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RISK ASSESSMENT OF BLASTING OPERATIONS IN OPEN PIT MINES USING FAHP METHOD

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ABSTRACT

Purpose. In the mining blasting operation, fragmentation is the most important output. Fly rock, ground vibration, air blast, and environmental effects are detrimental effects of blasting operations. Identifying and ranking the risk of blasting operations is considered as the most important stage in project management.

Methods. In this research, the problem of identifying and ranking the factors constituting the risk in blasting operations is considered with the methodology of the Fuzzy Analytical Hierarchy Process (FAHP). Criteria and sub-criteria have been determined based on historical research studies, field studies, and expert opinions for designing a hierarchical process.

Findings. Based on FAHP scores, non-control of the sub-criterion of health and safety (C3), blast operation results (C18) and knowledge, and skill and staffing (C2) with a score of 0.377, 0.334, and 0.294 respectively are the most effective sub-criterion for the creation of blasting operations risk. According to the score, the sub-criterion C18 is the most effective sub-criterion in providing the blasting operations risk. Effects and results of blasting operations (D8), with a score of 0.334 as the most effective criterion, and natural hazards (D10), with a score of 0.015, were the last priorities in the factors causing blasting operations risk.

Originality. Regarding the risk rating of blasting operations, the control of the sub-criteria C3, C18, and C2, and the D8 criterion, is of particular importance in reducing the risk of blasting operations and improving project management.

Practical implications. The evaluation of human resource performance and increase in the level of knowledge and skills and occupational safety and control of all outputs of blasting operations is necessary. Therefore, selecting the most important project risks and taking actions to remove them is essential for risk management.

Keywords: *blasting operation, open pit mine, risk assessment, FAHP method, criteria and sub-criteria*

1. INTRODUCTION

Engineering projects are typically designed and implemented under unavoidable circumstances of risks and uncertainties. Therefore, identification, measurement, and evaluation of hazards should be considered as integral and comprehensive components of the decision-making process (Haimes, 2009). In the meantime, mining is a high-risk industry due to its specific characteristics. With the extraction of more and more mines, the use of drilling and blasting operations is also expanding: more than 82% extraction and mining operations are carried out by the blasting process. Consequently, the importance of identifying and controlling the unwanted and destructive consequences of blasting operations have also increased (Taji & Bagheri, 2015).

Identifying risk factors, knowing the extent and type of impacts and their proper ranking are key steps in correctly assessing and timely responding to risk and to minimizing damage to mining, machinery, facilities and manpower as a result of these events (Sayadi, Monjezi, & Sharifi, 2014). In order to evaluate the risk of blasting operations in surface mines to reduce the adverse effects of blasting operations, it is necessary to examine the factors affecting blasting operations and to prioritize and grade these factors to identify the most important factors causing the risk of blasting operations.

Typically, blasting operations in mining projects are used for rock fragmentation (Bajpayee, Bhatt, Rehak, Mowrey, & Ingram, 2003). Therefore, fragmentation control in blast operations is dependent on the explosion design and its impact on productivity. This is a challenge for explosive engineers due to inadequate knowledge of the amount of explosion energy in the blast hole and the variety of explosion initiation methods and their impact on the properties of explosion propagation (Singh et al., 2016). In surface mines, only 20 to 30% of the energy

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produced is used for compression and movement of the rock mass: the remaining energy often produces unwanted environmental effects and explosive effects, such as excessive air pressure, ground vibration, fly rock, dust production, and back break (Marto, Hajihassani, Jahed Armaghani, Tonnizam Mohamad, & Makhtar, 2014; Dhekne, 2015). So, in studies to assess the dangers of blasting operations, numerous parameters have been investigated by researchers in accordance with Table 1 in recent years.

Table 1. Blasting operation studies (2001 – 2017)

No.	Author(s), year	Parameters
1	Workman, 2001	CR.P, DF, EL.CS, EN.CS, LP and OC
2	Eloranta, 2001a; Eloranta, 2001b	CR.P, DF, DL, EC, EL.CS, LP, MT, SC and TC
4	Grundstrom, Kanchibotla, Jankovic, & Thornton, 2001	DF, EL.CS, MT and SC
5	Harris, Mousset, & Daemen, 2001	DF, DI, EC, MU and OC
6	Singh & Yalcin, 2002	DF, DL, EC, MU and OC
7	Singh, Yalcin, Glogger, & Narendrula, 2003	DF, DL, EC, LP and OC
8	Bajpayee, Rehak, Mowrey, & Ingram, 2004	B.S, FR, HD, PF and SL
9	Bajpayee, Verakis, & Lobb, 2005	B.S, HD, PF, SL and SR
10	Cunningham, 2005	CR.P, DF and LP
11	Hamdi & du Mouza, 2005	CR.P, DF, MT and SD
12	Kojovic, 2005	DF, OC and SC
13	Mosher, 2005	CR.P, DF, EC and OC
14	Morin & Ficarazzo, 2006	DF, EC, OC and SC
15	Ryu, Shim, Han, & Ahn, 2006	CR.P, DF, EC, OC and SB
16	Bremer, Ethier, & Lilly, 2007	DF, EC, SC and SD
17	Eloranta, 2007	CR.P, DF, DL, EC, EL.CS, LP, MT, SC and TC
18	Calder & Workman, 2008	DF, EC, EL.CS, LP, OC and SC
19	Taji, 2008	BP, BS, DF, MU and WC.H
20	Workman & Eloranta, 2008	DF, EL.CS, EN.CS, OC and SB
21	Calder & Workman, 2009	DF, EC, EL.CS, LP, OC and SC
22	Monjezi, Bahrami, Varjani, & Sayadi, 2011	B.S, FL, HD, PF, SC and SL
23	Rezaei, Monjezi, & Yazdian Varjani, 2011	B.S, FL, HD, PF, SC, SD and SL
24	Verakis, 2011	E.CO, FR
25	Taji, Ataei, Goshtasbi, & Osanloo, 2012	BB, BP, DF, E.CO, LP and MU
26	Faramarzi, Ebrahimi Farsangi, & Mansouri, 2013	B.S, DF, HD and PF
27	Faramarzi, Mansouri, & Ebrahimi Farsangi, 2013	BB, B.S, HD, Im and PF
28	Armaghani, Hajihassani, Mohamad, Marto, & Noorani, 2013	B.S, FR, GV, HD, PF and SL
29	Sayadi, Monjezi, Talebi, & Khandelwal, 2013	BB, B.S, DF, HD, SC, SD and SL
30	Seccatore, Origliasso, & De Tomi, 2013	B.S, PF and SL
31	Faramarzi, Mansouri, & Farsangi, 2014	B.S, FL, HD, SC and SL
32	Marto, Hajihassani, Jahed Armaghani, Tonnizam Mohamad, & Makhtar, 2014	B.S, HD, PF and SL
33	Saadat, Khandelwal, & Monjezi, 2014	GV
34	Trivedi, Singh, & Raina, 2014	B.S, FR, HD, SC and SL
35	Dhekne, 2015	B.S, E.Co, HD and SL
36	Raina, Murthy, & Soni, 2015	FL, B.S, SL, SC and HD
37	Asri & Daafi, 2016	BB, BH, B.S, Im, PF and SL
38	Hasanipanah, Jahed Armaghani, Monjezi, & Shams, 2016	DF, B.S and blasting design and rock mass parameters
39	Hoseini, Sereshki, & Ataei 2016	B.S, HD, SD and SL
40	Kumar, Choudhury, & Bhargava, 2016	GV
41	Singh et al., 2016	B.S, DF, PF and SL
42	Tripathy, Shirke, & Kudale, 2016	B.S, HD, PF, SC, SD and SL
43	Bakhtavar, Nourizadeh, & Sahebi, 2017	B.S, FR, HD and SL
44	Ghaeini, Mousakhani, Amnieh, & Jafari, 2017	B.S, SC and SL
45	Ghasemi, 2017	BB
46	Yari, Bagherpour, & Jamali, 2015	B.S, HD and SL
47	Yuvka, Beyhan, & Uysal, 2017	GV, number of holes

BB – back break; BH – bench height; BP – boulder production; BS – block size; B.S – burden to spacing; Cr.P – crusher productivity and delays at the crusher; DF – degree of fragmentation and required size distribution of fragmented rocks; DI – dilution constrains; DL – diggability of loading machines; EC – explosive cost; E.Co – environmental considerations; El.Cs – electrical consumption; En.Cs – energy consumption; FR – fly rock; GV – ground vibration; HD – hole depth; Im – initiation method; LP – loading equipment productivity; MT – mill throughput; Mu – condition of muckpile; OC – operational (blasting, drilling or loading) cost; PE – personnel expert; PF – powder factor; SB – secondary blasting; SC – specific charge; SD – specific drilling; SL – stemming length; SR – safety regulation; TC – total costs of mining; WC.H – water content in hole.

In order to more accurately identify the hazards and to investigate the impact of any risk in the field of blasting operations in mines, it is necessary to classify and rank the risk of the blasting operations in order to identify the most significant factors that cause risk during blasting operations. As a result, the main criteria for the risk of blasting operations in the ten main groups of human resources, execution factors, operational conditions, rock engineering, drilling operations, blasting operation design, explosive block, effects and results of blasting operations, production and extraction consideration, and natural hazards are based on study of the open pit mines Gol-e-Gohar Iron Ore, Bama Lead and Zinc Mine, Sarcheshmeh Copper Mine, and Isfahan Stone Mobarake Iron & Steel Co.; historical research in this context was also identified. Each major criterion was subdivided according to the criteria that influence the main criterion. The main criteria of human resources, execution factors, operational conditions, and blasting operation design were divided into a number of sub-criteria: these were important in the process of studying and rating by experts. In this category of criteria, the comparison and consideration of the importance of sub-criteria is necessary.

2. BLASTING OPERATIONS RISKS

Identification of the risk of blasting operations is based on the process of identifying, recognizing, and recording the risks of blasting operations. The purpose of identifying the risk of a blasting operation is to determine what might happen and what situations may exist that could affect the achievement of the project's objectives. When identifying the risk of a blasting operation, all existing controls, such as design parameters, humans, processes, and systems must be identified. The risk identification process involves identifying the causes and sources of risk, events, situations, or conditions that could have a general impact on the purposes and nature of the blasting operation.

Methods for identifying the risk of blasting operations can include:

- evidence-based methods, including checklists and revision of historical data;
- systematic group approaches in which a group of professionals follow a systematic process to identify risks through a structured set of notifications or queries.

According to the methods for identification of the risk of blasting operations and the review of open pit mines as a case study, and considering background research studies, the considered criteria as well as the risks of explosion operations are classified as options in Figure 1.

3. FUZZY ANALYTICAL HIERARCHY PROCESS (FAHP)

In order to analyze critical infrastructure, comprehensive knowledge and information is needed. On the other hand, despite the connection between complexity and trust, so that increasing complexity leads to a reduction of assurance, it is necessary to provide an appropriate model for a more detailed study of project conditions (Ebrahimabadi, 2016). The Fuzzy Logic introduced by Professor A. Lotfizadeh, is an appropriate tool for verifying unspecified information and fuzzy phrases (Zadeh, 1965).

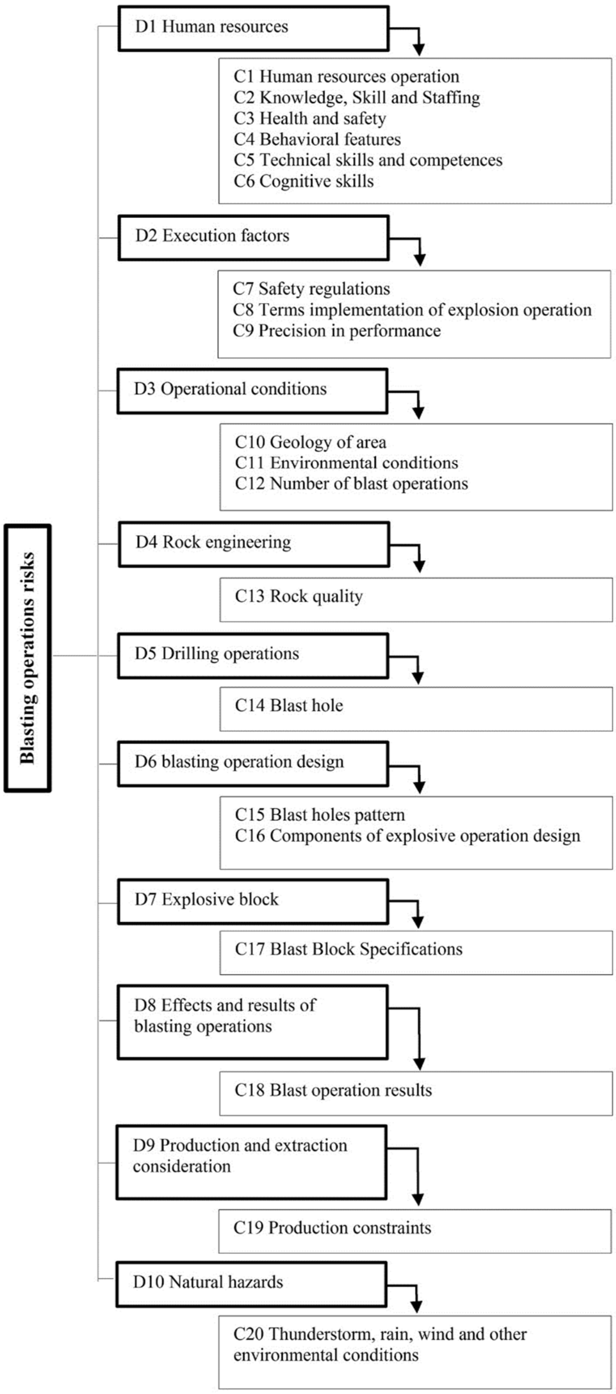


Figure 1. Hierarchical structure of blast operation risks

According to the development of fuzzy methods, the Analytical Hierarchy Process (AHP) developed by T.L. Saaty in 1980 for Multi-Criteria Decision-Making (MCDM) was presented to determine the priority among alternatives and to improve the decision-making method in terms of its qualitative and quantitative aspects (Saaty, 1980).

This method was defined in (Lee, Lau, Liu, & Tam, 2001), as a quantitative technique so that the structure of a complex, multi-faceted problem can be facilitated and dealt with differently from various decisions in the judgment process. In this way, decomposition is a hierarchy based on previous studies, research, and experimental experiences. With the development of hierarchy, an assessment of the relative importance of decision-making criteria is made. Then, the decision options are determined according to available comparison criteria, if any. Ultimately, the overall priority for each decision substitute and the overall ranking of alternative decisions is determined.

Assessing the relative importance of decision-making criteria and comparing decision alternatives to each criterion is done with a dual comparison (Lee, Lau, Liu, & Tam, 2001). Therefore, the AHP enables the Decision-Maker (DM) to examine a complex problem in a simple hierarchy and evaluate a large number of quantitative and qualitative factors in a regular system with multiple criteria (Badri, 1999; Kaboli, Aryanezhad, Shahanaghi, & Tavakkoli-Moghaddam, 2007). Since this selection process generally involves evaluating various criteria and characteristics of the supplier, it can be considered as a MCDM system (Ayhan, 2013).

In AHP, the computation process is divided into two stages: screening and evaluation (Rikalovic, Cosic, Labati, & Piuri, 2017). At first, the decision problem decomposes into a hierarchical structure with decision elements. This method involves six steps: structured problem definition, hierarchy creation, dual comparison, relative weight estimation, validation, and ultimately overall score (Safari, Ataei, Khalokakaie, & Karamozian, 2010). Subsequently, the fuzzy method provides the development of a standard method AHP in a fuzzy domain using fuzzy numbers to compute them instead of real numbers (Petkovic, Sevara, Jaksic, & Marinkovic, 2012). Using the theory of fuzzy sets allows decision-makers to consider uncertain information, incomplete information, inaccessible information, and minor facts in the decision model (Chou, Hsu, & Chen, 2008).

3.1. Determining criteria

Determining the criteria for evaluation using hierarchical charts, defining fuzzy numbers and forming a pairwise comparison matrix can be investigated.

3.1.1. Drawing a hierarchical chart

The first step in the fuzzy AHP method is to decompose the decision problem into various levels of the target, criteria, sub-criteria, and options. The hierarchical decision graph shows the comparative factors and competitive options evaluated in the decision. For this purpose, it is necessary to create a graphical representation of the problem.

3.1.2. Defining fuzzy numbers

A triangular fuzzy number (TFN) must have the following basic characteristics. The fuzzy number $\tilde{A}$ in R is considered as TFN if its membership function is equal to (Hsieh, Lu, & Tzeng, 2004):

$$\mu_{\tilde{A}}(X): R \quad [0,1]; \tag{1}$$

$$\mu_{\tilde{A}} = \begin{bmatrix} \left(\dfrac{X-L}{M-L}\right), L \ll X \ll M \\ \left(\dfrac{U-X}{U-M}\right), M \ll X \ll U \\ 0, \qquad OTHERWISE \\ \end{bmatrix}, \tag{2}$$

where:

L and $U-$ are considered as the lower and upper bounds of the fuzzy number $\tilde{A}$ and M as modal values according to Figure 2.

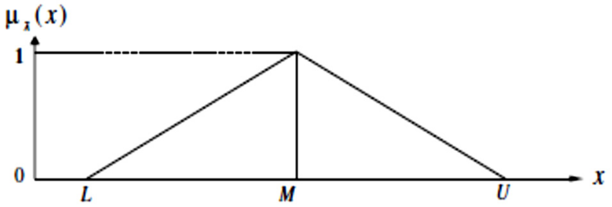


Figure 2. Fuzzy numbers membership function (Hsieh, Lu, & Tzeng, 2004)

According to (Zadeh, 1975a; Zadeh, 1975b), for a conventional measurement, it is very difficult to logically define conditions that are clearly complex or difficult; the concept of a linguistic variable is necessary in such circumstances. Here, using this form of expression, five basic linguistic terms emerge to facilitate comparison of the criteria: absolutely important, very strongly important, essentially important, weakly important, and equally importance. These terms are used according to the fuzzy membership function, shown for the language variables in Figure 3 (Hsieh, Lu, & Tzeng, 2004).

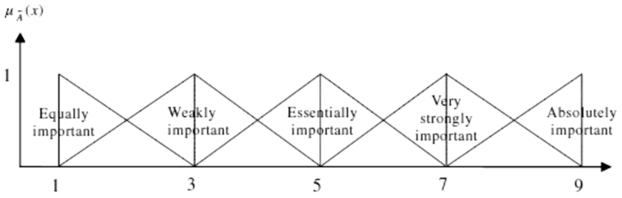


Figure 3. Fuzzy membership function for language variables (Hsieh, Lu, & Tzeng, 2004)

In a fuzzy hierarchical analysis method, decision-makers are asked to compare the elements of each row after providing a hierarchical graph. This is illustrated in Table 2, which represents an example of fuzzy numbers and the relative importance of the elements expressed by using fuzzy numbers.

Table 2. Membership function of fuzzy numbers

Fuzzy number	Linguistic scales	Scale of fuzzy number
$\tilde{1}$	Equal importance	(1,1,3)
$\tilde{3}$	Weakly important	(1,3,5)
$\tilde{5}$	Essentially important	(3,5,7)
$\tilde{7}$	Very strongly important	(5,7,9)
$\tilde{9}$	Absolutely important	(7,9,9)

3.1.3. Formation of a comparative matrix $\tilde{A}$ by applying fuzzy numbers

Pairwise comparison matrix is:

$$\tilde{A} = \begin{bmatrix} 1 & \tilde{a}_{12} & \dots & \tilde{a}_{1n} \\ \tilde{a}_{21} & 1 & \dots & \tilde{a}_{2n} \\ \tilde{a}_{n1} & \tilde{a}_{n2} & \dots & 1 \end{bmatrix}. \tag{3}$$

This matrix contains the following fuzzy numbers:

$$\tilde{a}_{ij} = \begin{cases} 1 & i = j \\ \tilde{1}, \tilde{3}, \tilde{5}, \tilde{7}, \tilde{9} & i \neq j \end{cases}. \tag{4}$$

For geometric averaging of expert opinions and weighting criteria, Buckley's method (Buckley, 1985) can be used as follows:

$$\tilde{r}_i = \left(\tilde{a}_{i1} \otimes \tilde{a}_{i2} \otimes \ldots \otimes \tilde{a}_{in}\right)^{\frac{1}{n}}; \tag{5}$$

$$\tilde{w}_i = \tilde{r}_i \otimes \left(\tilde{r}_1 \otimes \ldots \otimes \tilde{r}_n\right)^{-1}, \tag{6}$$

where:

$\tilde{a}_{in}$ – value of fuzzy comparison of criterion i to n;

$\tilde{r}_i$ – value of geometric mean of fuzzy comparison value of criterion i;

$\tilde{w}_i$ – the fuzzy weight of the ith criterion, which can be indicated by a TFN;

$\tilde{w}_i = \left(L_{wi}, M_{wi}, U_{wi}\right)$ stand for values of the lower, middle, and upper of the fuzzy weight of the ith criterion.

Finally, in order to rank the criteria, it is necessary to convert fuzzy numbers to non-fuzzy numbers. In this study, Best Non-fuzzy Performance Value (BNP). Method was used for defuzzy numbers. BNP value of the fuzzy number R can be found by the equation (6) (Hsieh, Lu, & Tzeng, 2004):

$$BNP_i = \frac{\left[\left(UR_i - LR_i\right) + \left(MR_i - LR_i\right)\right]}{3} + LR_i. \tag{7}$$

Ultimately, by multiplying the weights of the corresponding criteria, the final weight of each under the criteria is obtained.

4. RATINGS OF BLASTING OPERATIONS RISKS

In this study, after drawing a hierarchy in accordance with the conditions of the blasting operation and according to the experts' opinion, the scores were evaluated using the FAHP method to compare the pair between the criteria and each of the sub-criteria. Therefore, according to the experts' opinion, paired comparison matrices of the criteria were adjusted according to matrices A, B, and C (Figs. 4 – 6).

$$\begin{array}{c|cccccccccc}
 & D1 & D2 & D3 & D4 & D5 & D6 & D7 & D8 & D9 & D10 \\ \hline
D1 & 1 & \tilde{3} & \tilde{3} & \tilde{9} & \tilde{7} & \tilde{1} & \tilde{5} & \tilde{7}^{-1} & \tilde{5} & \tilde{7} \\
D2 & \tilde{3}^{-1} & 1 & \tilde{1} & \tilde{5} & \tilde{7} & \tilde{3}^{-1} & \tilde{3} & \tilde{5}^{-1} & \tilde{7} & \tilde{9} \\
D3 & \tilde{3}^{-1} & \tilde{1} & 1 & \tilde{7} & \tilde{5} & \tilde{3}^{-1} & \tilde{3} & \tilde{7}^{-1} & \tilde{5} & \tilde{7} \\
D4 & \tilde{9}^{-1} & \tilde{5}^{-1} & \tilde{7}^{-1} & 1 & \tilde{5}^{-1} & \tilde{7}^{-1} & \tilde{5}^{-1} & \tilde{9}^{-1} & \tilde{5}^{-1} & \tilde{1} \\
D5 & \tilde{7}^{-1} & \tilde{7}^{-1} & \tilde{5}^{-1} & \tilde{5} & 1 & \tilde{5}^{-1} & \tilde{1} & \tilde{7}^{-1} & \tilde{1} & \tilde{5} \\
D6 & \tilde{1} & \tilde{3} & \tilde{3} & \tilde{7} & \tilde{5} & 1 & \tilde{3} & \tilde{5}^{-1} & \tilde{5} & \tilde{7} \\
D7 & \tilde{5}^{-1} & \tilde{3}^{-1} & \tilde{3}^{-1} & \tilde{5} & \tilde{1} & \tilde{3}^{-1} & 1 & \tilde{5}^{-1} & \tilde{5} & \tilde{7} \\
D8 & \tilde{7} & \tilde{5} & \tilde{7} & \tilde{9} & \tilde{7} & \tilde{5} & \tilde{5} & 1 & \tilde{7} & \tilde{9} \\
D9 & \tilde{5}^{-1} & \tilde{7}^{-1} & \tilde{5}^{-1} & \tilde{5} & \tilde{1} & \tilde{5}^{-1} & \tilde{5}^{-1} & \tilde{7}^{-1} & 1 & \tilde{5} \\
D10 & \tilde{7}^{-1} & \tilde{9}^{-1} & \tilde{7}^{-1} & \tilde{1} & \tilde{5}^{-1} & \tilde{7}^{-1} & \tilde{7}^{-1} & \tilde{9}^{-1} & \tilde{5}^{-1} & 1
\end{array}$$

Figure 4. Matrix A, paired comparison of main criteria: Expert A

Finally, in order to integrate the experts' opinion and achieve a single matrix (matrix D) (Fig. 7), a geometric mean method was used in accordance with equation (5).

$$\begin{array}{c|cccccccccc}
 & D1 & D2 & D3 & D4 & D5 & D6 & D7 & D8 & D9 & D10 \\ \hline
D1 & 1 & \tilde{3} & \tilde{5} & \tilde{9} & \tilde{5} & \tilde{3}^{-1} & \tilde{3} & \tilde{7}^{-1} & \tilde{7} & \tilde{9} \\
D2 & \tilde{3}^{-1} & 1 & \tilde{3} & \tilde{9} & \tilde{3} & \tilde{1} & \tilde{3} & \tilde{7}^{-1} & \tilde{5} & \tilde{7} \\
D3 & \tilde{5}^{-1} & \tilde{3}^{-1} & 1 & \tilde{5} & \tilde{3} & \tilde{1} & \tilde{5} & \tilde{5}^{-1} & \tilde{3} & \tilde{5} \\
D4 & \tilde{9}^{-1} & \tilde{9}^{-1} & \tilde{5}^{-1} & 1 & \tilde{1} & \tilde{5}^{-1} & \tilde{3}^{-1} & \tilde{9}^{-1} & \tilde{3}^{-1} & \tilde{3} \\
D5 & \tilde{5}^{-1} & \tilde{3}^{-1} & \tilde{3}^{-1} & \tilde{1} & 1 & \tilde{3}^{-1} & \tilde{3}^{-1} & \tilde{1} & \tilde{7}^{-1} & \tilde{3} \\
D6 & \tilde{3} & \tilde{1} & \tilde{1} & \tilde{5} & \tilde{3} & 1 & \tilde{3} & \tilde{5}^{-1} & \tilde{3} & \tilde{5} \\
D7 & \tilde{3}^{-1} & \tilde{3}^{-1} & \tilde{5}^{-1} & \tilde{3} & \tilde{3} & \tilde{3}^{-1} & 1 & \tilde{5}^{-1} & \tilde{3} & \tilde{7} \\
D8 & \tilde{7} & \tilde{7} & \tilde{5} & \tilde{9} & \tilde{7} & \tilde{5} & \tilde{5} & 1 & \tilde{7} & \tilde{9} \\
D9 & \tilde{7}^{-1} & \tilde{5}^{-1} & \tilde{3} & \tilde{3} & \tilde{1} & \tilde{3}^{-1} & \tilde{3}^{-1} & \tilde{7}^{-1} & 1 & \tilde{3} \\
D10 & \tilde{9}^{-1} & \tilde{7}^{-1} & \tilde{5}^{-1} & \tilde{3}^{-1} & \tilde{3}^{-1} & \tilde{5}^{-1} & \tilde{7}^{-1} & \tilde{9}^{-1} & \tilde{3}^{-1} & 1
\end{array}$$

Figure 5. Matrix B, paired comparison of main criteria: Expert B

$$\begin{array}{c|cccccccccc}
 & D1 & D2 & D3 & D4 & D5 & D6 & D7 & D8 & D9 & D10 \\ \hline
D1 & 1 & \tilde{1} & \tilde{5} & \tilde{7} & \tilde{5} & \tilde{3}^{-1} & \tilde{5} & \tilde{5}^{-1} & \tilde{7} & \tilde{9} \\
D2 & \tilde{1} & 1 & \tilde{3} & \tilde{5} & \tilde{3} & \tilde{1} & \tilde{5} & \tilde{9}^{-1} & \tilde{3} & \tilde{7} \\
D3 & \tilde{5}^{-1} & \tilde{3}^{-1} & 1 & \tilde{5} & \tilde{5} & \tilde{1} & \tilde{5} & \tilde{3}^{-1} & \tilde{3} & \tilde{7} \\
D4 & \tilde{7}^{-1} & \tilde{5}^{-1} & \tilde{5}^{-1} & 1 & \tilde{1} & \tilde{3}^{-1} & \tilde{5}^{-1} & \tilde{9}^{-1} & \tilde{3}^{-1} & \tilde{3} \\
D5 & \tilde{5}^{-1} & \tilde{3}^{-1} & \tilde{5}^{-1} & \tilde{1} & 1 & \tilde{3}^{-1} & \tilde{3}^{-1} & \tilde{7}^{-1} & \tilde{3}^{-1} & \tilde{5} \\
D6 & \tilde{3} & \tilde{1} & \tilde{1} & \tilde{3} & \tilde{3} & 1 & \tilde{3} & \tilde{3}^{-1} & \tilde{5} & \tilde{7} \\
D7 & \tilde{5}^{-1} & \tilde{5}^{-1} & \tilde{5}^{-1} & \tilde{5} & \tilde{3} & \tilde{3}^{-1} & 1 & \tilde{7}^{-1} & \tilde{3} & \tilde{7} \\
D8 & \tilde{5} & \tilde{9} & \tilde{3} & \tilde{9} & \tilde{7} & \tilde{3} & \tilde{7} & 1 & \tilde{7} & \tilde{9} \\
D9 & \tilde{7}^{-1} & \tilde{3}^{-1} & \tilde{3}^{-1} & \tilde{3} & \tilde{3} & \tilde{5}^{-1} & \tilde{3}^{-1} & \tilde{7}^{-1} & 1 & \tilde{5} \\
D10 & \tilde{9}^{-1} & \tilde{7}^{-1} & \tilde{7}^{-1} & \tilde{3}^{-1} & \tilde{5}^{-1} & \tilde{7}^{-1} & \tilde{7}^{-1} & \tilde{9}^{-1} & \tilde{5}^{-1} & 1
\end{array}$$

Figure 6. Matrix C, paired comparison of main criteria: Expert C

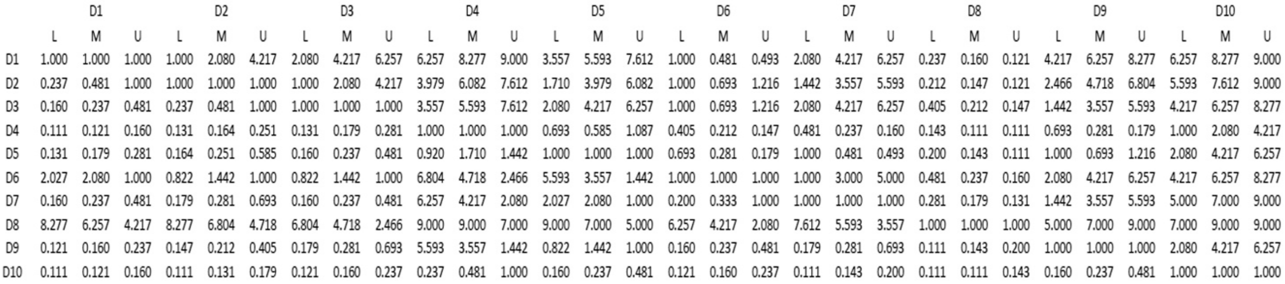
In the following, the matrix of the sub-criteria was also adjusted and, finally, was calculated as a single matrix for each sub-criterion by the geometric mean method. The average matrix of the group of sub-criteria is equal to the matrices C-D1, C-D2, C-D3, and C-D6.

The average of pairings' comparison of these matrices is provided in Figures 8 – 11. The specified criteria have a positive impact on blasting operations risks. This means that increase in the score of one criterion is based on experts' opinions over and above other criteria: this increases the level of the impact of the critical level of risk.

Considering the importance of the weights of the criteria in the pairwise matrices, the fuzzy weight obtained from the criteria and the sub criteria is given in Table 3.

5. RESULTS AND DISCUSSION

According to the scores of criteria and sub criteria, the weight of each criterion in its sub-criteria emerging from the FAHP method gives scores associated with each sub-criterion as provided in Table 4. Criterion of effects and results of blasting operations (D8) with score 0.334 were determined as the most effective criterion in blasting operations risk. Therefore, to reduce blasting operation risk it is necessary to examine, first and foremost, the factors that create this criterion. The larger aim herein is to control the outputs of the blast operation, including worse fragmentation, boulder production, back break, side break, pivot (toe) creation, misfire, noise production, ground vibration, air blast, fly rock, production of toxic gases from the explosion, dust production, premature blast, and inappropriate stability of remaining bench face. The remaining work chest is of particular importance. It should be noted that controlling some of these cases is related to human resources control as well as the principles of blasting design. Therefore, consideration of other criteria is also necessary.



	D1			D2			D3			D4			D5			D6			D7			D8			D9			D10		
	L	M	U	L	M	U	L	M	U	L	M	U	L	M	U	L	M	U	L	M	U	L	M	U	L	M	U	L	M	U
D1	1.000	1.000	1.000	1.000	2.080	4.217	2.080	4.217	6.257	6.257	8.277	9.000	3.557	5.593	7.612	1.000	0.481	0.493	2.080	4.217	6.257	0.237	0.160	0.121	4.217	6.257	8.277	6.257	8.277	9.000
D2	0.237	0.481	1.000	1.000	1.000	1.000	1.000	2.080	4.217	3.979	6.082	7.612	1.710	3.979	6.082	1.000	0.693	1.216	1.442	3.557	5.593	0.212	0.147	0.121	2.466	4.718	6.804	5.593	7.612	9.000
D3	0.160	0.237	0.481	0.237	0.481	1.000	1.000	1.000	1.000	3.557	5.593	7.612	2.080	4.217	6.257	1.000	0.693	1.216	2.080	4.217	6.257	0.405	0.212	0.147	1.442	3.557	5.593	4.217	6.257	8.277
D4	0.111	0.121	0.160	0.131	0.164	0.251	0.131	0.179	0.281	1.000	1.000	1.000	0.693	0.585	1.087	0.405	0.212	0.147	0.481	0.237	0.160	0.143	0.111	0.111	0.693	0.281	0.179	1.000	2.080	4.217
D5	0.131	0.179	0.281	0.164	0.251	0.585	0.160	0.237	0.481	0.920	1.710	1.442	1.000	1.000	1.000	0.693	0.281	0.179	1.000	0.481	0.493	0.200	0.143	0.111	1.000	0.693	1.216	2.080	4.217	6.257
D6	2.027	2.080	1.000	0.822	1.442	1.000	0.822	1.442	1.000	6.804	4.718	2.466	5.593	3.557	1.442	1.000	1.000	1.000	1.000	3.000	5.000	0.481	0.237	0.160	2.080	4.217	6.257	4.217	6.257	8.277
D7	0.160	0.237	0.481	0.179	0.281	0.693	0.160	0.237	0.481	6.257	4.217	2.080	2.027	2.080	1.000	0.200	0.333	1.000	1.000	1.000	1.000	0.281	0.179	0.131	1.442	3.557	5.593	5.000	7.000	9.000
D8	8.277	6.257	4.217	8.277	6.804	4.718	6.804	4.718	2.466	9.000	9.000	7.000	9.000	7.000	5.000	6.257	4.217	2.080	7.612	5.593	3.557	1.000	1.000	1.000	5.000	7.000	9.000	7.000	9.000	9.000
D9	0.121	0.160	0.237	0.147	0.212	0.405	0.179	0.281	0.693	5.593	3.557	1.442	0.822	1.442	1.000	0.160	0.237	0.481	0.179	0.281	0.693	0.111	0.143	0.200	1.000	1.000	1.000	2.080	4.217	6.257
D10	0.111	0.121	0.160	0.111	0.131	0.179	0.121	0.160	0.237	0.237	0.481	1.000	0.160	0.237	0.481	0.121	0.160	0.237	0.111	0.143	0.200	0.111	0.111	0.143	0.160	0.237	0.481	1.000	1.000	1.000

Figure 7. Matrix D, Average experts' opinion according to the main criteria

$$\begin{array}{c|cccccccccccccccccc|}
 & & \text{C1} & & & \text{C2} & & & \text{C3} & & & \text{C4} & & & \text{C5} & & & \text{C6} & \\
 & \text{L} & \text{M} & \text{U} & \text{L} & \text{M} & \text{U} & \text{L} & \text{M} & \text{U} & \text{L} & \text{M} & \text{U} & \text{L} & \text{M} & \text{U} & \text{L} & \text{M} & \text{U} \\
\text{C1} & 1.000 & 1.000 & 1.000 & 1.000 & 0.693 & 1.216 & 1.000 & 0.481 & 0.493 & 1.000 & 1.442 & 3.557 & 0.693 & 0.585 & 0.523 & 1.000 & 1.442 & 3.557 \\
\text{C2} & 0.822 & 1.442 & 1.000 & 1.000 & 1.000 & 1.000 & 1.000 & 0.693 & 1.216 & 1.000 & 3.000 & 5.000 & 1.000 & 1.442 & 3.557 & 1.442 & 3.557 & 5.593 \\
\text{C3} & 2.027 & 2.080 & 1.000 & 0.822 & 1.442 & 1.000 & 1.000 & 1.000 & 1.000 & 2.466 & 4.718 & 6.804 & 1.442 & 2.466 & 4.718 & 2.759 & 5.130 & 6.804 \\
\text{C4} & 0.281 & 0.693 & 1.000 & 0.200 & 0.333 & 1.000 & 0.147 & 0.212 & 0.405 & 1.000 & 1.000 & 1.000 & 0.333 & 0.200 & 0.143 & 1.000 & 0.481 & 0.493 \\
\text{C5} & 1.913 & 1.710 & 1.442 & 0.281 & 0.693 & 1.000 & 0.212 & 0.405 & 0.693 & 7.000 & 5.000 & 3.000 & 1.000 & 1.000 & 1.000 & 1.442 & 3.557 & 5.593 \\
\text{C6} & 0.281 & 0.693 & 1.000 & 0.179 & 0.281 & 0.693 & 0.147 & 0.195 & 0.362 & 2.027 & 2.080 & 1.000 & 0.179 & 0.281 & 0.693 & 1.000 & 1.000 & 1.000
\end{array}$$

Figure 8. Matrix C-D1, the average of experts' opinion on sub-criteria group of the criteria D1

$$\begin{array}{c|ccccccccc|}
 & & \text{C7} & & & \text{C8} & & & \text{C9} & \\
 & \text{L} & \text{M} & \text{U} & \text{L} & \text{M} & \text{U} & \text{L} & \text{M} & \text{U} \\
\text{C7} & 1.000 & 1.000 & 1.000 & 1.442 & 1.710 & 3.979 & 1.442 & 3.557 & 5.593 \\
\text{C8} & 0.251 & 0.585 & 0.693 & 1.000 & 1.000 & 1.000 & 1.000 & 2.080 & 4.217 \\
\text{C9} & 0.179 & 0.281 & 0.693 & 0.237 & 0.481 & 1.000 & 1.000 & 1.000 & 1.000
\end{array}$$

Figure 9. Matrix C-D2, the average of experts' opinion on sub-criteria group of the criteria D2

$$\begin{array}{c|ccccccccc|}
 & & \text{C10} & & & \text{C11} & & & \text{C12} & \\
 & \text{L} & \text{M} & \text{U} & \text{L} & \text{M} & \text{U} & \text{L} & \text{M} & \text{U} \\
\text{C10} & 1.000 & 1.000 & 1.000 & 0.693 & 0.281 & 0.179 & 0.693 & 0.405 & 0.441 \\
\text{C11} & 5.593 & 3.557 & 1.442 & 1.000 & 1.000 & 1.000 & 1.000 & 3.000 & 5.000 \\
\text{C12} & 2.268 & 2.466 & 1.442 & 0.200 & 0.333 & 1.000 & 1.000 & 1.000 & 1.000
\end{array}$$

Figure 10. Matrix C-D3, the average of experts' opinion on sub-criteria group of the criteria D3

$$\begin{array}{c|cccccc|}
 & & \text{C15} & & & \text{C16} & \\
 & \text{L} & \text{M} & \text{U} & \text{L} & \text{M} & \text{U} \\
\text{C15} & 1.000 & 1.000 & 1.000 & 0.693 & 0.281 & 0.179 \\
\text{C16} & 5.593 & 3.557 & 1.442 & 1.000 & 1.000 & 1.000
\end{array}$$

Figure 11. Matrix C-D6, the average of experts' opinion on sub-criteria group of the criteria D6

The second most effective criterion determining the risk of blasting operations is criterion D1. This criterion includes the sub-criteria regarding the performance and knowledge of manpower in the process of blast operations. Identifying and controlling this criterion is essential in order to prevent damage to human resources and reduce potential risks associated with the risk of blasting operations.

It has also been observed by examining the privileges of all the sub-criteria that occupational health and safety (C3) including job stress, safety risks of workshop and site, and imbalance of work and life with a score of 0.377 is the first sub-criterion and sub-criterion (C18) with a score of 0.334 is the second sub-criterion of blasting operation risk factors. On the other hand, natural hazards (D10) and sub-criterion (C20) with the introduction of thunderstorms, rain, wind, and other environmental conditions with a score of 0.015 have the least priority amongst factors causing blast operation risk.

Table 3. Fuzzy weights obtained from criteria and sub-criteria

Criteria and sub-criteria	Local weight		
D1	0.117	0.157	0.211
C1	0.748	1.000	1.337
C2	0.818	1.833	2.364
C3	1.266	2.760	2.608
C4	0.298	0.476	0.588
C5	0.814	1.662	1.701
C6	0.296	0.616	0.794
D2	0.075	0.115	0.179
C7	0.249	0.536	1.247
C8	0.123	0.313	0.634
C9	0.068	0.151	0.392
D3	0.064	0.093	0.145
C10	0.224	0.134	0.129
C11	0.509	0.608	0.581
C12	0.220	0.259	0.340
D4	0.021	0.020	0.025
C13	1.000	1.000	1.000
D5	0.031	0.033	0.044
C14	1.000	1.000	1.000
D6	0.106	0.133	0.118
C15	0.513	0.219	0.132
C16	1.457	0.781	0.376
D7	0.042	0.055	0.077
C17	1.000	1.000	1.000
D8	0.371	0.346	0.286
C18	1.000	1.000	1.000
D9	0.024	0.035	0.052
C19	1.000	1.000	1.000
D10	0.010	0.014	0.023
C20	1.000	1.000	1.000

Therefore, in assessing the risks of explosive operations, considering all the effective criteria is important: firstly, the criteria of the effects and results of blasting operation, and then the human resources. After reviewing and ranking the sub-criteria, the sub-criteria related to human resources appear to be of particular importance. Further, other criteria based on the score obtained have significant effects on the risk of blasting operations.

Table 4. Final Scores of Criteria and Sub-criteria for blasting operation risks

Criteria	Local weight			Overall weight			BNP	Rank
D1	0.117	0.157	0.211				0.162	2
C1	0.748	1.000	1.337	0.087	0.157	0.282	0.176	4
C2	0.818	1.833	2.364	0.096	0.287	0.499	0.294	3
C3	1.266	2.760	2.608	0.148	0.432	0.551	0.377	1
C4	0.298	0.476	0.588	0.035	0.075	0.124	0.078	8
C5	0.814	1.662	1.701	0.095	0.260	0.359	0.238	5
C6	0.296	0.616	0.794	0.035	0.097	0.168	0.100	7
D2	0.075	0.115	0.179				0.123	3
C7	0.249	0.536	1.247	0.019	0.062	0.224	0.101	6
C8	0.123	0.313	0.634	0.009	0.036	0.114	0.053	10
C9	0.068	0.151	0.392	0.005	0.017	0.070	0.031	13
D3	0.064	0.093	0.145				0.101	5
C10	0.224	0.134	0.129	0.014	0.012	0.019	0.015	16
C11	0.509	0.608	0.581	0.033	0.057	0.084	0.058	9
C12	0.220	0.259	0.340	0.014	0.024	0.049	0.029	14
D4	0.021	0.020	0.025				0.022	9
C13	1.000	1.000	1.000	0.021	0.020	0.025	0.022	15
D5	0.031	0.033	0.044				0.036	8
C14	1.000	1.000	1.000	0.031	0.033	0.044	0.036	12
D6	0.106	0.133	0.118				0.119	4
C15	0.513	0.219	0.132	0.054	0.029	0.016	0.033	13
C16	1.457	0.781	0.376	0.154	0.104	0.044	0.101	6
D7	0.042	0.055	0.077				0.058	6
C17	1.000	1.000	1.000	0.042	0.055	0.077	0.058	9
D8	0.371	0.346	0.286				0.334	1
C18	1.000	1.000	1.000	0.371	0.346	0.286	0.334	2
D9	0.024	0.035	0.052				0.037	7
C19	1.000	1.000	1.000	0.024	0.035	0.052	0.037	11
D10	0.010	0.014	0.023				0.015	10
C20	1.000	1.000	1.000	0.010	0.014	0.023	0.015	16

Thus, it can be seen from Figure 12 that the sub-criteria for safety regulations (C7) and components of explosive operation design (C16) with a score of 0.032; sub criteria for environmental conditions (C11) and blast block specifications (C17) with a score of 0.018; sub-criteria of geology of area (C10) and environmental anomalies (C20) with a score of 0.005 will be in the next category of sub-criteria.

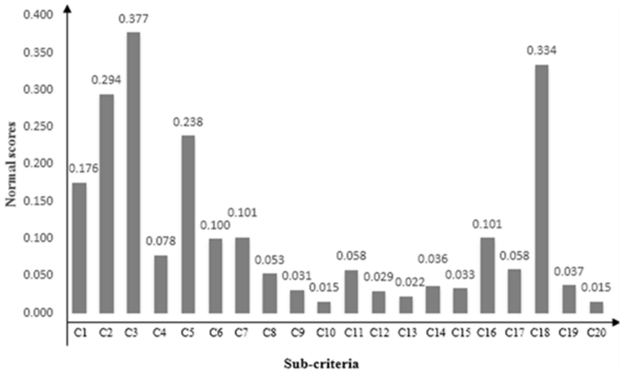


Figure 12. Sub-criteria ranking charts

So, sub-criteria of different categories of criteria can be placed at the same level with equal privileges in the same categories since they simultaneously affect the risk of explosion operations. Effective sub-criteria with equal privileges play the same role in creating the risk of blasting operations. Therefore, the criteria affecting the risk of blasting operations will have an effective impact on both project conditions and the risk of blasting operations. Control of equal priorities is of paramount importance. With the simultaneous occurrence of the risk factors of the blasting operation, project control will be more difficult.

The ranking of risks of blasting operations according to the studies carried out and the opinion of the experts is of particular importance. According to this rating, the most important risks of blasting operations can be identified and attempts can then be made to reduce them. Although blasting operation risks will be ranked according to the importance and impact of the ranking, but considering the conditions of the mining projects it should be noted that all criteria are simultaneously effective and significant. Therefore, control of all priorities is necessary.

Meanwhile, human resources and the effects and results of blasting operations, both of which affect each other, are more important. Manpower is a factor in the occurrence of errors and the creation of adverse conditions in the event of accidents resulting from explosions: it subsequently impacts the operational conditions of the project. Therefore, the evaluation of human resource performance and increase in the level of knowledge and skills and occupational safety and control of all outputs of blasting operations such as fly rock, air blast, and ground vibration is necessary. It should be noted that the severity of the risks is not equal altogether. Some require immediate and urgent action, and others can be scrutinised over a wider range of time. Therefore, selecting the most important project risks and taking actions to remove them is essential for risk management.

5. CONCLUSIONS

Due to the complexity of the project, the size of the project, competition and economic and political issues, the need for risk management in projects is inevitable. Because there is no possibility of managing and responding to all identified risks, evaluating and prioritizing risks is critical to managing and responding to them once they have been identified. The existence of risk in projects shows that uncertainty exists in the implementation environment of projects. Fuzzy calculations are a very good tool for modeling and measuring these uncertainties.

The proposed method in this study is the ability to consider the relationship between criteria: it has special features in terms of linguistic variables, qualitative opinions of experts and decision-makers, and their conversion into quantitative variables. With the introduction of fuzzy concepts in order to prioritize the risks of blasting operations, uncertainty – which is the main component of project planning is considered. Because this model has the ability to consider the opinions of several experts or decision-makers, it is compatible with the nature of project planning, which is premised on group decision-making. As a result, decisions were made according to expert judgment and after considering group decision-making with fuzzy logic to rank the risks of blast operations. Therefore, identifying risk factors, knowing the extent and type of impacts, and their proper ranking is a major step in correct assessment and timely risk responsiveness.

Determining the risks of blast operations with a set of criteria based on research background studies, field studies, and experts experiences based on a fuzzy AHP approach have been presented. The most important risk factors in blasting operations in accordance with the specified criteria for reducing the risks were identified in ten groups and twenty sub-groups. The comparison of criteria and sub-criteria by using a questionnaire and experts' opinions was done. In evaluating the scores, the criterion Effects and results of blasting operations (D8) was found to have the highest score in terms of effective parameters in producing explosive results and environmental impacts. Subsequently, performance and knowledge of manpower (D1) was the second most effective factor in the risk of blasting operations. On the other hand, the natural hazards (D10) was the last priority of the factors that caused the risk of blasting operations. Also, based on the FAHP method, the lack of control of sub-criteria for health and safety (C3), blast operation results (C18), and knowledge, skill and staffing (C2) as factors affecting the risk of blasting operations are introduced. The two sub-criteria C3 and C2 in relation to the D1 and sub-criterion C18 in relation to the D8, are considered to be the most effective in the risk of blasting operations. Therefore, it is essential to control these category of criteria and the sub-criteria related to them in blasting operations.

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ОЦІНКА РИЗИКУ ПРОВЕДЕННЯ ВИБУХОВИХ РОБІТ У ВІДКРИТИХ КАР’ЄРАХ ІЗ ВИКОРИСТАННЯМ НЕЧІТКОГО МЕТОДУ АНАЛІЗУ ІЄРАРХІЙ (НМАІ)

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Мета. Визначення ризиків проведення вибухових робіт та їх оцінка на основі використанням нечіткого методу аналізу ієрархій (НМАІ) для покращення управління якістю проектів.

Методика. В рамках даного дослідження, проблеми визначення та оцінки ризиків вибухових робіт розглядалися із застосуванням нечіткого методу аналізу ієрархій. На базі аналізу історичних даних і польового дослідження з урахуванням експертних оцінок були визначені критерії та підкритерії для побудови ієрархій.

Результати. За результатами НМАІ, неконтролюючий підкритерій здоров’я та безпеки (C3), підкритерій результатів вибухових робіт (C18), знань, умінь і кадрів (C2) зі значеннями 0.377, 0.334 і 0.294 відповідно найбільш ефективні в появі ризику проведення вибухових робіт. Підкритерій C18 чинить найбільший вплив на ризик проведення вибухових робіт. Критерій результатів і наслідків вибухових робіт (D8) з найефективнішим значенням 0.334 та критерій природних катастроф (D10) зі значенням 0.015 є останніми пріоритетами серед чинників, які визначають ризик проведення вибухових робіт.

Наукова новизна. Отримав доповнення та подальший розвиток науково-методичний підхід до визначення ризиків при проведенні вибухових робіт, заснований на їх ранжуванні з використанням системи виявлених критеріїв і підкритеріїв методом НМАІ.

Практична значимість. Для успішного керування проектом важливо визначати найсерйозніші ризики проекту й вжити заходів щодо їх усунення. Відносно ранжирування ризиків проведення вибухових робіт управління підкритеріями C3, C18 і C2, а також критерієм D8, особливо важливо для зниження цих ризиків та покращення якості управління проектом.

Ключові слова: *вибухові роботи, відкритий кар’єр, оцінка ризику, метод НМАІ, критерії та підкрітерії*

ОЦЕНКА РИСКА ПРОВЕДЕНИЯ ВЗРЫВНЫХ РАБОТ В ОТКРЫТЫХ КАРЬЕРАХ С ИСПОЛЬЗОВАНИЕМ НЕЧЕТКОГО МЕТОДА АНАЛИЗА ИЕРАРХИЙ (НМАИ)

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Цель. Определение рисков проведения взрывных работ и их оценка на основе использования нечеткого метода анализа иерархий (НМАИ) для улучшения управления качеством проектов.

Методика. В рамках данного исследования, проблемы определения и оценки рисков взрывных работ рассматривались с применением нечеткого метода анализа иерархий. На базе анализа исторических данных и полевого исследования с учетом экспертных оценок были определены, критерии и подкритерии для построения иерархий.

Результаты. По результатам НМАИ, неконтролирующий подкритерий здоровья и безопасности (C3), подкритерий результатов взрывных работ (C18), знаний, умений и кадров (C2) со значениями 0.377, 0.334 и 0.294 соответственно наиболее эффективны в появлении риска проведения взрывных работ. Подкритерий C18 оказывает самое большое влияние на риск проведения взрывных работ. Критерий результатов и последствий взрывных работ (D8) с самым эффективным значением 0.334 и критерий природных катастроф (D10) со значением 0.015 являются последними приоритетами среди факторов, которые определяют риск проведения взрывных работ.

Научная новизна. Получил дополнение и дальнейшее развитие научно-методический подход к определению рисков при проведении взрывных работ, основанный на их ранжировании с использованием системы выявленных критериев и подкритериев методом НМАИ.

Практическая значимость. Для успешного руководства проектом важно определять самые серьезные риски проекта и предпринять действия по их устранению. В отношении ранжирования рисков проведения взрывных работ управление подкритериями C3, C18 и C2, а также критерием D8, особенно важно для снижения этих рисков и улучшения руководства проектом.

Ключевые слова: *взрывные работы, открытый карьер, оценка риска, метод НМАИ, критерии и подкритерии*

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