software, Validation, Writing the original draft, Writing, editing and review. Saeed Jamali: Data curation, Writing the original draft, Analysis, editing and review. Gamil M. S. Abdullah, Mahmood Ahmad, Muhammad Usman Badshah, and Taoufik Najeh: Investigation, Analysis, Validation, Writing, editing and review.

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Competing interests

The authors declare no competing interests.

Additional information

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