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Risk criteria classification and the evaluation of blasting operations in open pit mines by using the FDANP method

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Abstract

Purpose. Mineral projects are heavily influenced by risk factors. By providing evidence-based information and analysis to make informed decisions about how to choose between options, a risk assessment can be made.

Methods. In this study, the relationships of 46 criteria and 10 dimensions affecting the risk of blasting operations were investigated in order to determine the significance, effectiveness, relative weight of the criteria and dimensions as well as to prioritize the risk criteria of blasting operations. For this purpose, the combination of the FDEMATEL method and FANP method are used as FDANP.

Findings. The most important criterion is the lack of specialized knowledge (C_1). The damage to manpower criterion (C_{46}) will receive the greatest impact from other criteria. The criterion for implementing the explosion plan, without respecting the design principles (C_{12}) has most interactions with other criteria and the failure to determine the amount of production capacity (low or high) criterion (C_{45}) has the least interactions with other criteria. According to the FDANP method, the number of explosions in one stage (C_{14}) is the first criterion of the blasting operations risk.

Originality. By controlling this criterion, the effects and destructive consequences of blasting operations can be prevented. Controlling this criterion reduces the risk of blasting operations and also reduces the damage by C_{46} criterion. From comparison, human resources dimension (D_1) is the most effective and natural hazards dimension (D_{10}) has the greatest interactions with other dimensions and is most affected among the other dimensions. The production and extraction consideration dimension (D_9) has the least interaction with other dimensions and is less important.

Practical implications. By reducing the destructive effects of blasting operations, two favorable results will be achieved: the reduction of damage caused by undesirable consequences and the assignment of a greater share of blast energy to the desired outcomes.

Keywords: *blasting evaluation, blasting operation, open pit mine, FDANP method*

1. Introduction

Released explosives, in addition to fragmentation and moving the rock, will cause undesirable consequences such as fly rock, ground vibration, air blast, back break, noise production, and dust production [1]. In 2008, the dimensions of the explosive block, the amount of moisture and water in the holes, the type of explosive rock (ore or waste), and the need for mixing the ore and waste on the blasting outputs such as fragmentation, the boulder, the floor and toe position, and the geometric shape of the fragmentation stone have been investigated by Taji in open-pit mines by using the Blast Block Situation Rating (BBSR) method [2]. The following the Optimization Demand Measurement (ODM) method was used to evaluate the blasting according to the results of the blasting operations in open-pit mines [3]. By using the Artificial Neural Network (ANN) model, Monjezi evaluated 192 datasets and proposed a method to predict fly rock. Based on these results, it was found that the index of blast capability, charge per delay, hole diameter, stemming length, and powder factor are among the most effective factors in creating fly rock [4]. In 2013, the prediction of fly rock distance, by using the Particle Swarm Optimization (PSO) and ANN methods, was carried out by Jahed Armaghani et al. [5]. In the same year, the prediction of fragmentation and back break was introduced by Back Propagation Neural Network (BPNN) and Radial Base Function Neural Network

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(RBFNN) [6]. In 2014, the prediction of ground vibration by the ANN methodology was also studied [7]. Marto et al. (2014), in order to predict fly rock, investigated the parameters of 113 blast operations by using ANN and Imperialist Competitive Algorithm (ICA) [8]. In 2014, the prediction of fly rock by using the ANN method and Multivariate Regression Analysis (MVRA) was also investigated by Trivedi [9]. In 2013 and 2014, new models were presented, which were to be used as forms of risk assessment in blasting operations to predict back break, rock fragmentation, and flyrock [10], [11]. In 2016, fragmentation control was carried out by Singh. In this work, a systematic study was conducted investigating the impact of blasting design parameters on rock fragmentation by taking photographs of all the stages of the blast and after rock fragmentation for software analysis of the photos in the mines of India [12]. In 2017, rock fragmentation studies, back break, and the most effective explosive pattern and design were carried out by using Mutual Information (MI) methods at the Meydook copper mine [13], Particle Swarm Optimization (PSO) [14], and Data Envelopment Analysis (DEA) [15] have been studied.

Studies are only intended to predict the risks of blasting operations or methods for investigating and managing the risks of mining projects. In addition to predicting and investigating one or more destructive effects of blasting operations, attention should be paid to all the criteria for the risk of blasting operations in open-pit mines. This creates the overall risk of the blasting operations to be investigated and, by identifying the relationships and ranking of risk criterion through blasting operations, it reduces the risk of blasting in mining projects. For this purpose, by defining all the effective criteria that have an effect on the risk of blasting operations from research findings and expert opinions in this paper, the Decision Making Trial and Evaluation (DEMATEL) method was first developed to establish a communication-mapping structure to determine the causal relationship between the dimensions and criteria based on graph theory. It is possible to determine the relationship between the criteria by dividing the causes and effects [16]. This methodology was developed by Fontela & Gabus (1971), and was used in 1976 with a view of using the experts in scientific, political, and economic fields. The DEMATEL method accommodates visual programming and problem-solving so that the related factors can be categorized as causes and effects. In this case, the final result of DEMATEL is a visual map in which the relationship between the criteria is displayed [17]. Following the DEMATEL method, the Analytic Network Process (ANP) method can be used to rank each criterion [18], [19]. The DANP method was introduced in 2008 by Yang et al. In this method, the interrelationship between the criteria and the dimensions of the problem is obtained by the DEMATEL method; then, the weight of the impact of the criteria and the dimensions can be calculated by using the concept of ANP [20].

Therefore, in this paper, the combination of the two methods of DEMATEL and ANP, called DANP, is used to determine the relationships and calculate the weight of the criteria causing a risk of the blasting operations according to Figure 1.

2. Determine the dimensions and criteria that affect the risk of blasting operations

In studies on identifying hazards and assessing the impact of any risk in the field of mine blasting, only a few major factors have been considered. Owing to the connection between the criteria for blasting operations, all the criteria must be simultaneously considered in order to measure the impact of effective measures on each other.

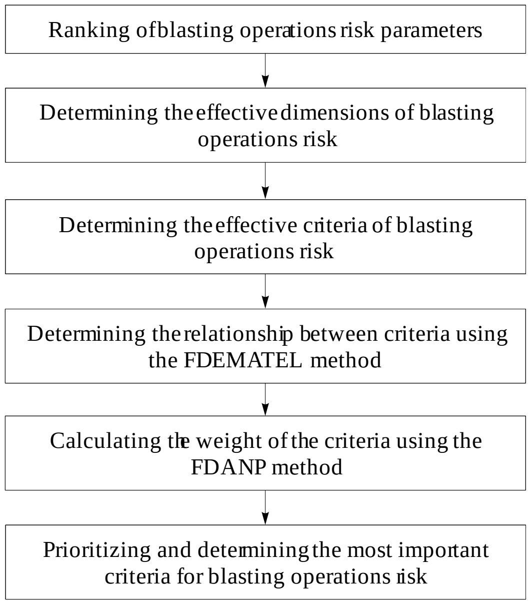

Figure 1. Flowchart of the ranking of blasting operation risk parameters

In general, the dimensions and criteria for blasting operations are divided into three main categories: quantitative, qualitative, and quantitative-qualitative. In analytical studies, the independent aspect or the dependence of dimensions and criteria must also be taken into account. In this regard, in addition to the criteria presented on the basis of previous research studies, the conditions of the blasting operations at the open-pit mine of Isfahan Stone Mobarake Iron & Steel Co need to be investigated. It can be seen that the impact dimensions on the risk of the blasting operations are in accordance with expert opinions as shown in Table 1.

Table 1. Dimensions of blasting operations risk in open pit mines

No.	Dimensions	
1	Human resources	Human resources operation Knowledge, skill and staffing Health and safety Behavioral features Technical skills and competences Cognitive skills
2	Execution factors	Safety regulations Terms implementation of explosion operation Precision in performance
3	Operational conditions	Geology of area Environmental conditions Number of blast operations
4	Rock engineering	Rock quality
5	Drilling operations	Blast hole
6	Blasting operation design	Blast holes pattern Components of explosive operation design
7	Explosive block	Blast block specifications
8	Effects and results of blasting operations	Blast operation results
9	Production and extraction consideration	Production constraints
10	Natural hazards	

In view of the multitude of criteria affecting the risk of blasting operations, this study examined 46 criteria affecting the risks of explosion operations based on 10 major dimensions 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 considerations, and natural hazards. In the following, by considering the criteria for creating a risk of blasting operations, the dimensions determined by the effective criteria will be divided according to Table 2.

Table 2. Dimensions and criteria of blasting operations risk in open pit mines

No.	Dimensions	Criteria
1	Human resources	C_1: Lack of specialized knowledge C_2: Lack of practical application of specialized knowledge C_3: Lack of skills in system understanding and effective decision-making skills
2	Execution factors	C_4: Lack of supervision and technical inspection C_5: Negligence to observe safety inspections at various stages of the explosion operation C_6: The lack of regular and intermittent training during the service C_7: Error due to lack of quality of the explosion-initiating system C_8: The lack of correct connection between blast holes and blast lines C_9: Lack of charging quality and quantity C_{10}: Use of untrained blaster C_{11}: Lack of attention to the safety warnings and regulations C_{12}: Implement the explosion plan without respecting the design principles
3	Operational conditions	C_{13}: Proximity to geologic deformations (Fault – Losing zone – Karst cavities – Folding) C_{14}: Number of explosions in one stage
4	Rock engineering	C_{15}: Joints and cracks
5	Drilling operations	C_{16}: Explosive hole deviation C_{17}: Non-compliance of the length-to-diameter ratio
6	Blasting operation design	C_{18}: Failure to observe the number of rows of blast holes in blast operation C_{19}: Failure to observe the ratio of the burden to the spacing C_{20}: Failure to observe the appropriate delay in blast rows C_{21}: Failure to comply with design and calculation principles in determining the appropriate height of bench C_{22}: Failure to comply with design and computational principles in determining the appropriate diameter of drilling hole C_{23}: Failure to comply with design and computational principles in determining appropriate angle (gradient) of drilling hole C_{24}: Failure to observe design and calculation principles in determining the appropriate stemming in drilling hole C_{25}: Application of inappropriate material for stemming C_{26}: Failure to observe design and computation principles in determining the length and blast hole of bottom charge C_{27}: Failure to observe design and computation principles in determining the length and column blast hole bottom charge C_{28}: Primer and Booster Location C_{29}: Incorrect estimate of specific charge
7	Explosive block	C_{30}: The length of the explosive block C_{31}: Failure to observe the length to width ratio of the explosive block C_{32}: Lack of free face
8	Effects and results of blasting operations	C_{33}: Worse fragmentation C_{34}: Boulder production C_{35}: Back break C_{36}: Side break C_{37}: Pivot creation C_{38}: Misfire C_{39}: Ground vibration C_{40}: Air blast C_{41}: Fly rock C_{42}: Production of toxic gases from the explosion C_{43}: Premature blast C_{44}: Inappropriate stability of remains bench face
9	Production and extraction consideration	C_{45}: Failure to determine the amount of production capacity (low or high)
10	Natural hazards	C_{46}: Damage to manpower (production of noise and gases from blasting operations); Damage to animals and vegetables; Create unusual environmental effects; Pollution of the water area

3. DEMATEL and FANP methods

The DEMATEL method was first presented by Fontela and Gabus (1971). This technique is based on paired comparison and decision-making tools, which are based on graph theory [21], [22]. By examining the interrelationship between the criteria, DEMATEL determines their impact and importance as numerical scores [16]. The most important feature of DEMATEL is its function to create relationships and structure between criteria. Therefore, DEMATEL, in addition to transforming causation relationships into a structural-visual model, is also able to identify and understand the interdependencies between the metrics [23]. In addition to the DEMATEL method, ANP can be used to organize different criteria and evaluate the importance and priority of each criterion [24]. The ANP analysis process was developed by Saaty in 1980 and it was expanded in 1996. This approach was proposed to solve the dependency problem among dimensions and criteria. The ANP method considers the complex internal relations of decision levels and ratios [18], [19]. By doing so, it is able to determine the relationship between the decision-making dimensions and criteria by obtaining combined weights through the structure of the super matrix [25]. As a result, the DEMATEL method can be used to identify the relationship and impact of the criteria on each other. The ANP technique is used in order to identify the priority of the criteria. On the other hand, by using a fuzzy method, the development of a standard method for both DEMATEL and ANP can be proposed. The use of the fuzzy set theory allows decision makers to look for uncertain, incomplete, inaccessible, and partial facts in the decision model [26]. Under conditions of uncertainty, it is very difficult to estimate the opinions of experts with respect to precise numerical values. The expression and concept of a linguistic variable is necessary to define complex and difficult conditions [27]. This factor calls for fuzzy logic in both DEMATEL and ANP. As a result, using fuzzy language variables can facilitate decision-making in conditions of uncertainty.

4. Determine the relationship of criteria by the FDEMATEL method

The complex relationships between the components of a system can be modeled by using the DEMATEL method. A paired comparison questionnaire was designed to measure the relationship between the criteria. The degree of impact of the criteria with a five-level scale, consisting of verbal expressions and corresponding fuzzy triangular numbers, was used according to the Li proposal in 1999 Table 3.

Table 3. Verbal phrases and related fuzzy numbers [28]

Definitive equivalent	Description	Fuzzy equivalent
No influence	0	(0, 0, 0.25)
Very low influence	1	(0, 0.25, 0.5)
Low influence	2	(0.25, 0.5, 0.75)
High influence	3	(0.5, 0.75, 1.0)
Very high influence	4	(0.75, 1.0, 1.0)

4.1. Average matrix (A)

The $n \times n$ pair comparison matrix is formed according to the opinions of experts. The variable H is the number of experts and n is the number of criteria considered. The comparison between the two factors i and j by the expert k is shown as b_{ij}^{k}. According to the fuzzy theory in Table 3, the value of "no influence" is 0, "very low influence" is 1, "low influence" is 2, "high influence" is 3, and "very high influence" is 4. As a result, with the score of each expert, the matrix of the answer is formed by Equation (1). Given the fact that each component has no effect on itself, the components of the diameter of each matrix of the answer $B^{(k)}$ are zero:

$$\left(1 \le k \le H\right) B^{(k)} = \left[b_{ij}^{k}\right]_{n \times n}. \quad (1)$$

The average matrix $A = \left[a_{ij}\right]_{n \times n}$ is the direct-influence matrix and the mean of the expert scores can be calculated according to Equation (2). This matrix represents the direct effects of each criterion on the other criteria:

$$a_{ij} = \frac{1}{H}\sum_{K=1}^{H} b_{ij}^{(k)}. \quad (2)$$

4.2. Normal direct-influence matrix (D)

Matrix D can be calculated from Equations (3) and (4):

$$D = \left[d_{ij}\right]_{n \times n} = \frac{A}{S}; \quad (3)$$

$$S = \left(\max_{1 \ll 1 \ll n} \sum_{j=1}^{n} a_{ij}, \max_{1 \ll j \ll n} \sum_{j=1}^{n} a_{ij}\right). \quad (4)$$

4.3. Total-influence matrix of criteria (T_c)

The matrix T_c can be calculated according to Equation (5). In this Equation, I is the unit matrix. Each element of the matrix T_c can be formed with respect to the fuzzy number $\tilde{\tau}_{ij} = \left(l_{ij}^{t}, m_{ij}^{t}, u_{ij}^{t}\right)$. Given the Equations (5), (6), (7), and (8). D_1, D_m, D_u – each is a matrix $n \times n$.

$$T_c = D\left(I - D\right)^{-1}; \quad (5)$$

$$\left[l_{ij}^{t}\right] = D_1\left(I - D\right)^{-1}; \quad (6)$$

$$\left[m_{ij}^{t}\right] = D_m\left(I - D_m\right)^{-1}; \quad (7)$$

$$\left[u_{ij}^{t}\right] = D_u\left(I - D_u\right)^{-1}. \quad (8)$$

4.4. The extent of the effect and relevance of criteria

In order to determine the effect and relevance of the criteria, first the T_c matrix should non-fuzzy. In order to non-fuzzy of the T_c matrix, Equation (9) will be used.

Determine the effect and relevance of the criteria by using the r and c values. The values of the Equations (10) and (11) can be calculated:

$$B = \frac{l_1 + m_3 + 2u_2}{4}; \quad (9)$$

$$r = \left[r_i\right]_{n \times 1} = \left[\sum_{j=1}^{n} t_{ij}\right]_{n \times 1}; \quad (10)$$

$$c = \left[c_j\right]_{n \times 1} = \left[\sum_{i=1}^{n} t_{ij}\right]_{n \times 1}. \quad (11)$$

r is the sum of the row i and c is the sum of the j column of the T_c matrix. r shows the overall effect of the direct and indirect effects i on the other criteria and c shows the direct and indirect general effects of the factor j on the other factors. As a result, $r + c$ indicates the importance of the criterion i in the system. $r - c$ shows the effect of criterion i in the system. If $r - c$ is positive, the effect of the criterion i belongs to the cause group and if $r - c$ is negative, the effect of the criterion i belongs to the disabled group.

4.5. Network relationship map (NRM)

In order to explain the structure of the relationship between the system criteria, threshold values and a mapping of effective relationships are required. The only factors that have threshold values greater than the threshold value calculated should be selected and displayed in the map of the effect of the relationship [29].

5. Investigate the relationship between the blasting operations risk criteria

Making a model of the process of network analysis involves understanding the relationships and interactions between the criteria and dimensions of the problem. Therefore, by identifying the criteria and dimensions of the risk of blasting operations, the FDEMATEL and FANP models can be used to extract the weight of the criteria. At first, the effect of the component *i* on the component *j* is determined by the respondent team by using numbers 0 through 4. Then, the fuzzy equation will be used for fuzzy numbers. If the respondents include more than one person, the mean score for the experts is the final matrix of Equation (12):

$$\tilde{A} = \begin{bmatrix} \tilde{a}_{11} & \tilde{a}_{1j} & \cdots & \tilde{a}_{1n} \\ \tilde{a}_{i1} & \tilde{a}_{ij} & \cdots & \tilde{a}_{in} \\ \vdots & \vdots & \ddots & \vdots \\ \tilde{a}_{n1} & \tilde{a}_{nj} & \cdots & \tilde{a}_{nn} \end{bmatrix}. \quad (12)$$

With regard to the volume of calculations and the number of criteria, only the calculations related to criterion C_1 are presented in Table 4. Other criteria will also be evaluated in the same way. Finally, the average matrix of the opinions of experts will be formed as an Equation (12) ratio for all the criteria. By forming the direct-influence matrix (A), the normal direct-influence matrix (D) can be calculated from Equations (3) and (4).

By determining the number *s* of Equation (13) and multiplying it in each matrix element, A, the matrix D is obtained according to Table 5 for the C_1 criterion:

$$S = \max\left(\sum_{j=1}^{46} u_{ij}\right) = 33.25\,. \quad (13)$$

Given the Equation (5)-(8), the T_c matrix for the C_1 criterion is in accordance with Table 6.

From the combination of the two methods, DEMATEL and ANP, the total-influence matrix of dimensions (T_D) can be deduced according to Equation (14) of the T_c matrix.

Each t''_{ij} is obtained from the mean of each T_c^{ij}.

$$T_D = \begin{bmatrix} t_D^{11} & \cdots & t_D^{1j} & \cdots & t_D^{1m} \\ t_D^{i1} & \cdots & t_D^{ij} & \cdots & t_D^{Dim} \\ & & \vdots\,\vdots\,\vdots & & \\ t_D^{m1} & \cdots & t_D^{mj} & \cdots & t_D^{mm} \end{bmatrix}. \quad (14)$$

In order to non-fuzzy the T_D matrix, Equation (9) will be used. The non-fuzzy matrix of the dimension is in accordance with Figure 2. The values of *r* and *c* for the criteria and dimensions can be calculated from the Equations (10) and (11). Given the calculated values of the T_c and T_D matrices, the index values $(r + c)$ and $(r - c)$ can be obtained for the dimensions of Table 7 and for the criteria of Table 8.

Table 4. Average experts' opinion C_1 criterion in comparison to the other criteria

Criteria	Fuzzy number	Criteria	Fuzzy number	Criteria	Fuzzy number
C_1-C_2	(0.750, 1.000, 1.000)	C_1-C_{17}	(0.250, 0.500, 0.750)	C_1-C_{32}	(0.000, 0.000, 0.250)
C_1-C_3	(0.375, 0.625, 0.870)	C_1-C_{18}	(0.250, 0.500, 0.750)	C_1-C_{33}	(0.250, 0.500, 0.750)
C_1-C_4	(0.000, 0.000, 0.250)	C_1-C_{19}	(0.375, 0.625, 0.875)	C_1-C_{34}	(0.250, 0.500, 0.750)
C_1-C_5	(0.250, 0.500, 0.750)	C_1-C_{20}	(0.625, 0.875, 1.000)	C_1-C_{35}	(0.375, 0.625, 0.875)
C_1-C_6	(0.000, 0.000, 0.250)	C_1-C_{21}	(0.500, 0.750, 0.875)	C_1-C_{36}	(0.375, 0.625, 0.875)
C_1-C_7	(0.125, 0.375, 0.625)	C_1-C_{22}	(0.250, 0.500, 0.750)	C_1-C_{37}	(0.375, 0.625, 0.875)
C_1-C_8	(0.250, 0.500, 0.750)	C_1-C_{23}	(0.250, 0.500, 0.750)	C_1-C_{38}	(0.250, 0.500, 0.750)
C_1-C_9	(0.250, 0.500, 0.750)	C_1-C_{24}	(0.375, 0.625, 0.875)	C_1-C_{39}	(0.375, 0.625, 0.875)
C_1-C_{10}	(0.125, 0.375, 0.625)	C_1-C_{25}	(0.375, 0.625, 0.875)	C_1-C_{40}	(0.250, 0.500, 0.750)
C_1-C_{11}	(0.250, 0.500, 0.750)	C_1-C_{26}	(0.375, 0.625, 0.875)	C_1-C_{41}	(0.250, 0.500, 0.750)
C_1-C_{12}	(0.750, 1.000, 1.000)	C_1-C_{27}	(0.375, 0.625, 0.875)	C_1-C_{42}	(0.125, 0.375, 0.625)
C_1-C_{13}	(0.000, 0.000, 0.250)	C_1-C_{28}	(0.500, 0.750, 0.875)	C_1-C_{43}	(0.250, 0.500, 0.750)
C_1-C_{14}	(0.000, 0.000, 0.250)	C_1-C_{29}	(0.500, 0.750, 0.875)	C_1-C_{44}	(0.000, 0.250, 0.500)
C_1-C_{15}	(0.000, 0.000, 0.250)	C_1-C_{30}	(0.125, 0.375, 0.625)	C_1-C_{45}	(0.375, 0.625, 0.875)
C_1-C_{16}	(0.000, 0.125, 0.375)	C_1-C_{31}	(0.250, 0.500, 0.750)	C_1-C_{46}	(0.500, 0.750, 1.000)

Table 5. The first element of the normal direct-influence matrix (D) – C_1 relative to other criteria

Criteria	Fuzzy number	Criteria	Fuzzy number	Criteria	Fuzzy number
C_1-C_2	(0.023, 0.030, 0.030)	C_1-C_{17}	(0.008, 0.015, 0.023)	C_1-C_{32}	(0.000, 0.000, 0.008)
C_1-C_3	(0.011, 0.019, 0.026)	C_1-C_{18}	(0.008, 0.015, 0.023)	C_1-C_{33}	(0.008, 0.015, 0.023)
C_1-C_4	(0.000, 0.000, 0.008)	C_1-C_{19}	(0.011, 0.019, 0.026)	C_1-C_{34}	(0.008, 0.015, 0.023)
C_1-C_5	(0.008, 0.015, 0.023)	C_1-C_{20}	(0.019, 0.026, 0.030)	C_1-C_{35}	(0.011, 0.019, 0.026)
C_1-C_6	(0.000, 0.000, 0.008)	C_1-C_{21}	(0.015, 0.023, 0.026)	C_1-C_{36}	(0.011, 0.019, 0.026)
C_1-C_7	(0.004, 0.011, 0.019)	C_1-C_{22}	(0.008, 0.015, 0.023)	C_1-C_{37}	(0.011, 0.019, 0.026)
C_1-C_8	(0.008, 0.015, 0.023)	C_1-C_{23}	(0.008, 0.015, 0.023)	C_1-C_{38}	(0.008, 0.015, 0.023)
C_1-C_9	(0.008, 0.015, 0.023)	C_1-C_{24}	(0.011, 0.019, 0.026)	C_1-C_{39}	(0.011, 0.019, 0.026)
C_1-C_{10}	(0.004, 0.011, 0.019)	C_1-C_{25}	(0.011, 0.019, 0.026)	C_1-C_{40}	(0.008, 0.015, 0.023)
C_1-C_{11}	(0.008, 0.015, 0.023)	C_1-C_{26}	(0.011, 0.019, 0.026)	C_1-C_{41}	(0.008, 0.015, 0.023)
C_1-C_{12}	(0.023, 0.030, 0.030)	C_1-C_{27}	(0.011, 0.019, 0.026)	C_1-C_{42}	(0.004, 0.011, 0.019)
C_1-C_{13}	(0.000, 0.000, 0.008)	C_1-C_{28}	(0.015, 0.023, 0.026)	C_1-C_{43}	(0.008, 0.015, 0.023)
C_1-C_{14}	(0.000, 0.000, 0.008)	C_1-C_{29}	(0.015, 0.023, 0.026)	C_1-C_{44}	(0.000, 0.008, 0.015)
C_1-C_{15}	(0.000, 0.000, 0.008)	C_1-C_{30}	(0.004, 0.011, 0.019)	C_1-C_{45}	(0.011, 0.019, 0.026)
C_1-C_{16}	(0.000, 0.004, 0.011)	C_1-C_{31}	(0.008, 0.015, 0.023)	C_1-C_{46}	(0.015, 0.023, 0.030)

Table 6. The first element of the total-influence matrix of criteria (T_c) – C_1 compared to other criteria

Criteria	Fuzzy number	Criteria	Fuzzy number	Criteria	Fuzzy number
C_1-C_2	(2E-02, 2E-02, 5E-02)	C_1-C_{17}	(8E-03, 2E-02, 5E-02)	C_1-C_{32}	(6E-05, 8E-04, 3E-02)
C_1-C_3	(1E-02, 2E-02, 5E-02)	C_1-C_{18}	(8E-03, 2E-02, 5E-02)	C_1-C_{33}	(1E-02, 2E-02, 7E-02)
C_1-C_4	(4E-04, 1E-03, 3E-02)	C_1-C_{19}	(1E-02, 2E-02, 6E-02)	C_1-C_{34}	(1E-02, 3E-02, 7E-02)
C_1-C_5	(8E-03, 2E-02, 5E-02)	C_1-C_{20}	(2E-02, 3E-02, 7E-02)	C_1-C_{35}	(1E-02, 3E-02, 8E-02)
C_1-C_6	(3E-04, 1E-03, 3E-02)	C_1-C_{21}	(2E-02, 3E-02, 6E-02)	C_1-C_{36}	(1E-02, 3E-02, 8E-02)
C_1-C_7	(4E-03, 1E-02, 5E-02)	C_1-C_{22}	(8E-03, 2E-02, 5E-02)	C_1-C_{37}	(1E-02, 3E-02, 7E-02)
C_1-C_8	(9E-03, 2E-02, 6E-02)	C_1-C_{23}	(8E-03, 2E-02, 5E-02)	C_1-C_{38}	(1E-02, 3E-02, 7E-02)
C_1-C_9	(9E-03, 2E-02, 6E-02)	C_1-C_{24}	(1E-02, 2E-02, 6E-02)	C_1-C_{39}	(2E-02, 3E-02, 8E-02)
C_1-C_{10}	(5E-03, 2E-02, 5E-02)	C_1-C_{25}	(1E-02, 3E-02, 7E-02)	C_1-C_{40}	(1E-02, 3E-02, 8E-02)
C_1-C_{11}	(8E-03, 2E-02, 5E-02)	C_1-C_{26}	(1E-02, 3E-02, 7E-02)	C_1-C_{41}	(1E-02, 3E-02, 8E-02)
C_1-C_{12}	(3E-02, 4E-02, 8E-02)	C_1-C_{27}	(1E-02, 3E-02, 7E-02)	C_1-C_{42}	(6E-03, 2E-02, 7E-02)
C_1-C_{13}	(6E-06, 4E-04, 3E-02)	C_1-C_{28}	(2E-02, 3E-02, 7E-02)	C_1-C_{43}	(1E-02, 2E-02, 7E-02)
C_1-C_{14}	(8E-04, 5E-03, 4E-02)	C_1-C_{29}	(2E-02, 3E-02, 7E-02)	C_1-C_{44}	(3E-03, 2E-02, 7E-02)
C_1-C_{15}	(9E-08, 1E-05, 3E-02)	C_1-C_{30}	(4E-02, 1E-02, 4E-02)	C_1-C_{45}	(1E-02, 2E-02, 5E-02)
C_1-C_{16}	(2E-04, 5E-03, 4E-02)	C_1-C_{31}	(8E-03, 2E-02, 5E-02)	C_1-C_{46}	(2E-02, 4E-02, 9E-02)

	D_1	D_2	D_3	D_4	D_5	D_6	D_7	D_8	D_9	D_{10}
D_1	0.015	0.024	0.015	0.007	0.016	0.029	0.018	0.033	0.024	0.041
D_2	0.011	0.016	0.012	0.006	0.010	0.017	0.008	0.029	0.012	0.035
D_3	0.007	0.016	0.015	0.017	0.015	0.023	0.012	0.032	0.020	0.035
D_4	0.007	0.012	0.025	0.005	0.027	0.027	0.011	0.032	0.014	0.032
D_5	0.006	0.012	0.008	0.006	0.010	0.021	0.007	0.028	0.010	0.024
D_6	0.006	0.013	0.011	0.006	0.009	0.017	0.007	0.029	0.009	0.032
D_7	0.006	0.014	0.013	0.006	0.007	0.017	0.017	0.031	0.008	0.032
D_8	0.004	0.006	0.006	0.004	0.005	0.007	0.005	0.013	0.006	0.028
D_9	0.005	0.007	0.010	0.004	0.005	0.010	0.011	0.009	0.004	0.016
D_{10}	0.004	0.006	0.005	0.004	0.004	0.005	0.004	0.007	0.005	0.006

Figure 2. Non-fuzzy matrix of dimensions

Table 7. Importance (r + c) and effect level (r – c) of the blasting operations risk dimension

Dimensions	$(r + c)$	Dimensions	$(r – c)$
D_1	0.294	D_1	0.152
D_2	0.282	D_2	0.029
D_3	0.308	D_3	0.073
D_4	0.255	D_4	0.127
D_5	0.240	D_5	0.023
D_6	0.312	D_6	-0.035
D_7	0.251	D_7	0.050
D_8	0.326	D_8	-0.158
D_9	0.191	D_9	-0.031
D_{10}	0.330	D_{10}	-0.230

Table 8. Importance (r + c) and effect level (r − c) of the blasting operations risk criteria

Criteria	$(r + c)$	Criteria	$(r + c)$	Criteria	$(r – c)$	Criteria	$(r – c)$
C_1	1.497	C_{24}	1.571	C_1	0.988	C_{24}	0.028
C_2	1.610	C_{25}	1.520	C_2	0.859	C_{25}	-0.078
C_3	1.472	C_{26}	1.596	C_3	0.763	C_{26}	-0.079
C_4	1.598	C_{27}	1.610	C_4	0.908	C_{27}	0.034
C_5	1.356	C_{28}	1.711	C_5	0.638	C_{28}	0.011
C_6	1.268	C_{29}	1.625	C_6	0.615	C_{29}	-0.073
C_7	1.083	C_{30}	1.204	C_7	0.053	C_{30}	0.384
C_8	1.295	C_{31}	1.332	C_8	-0.115	C_{31}	0.384
C_9	1.534	C_{32}	1.213	C_9	-0.054	C_{32}	0.610
C_{10}	1.595	C_{33}	1.529	C_{10}	0.387	C_{33}	-0.545
C_{11}	1.175	C_{34}	1.497	C_{11}	0.259	C_{34}	-0.655
C_{12}	1.920	C_{35}	1.458	C_{12}	-0.105	C_{35}	-0.767
C_{13}	1.499	C_{36}	1.441	C_{13}	0.837	C_{36}	-0.696
C_{14}	1.429	C_{37}	1.308	C_{14}	0.213	C_{37}	-0.693
C_{15}	1.289	C_{38}	1.507	C_{15}	0.755	C_{38}	-0.784
C_{16}	1.294	C_{39}	1.626	C_{16}	0.510	C_{39}	-0.956
C_{17}	1.156	C_{40}	1.521	C_{17}	0.284	C_{40}	-0.911
C_{18}	1.265	C_{41}	1.544	C_{18}	0.178	C_{41}	-0.969
C_{19}	1.501	C_{42}	1.433	C_{19}	0.229	C_{42}	-0.877
C_{20}	1.369	C_{43}	1.415	C_{20}	-0.060	C_{43}	-0.491
C_{21}	1.373	C_{44}	1.720	C_{21}	0.232	C_{44}	-0.593
C_{22}	1.451	C_{45}	0.851	C_{22}	0.342	C_{45}	-0.074
C_{23}	1.364	C_{46}	1.679	C_{23}	0.236	C_{46}	-1.162

6. Determining the effective weight of the blasting operations risk criteria with the FDANP method

In order to determine the effective weight of the criteria with the FDANP method, the normalization of total-influence matrix (T_c) and T_D is calculated and the unweighted super-matrix and then the weighted super-matrix are formed. In the end, the final weight vector with a limit of the weighted super-matrix to sufficiently until it converges is calculated.

6.1. Normalization of the T_c matrix and the formation of the unweighted super-matrix (W)

Firstly, the T_c matrix obtained from the DEMATEL method and Equation (15) are normalized.

At this stage, the sum of each row T_c^{ij} is calculated with respect to the related dimension of Equation (16); then, each element is divided into the sum of the elements of the corresponding row (Equation 17).

$$T_c^{\alpha} = \begin{matrix} D_1 \\ \vdots \\ D_i \\ \vdots \\ D_n \end{matrix} \begin{matrix} c_{11} \\ c_{12} \\ \vdots \\ c_{1m_1} \\ \vdots \\ c_{i1} \\ c_{i2} \\ \vdots \\ c_{im_i} \\ \vdots \\ c_{n1} \\ c_{n2} \\ \vdots \\ c_{nm_n} \end{matrix} \overset{\begin{matrix} D_1 & & D_j & & D_n \\ c_{11}\ldots c_{1m_1} & \cdots & c_{j1}\ldots c_{jm_j} & \cdots & c_{n1}\ldots c_{nm_n} \end{matrix}}{\begin{bmatrix} T_c^{\alpha 11} & \cdots & T_c^{\alpha 1j} & \cdots & T_c^{\alpha 1n} \\ \vdots & & \vdots & & \vdots \\ T_c^{ai1} & \cdots & T_c^{aij} & \cdots & T_c^{ain} \\ \vdots & & \vdots & & \vdots \\ T_c^{\alpha n1} & \cdots & T_c^{anj} & \cdots & T_c^{ann} \end{bmatrix}} ; \quad (15)$$

$$d_{ci}^{11} = \sum_{j=1}^{m_1} t_{cij}^{11}, i = 1, 2, \ldots m_1 . \quad (16)$$

$$T_c^{\infty 11} = \begin{bmatrix} t_{c11}^{11}/d_{c1}^{11} & \cdots & t_{c1j}^{11}/d_{c1}^{11} & \cdots & t_{c1m1}^{11}/d_{c1}^{11} \\ \vdots & & \vdots & & \vdots \\ t_{ci1}^{11}/d_{ci}^{11} & \cdots & t_{cij}^{11}/d_{ci}^{11} & \cdots & t_{cim1}^{11}/d_{ci}^{11} \\ \vdots & & \vdots & & \vdots \\ t_{cm11}^{11}/d_{cm1}^{11} & \cdots & t_{cm1j}^{11}/d_{cm1}^{11} & \cdots & t_{cm1m1}^{11}/d_{cm1}^{11} \end{bmatrix} =$$

$$= \begin{bmatrix} t_{c11}^{\infty 11} & \cdots & t_{c1j}^{\infty 11} & \cdots & t_{c1m1}^{\infty 11} \\ \vdots & & \vdots & & \vdots \\ t_{ci1}^{\infty 11} & \cdots & t_{cij}^{\infty 11} & \cdots & t_{cim1}^{\infty 11} \\ \vdots & & \vdots & & \vdots \\ t_{cm11}^{\infty 11} & \cdots & t_{cm1j}^{\infty 11} & \cdots & t_{cm1m1}^{\infty 11} \end{bmatrix}. \quad (17)$$

With the transpos of the matrix T_c^{∞}, unweighted super-matrix (W) is obtained from equation (18):

$$W = \left(T_c^{\alpha}\right)' = \begin{matrix} & & D_1 & \cdots & D_i & \cdots & D_n \\ & & c_{11} \ldots c_{1m_1} & \cdots & c_{i1} \ldots c_{im_i} & \cdots & c_{n1} \ldots c_{nm_n} \\ D_1 & \begin{matrix} c_{11} \\ c_{12} \\ \vdots \\ c_{1m_1} \end{matrix} & W^{11} & \cdots & W^{i1} & \cdots & W^{n1} \\ \vdots & & \vdots & & \vdots & & \vdots \\ D_i & \begin{matrix} c_{j1} \\ c_{j2} \\ \vdots \\ c_{jmj} \end{matrix} & W^{1j} & \cdots & W^{ij} & \cdots & W^{nj} \\ \vdots & & \vdots & & \vdots & & \vdots \\ D_n & \begin{matrix} c_{n1} \\ c_{n2} \\ \vdots \\ c_{nm_n} \end{matrix} & W^{1n} & \cdots & W^{in} & \cdots & W^{nn} \end{matrix}. \quad (18)$$

6.2. Normalization of the matrix T_D

Depending on Equations (19) and (20), the T_D matrix is normalized. The sum of each row of the T_D matrix is calculated with respect to the corresponding dimension of Equation (19):

$$T_D = \begin{bmatrix} t_{11}^{D11} & \ldots & t_{1j}^{D1j} & \ldots & t_{1m}^{D1m} \\ & & \vdots & & \\ t_{i1}^{Di1} & \ldots & t_{ij}^{Dij} & \ldots & t_{im}^{Dim} \\ & & \vdots & & \\ t_{m1}^{Dm1} & \ldots & t_{mj}^{Dmj} & \ldots & t_{mm}^{Dmm} \end{bmatrix}. \quad (19)$$

Then, the element of each row is divided into the sum of the elements of the row (Equation (20)) and the resul-ting matrix is transposed:

$$d_i = \sum_{j=1}^{m} t_{ij}^{D_{ij}}, \quad i = 1, 2, \ldots, m. \quad (20)$$

6.3. Weighted super-matrix (W^{α})

At this stage, the matrix T_D^{∞} is multiplied in the W matrix and the weighted super-matrix is obtained according to Equation (21):

$$W^{\alpha} = T_D^{\alpha} W = \begin{bmatrix} t_D^{\alpha 11} \times W^{11} \ldots t_D^{\alpha i1} \times W^{i1} \ldots t_D^{\alpha n1} \times W^{n1} \\ \vdots \\ t_D^{\alpha 1j} \times W^{1j} \ldots t_D^{\alpha ij} \times W^{ij} \ldots t_D^{\alpha nj} \times W^{nj} \\ \vdots \\ t_D^{\alpha 1n} \times W^{11} \ldots t_D^{\alpha in} \times W^{in} \ldots t_D^{\alpha nn} \times W^{nn} \end{bmatrix}. \quad (21)$$

In order to calculate the final weight vector, Equation (22) can be used [30]:

$$W_Z = \lim_{Z \to \infty} \left(W^{\alpha}\right)^Z. \quad (22)$$

7. Results and discussion

While determining the threshold value and producing Network Relationship Map (NRM), to draw up a meaningful relationship network can result in ignoring partial relationships. Only relationships whose values in the T_c and T_D non-fuzzy matrix are larger than the threshold value will be displayed in the NRM. The threshold value calculated for the T_c non-fuzzy matrix is 0.016 and for the non-fuzzy T_D matrix, it is 0.014. According to the value of the threshold, the matrix of the relations of the criteria is in accordance with Figure 3 and the matrix of the relationship of the dimensions is in accordance with Figure 4.

c	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	32	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46
1	0	1	1	0	1	0	1	1	1	1	1	1	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1
2	0	0	1	1	1	1	1	1	1	1	1	1	0	1	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1
3	0	1	0	0	1	1	1	1	1	1	1	1	0	1	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1
4	0	1	0	0	1	1	1	1	1	1	1	1	0	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1
5	0	0	0	1	0	1	1	1	1	1	1	1	0	1	0	0	0	0	1	1	0	0	0	1	1	1	1	1	1	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	0	1
6	0	1	1	1	1	0	1	1	0	0	1	1	0	0	0	0	0	0	1	0	0	0	0	1	1	1	1	1	1	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	0	1
7	0	0	0	0	0	0	0	1	0	0	0	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	0	1	1	1	1	1	1	1	0	1
8	0	0	0	0	0	0	0	0	0	0	0	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	0	1	1	1	1	1	1	0	0	1
9	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	0	1
10	0	1	1	1	0	0	0	1	1	0	1	1	0	0	0	0	0	0	0	1	0	0	0	1	1	1	1	1	1	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	0	1
11	0	1	1	1	1	1	0	0	1	0	0	1	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	0	1
12	0	0	0	0	0	0	0	1	1	0	0	0	0	1	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1
13	0	0	0	0	0	0	1	1	1	0	0	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1
14	0	0	0	0	0	0	1	1	1	0	0	1	1	0	0	0	0	1	1	1	0	0	0	1	1	1	1	1	1	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1
15	0	0	0	0	0	0	0	0	1	0	0	1	1	1	0	1	1	0	1	1	1	1	1	1	1	1	1	1	1	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	0	1
16	0	0	0	0	0	0	0	0	1	0	0	1	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	0	1
17	0	0	0	0	0	0	1	1	1	0	0	1	0	0	0	0	0	0	0	1	1	1	1	0	0	1	1	1	1	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	0	1
18	0	0	0	0	0	0	0	1	0	0	0	1	0	1	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	0	1
19	0	0	0	0	0	0	0	1	1	0	0	1	0	1	0	0	0	1	0	1	1	0	0	1	1	1	1	1	1	0	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1
20	0	0	0	0	0	0	0	1	0	0	0	1	0	1	0	0	0	1	0	0	0	0	0	0	0	1	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	0	1	0	1
21	0	0	0	0	0	0	0	0	1	0	0	1	0	0	0	1	1	0	0	0	0	1	1	1	1	1	1	1	1	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	0	1
22	0	0	0	0	0	0	0	1	1	1	0	1	0	0	0	1	1	0	0	1	1	0	0	1	1	1	1	1	1	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	0	1
23	0	0	0	0	0	0	0	0	1	0	0	1	0	0	0	1	0	0	1	0	0	0	0	1	1	1	1	1	1	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	0	1
24	0	0	0	0	0	0	0	0	1	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	0	0	0	1	1	1	1	1	1	1	1	1	1	0	1	0	1
25	0	0	0	0	0	0	0	0	1	0	0	1	0	1	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	0	1
26	0	0	0	0	0	0	0	0	1	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	0	1
27	0	0	0	0	0	0	0	0	1	1	0	1	0	0	0	0	0	0	0	1	1	1	0	1	1	1	0	1	1	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	0	1
28	0	0	0	0	0	0	0	1	1	1	0	1	0	1	0	0	0	0	0	0	1	0	0	1	1	1	1	0	1	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	0	1
29	0	0	0	0	0	0	0	0	1	1	0	1	0	0	0	0	0	0	0	1	0	0	0	1	0	1	0	1	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	0	1
30	0	0	0	0	0	0	0	1	1	0	0	1	0	0	0	0	0	1	1	1	0	0	0	1	1	0	1	1	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1
31	0	0	0	0	0	0	0	1	1	0	0	1	0	0	0	0	0	1	1	1	0	0	0	1	1	0	1	1	1	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1
32	0	0	0	0	0	0	0	1	1	1	0	1	0	0	0	0	0	0	0	1	0	0	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	1	1	1	1	1	1	0	1
33	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	0	1	0	1
34	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	0	1	0	1	0	1
35	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	0	0	1	0	1
36	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	0	0	1	0	1
37	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	1
38	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	1	1	1	0	1
39	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	0	1
40	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	1
41	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1
42	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
43	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	0	1	1	1	0	0	0	1	0	1
44	0	0	0	0	0	0	0	0	0	0	0	1	0	1	0	0	0	0	1	0	0	0	1	1	1	0	0	0	0	0	0	0	0	0	1	1	0	1	1	1	1	0	0	0	0	1
45	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
46	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Figure 3. Relationships' matrix of criteria

D	1	2	3	4	5	6	7	8	9	10
1	1	1	1	0	1	1	1	1	1	1
2	0	1	0	0	1	1	0	1	0	1
3	0	1	1	1	1	1	0	1	1	1
4	0	0	1	0	1	1	0	1	1	1
5	0	0	0	0	1	1	0	1	0	1
6	0	0	0	0	0	1	0	1	0	1
7	0	1	0	0	0	1	1	1	0	1
8	0	0	0	0	0	0	0	0	0	1
9	0	0	0	0	0	0	0	0	0	1
10	0	0	0	0	0	0	0	0	0	0

Figure 4. Relationships' matrix of dimension

In these figures, the number 1 represents the relationship between the criteria or the dimensions and the zero number of the non-relation between the criteria or dimensions. As observable, all of the criteria examined will affect the criterion of damage to manpower (production of noise and gases from blasting operations) (C_{46}). By examining the dimensions of the matrix, the natural hazards (D_{10}) dimension has the greatest interactions with other dimensions. The criterion C_{46} is the next subset of the D_{10} dimension. The D_{10} dimension, in this review, is generally based on the risk-control approach damage to manpower, damage to animals, damage to vegetables, creation of unusual environmental effects, and the pollution in the water area is considered. All the criteria in this category will cause natural hazards and, in general terms, damage human life. Therefore, it is necessary to examine all the criteria in order to reduce the damage to the manpower in the operation of blasting. It should be considered that the control of each criterion depends on the degree of effectiveness and the importance of that criterion to other criteria.

By drawing the Cartesian coordinate system according to Figure 5. Implement the explosion plan without respecting the design principles (C_{12}) has the highest interaction with other criteria, with a score of 1.920.

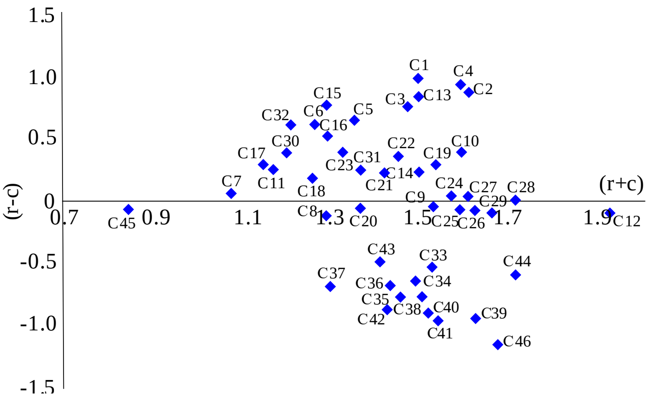

Figure 5. Graphic diagram of the relationships between the between the blasting operation risks criteria

The criterion failure to determine the amount of production capacity (low or high) (C_{45}), with a score of 0.851, has the least interaction with other criteria. The criterion lack of specialized knowledge (C_1), with a score of 0.988, is the most influential criterion on the other criteria of the system. Damage to manpower (production of noise and gases from blasting operations) (C_{46}), with a score of -1.162, is the most affected criterion of the other criteria.

According to Figure 6, the natural hazards (D_{10}) dimension, with a score of 0.330, has greater interaction with the other dimensions and is more important. Production and extraction consideration (D_9) with a score of 0.191, has the least interaction with the other dimensions and is less important. Human resources (D_1) with a score of 0.152, is the most influential dimension and natural hazards (D_{10}) with a score of -0.230 is the most affected dimension.

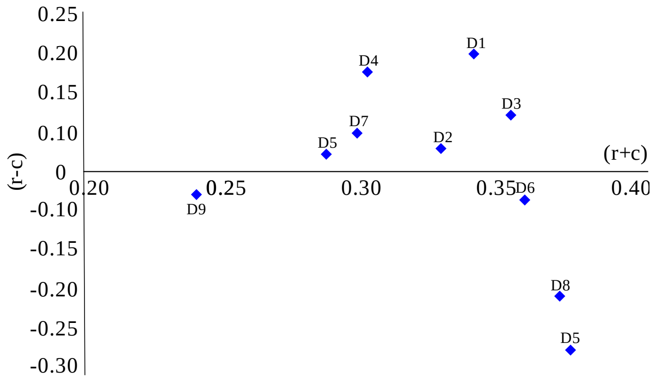

Figure 6. Graphic diagram of the relationships between the blasting operation risks dimension

According to the results of the analysis and the graphic diagrams of Figures 5 and 6, the prioritization of the effective criteria on the risk of the blasting operations according to the degree of importance and in terms of the impact level in Table 9 and the prioritization of dimensions is shown in Table 10.

Table 9. Prioritize the risk criteria of the blasting operations based on the degree of importance (r + c) and impact level (r − c)

Criteria	$(r + c)$	Rank	Criteria	$(r + c)$	Rank	Criteria	$(r - c)$	Rank	Criteria	$(r - c)$	Rank
C_1	1.497	21	C_{24}	1.571	12	C_1	0.988	1	C_{24}	0.028	24
C_2	1.610	7	C_{25}	1.520	17	C_2	0.859	3	C_{25}	-0.078	30
C_3	1.472	23	C_{26}	1.596	10	C_3	0.763	5	C_{26}	-0.079	31
C_4	1.598	9	C_{27}	1.610	8	C_4	0.908	2	C_{27}	0.034	23
C_5	1.356	33	C_{28}	1.711	3	C_5	0.638	7	C_{28}	0.011	25
C_6	1.268	39	C_{29}	1.625	6	C_6	0.615	8	C_{29}	-0.073	28
C_7	1.083	45	C_{30}	1.204	42	C_7	0.053	22	C_{30}	0.384	12
C_8	1.295	36	C_{31}	1.332	34	C_8	-0.115	33	C_{31}	0.384	13
C_9	1.534	14	C_{32}	1.213	41	C_9	-0.054	26	C_{32}	0.610	9
C_{10}	1.595	11	C_{33}	1.529	15	C_{10}	0.387	11	C_{33}	-0.545	35
C_{11}	1.175	43	C_{34}	1.497	22	C_{11}	0.259	16	C_{34}	-0.655	37
C_{12}	1.920	1	C_{35}	1.458	24	C_{12}	-0.105	32	C_{35}	-0.767	40
C_{13}	1.499	20	C_{36}	1.441	26	C_{13}	0.837	4	C_{36}	-0.696	39
C_{14}	1.429	28	C_{37}	1.308	35	C_{14}	0.213	20	C_{37}	-0.693	38
C_{15}	1.289	38	C_{38}	1.507	18	C_{15}	0.755	6	C_{38}	-0.784	41
C_{16}	1.294	37	C_{39}	1.626	5	C_{16}	0.510	10	C_{39}	-0.956	44
C_{17}	1.156	44	C_{40}	1.521	16	C_{17}	0.284	15	C_{40}	-0.911	43
C_{18}	1.265	40	C_{41}	1.544	13	C_{18}	0.178	21	C_{41}	-0.969	45
C_{19}	1.501	19	C_{42}	1.433	27	C_{19}	0.229	19	C_{42}	-0.877	42
C_{20}	1.369	31	C_{43}	1.415	29	C_{20}	-0.060	27	C_{43}	-0.491	34
C_{21}	1.373	30	C_{44}	1.720	2	C_{21}	0.232	18	C_{44}	-0.593	36
C_{22}	1.451	25	C_{45}	0.851	46	C_{22}	0.342	14	C_{45}	-0.074	29
C_{23}	1.364	32	C_{46}	1.679	4	C_{23}	0.236	17	C_{46}	-1.162	46

Table 10. Prioritize the risk dimension of the blasting operations based on the degree of importance (r + c) and impact level (r – c)

Dimensions	$(r + c)$	Rank	Dimensions	$R = c$	Rank
D_1	0.294	5	D_1	0.152	1
D_2	0.282	6	D_2	0.029	5
D_3	0.308	4	D_3	0.073	3
D_4	0.255	7	D_4	0.127	2
D_5	0.240	9	D_5	0.023	6
D_6	0.312	3	D_6	-0.035	7
D_7	0.251	8	D_7	0.050	4
D_8	0.326	2	D_8	-0.158	9
D_9	0.191	10	D_9	-0.031	8
D_{10}	0.330	1	D_{10}	-0.230	10

Based on Figures 4 and 6, the map of the relationship between the dimensions of the blasting operations risk can be shown in accordance to Figure 7. The greatest affected can see on the dimensions D_{10} and D_8. On the other hand, has the most effecting D_1 dimension on the other dimensions.

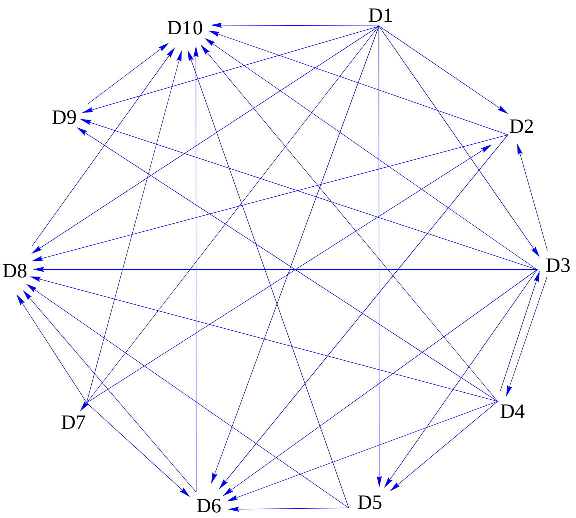

Figure 7. The map of the relationship between the dimensions of operations risk

The criteria of lack of specialized knowledge (C_1), lack of supervision and technical inspection (C_4), lack of practical application of specialized knowledge (C_2), proximity to geologic deformations (fault – losing zone – karst cavities – folding) (C_{13}) and lack of skills in the system of understanding and effective decision-making skills (C_3), have the greatest effect on the blasting operations risk criteria in open-pit mines. The C_1, C_2, and C_3 criteria of the D_1 dimension in relation to human resources and the C_4 criterion of the D_2 dimension in relation to execution factors and the C_{13} criterion represent the conditions of the explosion environment. Controlling this group of criteria reduces the severity of the affected factors.

The criteria of damage to manpower (production of noise and gases from blasting operations) (C_{46}), fly rock (C_{41}), ground vibration (C_{39}), air blast (C_{40}) and production of toxic gases from the explosion (C_{42}), are affected most substantially from other criteria and are to be formed with effective parameters. Damage to human resources is the most important affected criterion. The most affected the blasting criterion C_{46} is, therefore, the most dependent criterion and the control of this criterion is of particular importance. To this end, the accuracy of identifying and controlling the dimensions of the blasting operations risk is very important. In this study, the dimensions of production and extraction consideration (D_9) with the criterion of failure to determine the amount of production capacity (low or high) (C_{45}), drilling operations (D_5) with the criteria of explosive hole deviation (C_{16}) and non-compliance of the length-to-diameter ratio (C_{17}), are the least important dimensions. The dimensions of natural hazards (D_{10}) with criterion damage to manpower (production of noise and gases from blasting operations) (C_{46}), effects and results of blasting operations (D_8) with criteria of worse fragmentation (C_{33}) boulder production (C_{34}) back break (C_{35}) Side break (C_{36}) pivot creation (C_{37}) misfire (C_{38}) ground vibration (C_{39}) air blast (C_{40}) fly rock (C_{41}) production of toxic gases from the explosion (C_{42}) premature blast (C_{43}) inappropriate stability of remains bench face (C_{44}), are the most important dimensions, respectively. Controlling these two dimensions and their related criteria is of particular importance. In order to control the dimensions, the determination and composition of the weight of the risk parameters of the blasting operations with the dimensions related to each criterion must be considered. The determination of the relative weight, priority, and prioritization of blasting operations risk can be calculated by using the FDANP method according to the equations 21 and 22 of the weighted super-matrix. The relative weight of the risk criteria of the blasting operations can be seen in Table 11 according to the weight composition of the criteria and dimensions. Therefore, the criteria can be prioritized according to importance.

Table 11. Influential weights by stable matrix of DANP $W_Z = \lim_{Z \to \infty} \left(W^{\alpha}\right)^Z$

Criteria	Global weight (DANP)	Rank	Criteria	Global weight (DANP)	Rank
C_1	0.006	19	C_{24}	0.010	15
C_2	0.013	12	C_{25}	0.010	15
C_3	0.012	13	C_{26}	0.012	13
C_4	0.004	20	C_{27}	0.010	15
C_5	0.004	20	C_{28}	0.011	14
C_6	0.003	21	C_{29}	0.011	14
C_7	0.007	18	C_{30}	0.016	9
C_8	0.013	12	C_{31}	0.019	6
C_9	0.013	12	C_{32}	0.011	14
C_{10}	0.018	7	C_{33}	0.016	9
C_{11}	0.006	19	C_{34}	0.016	9
C_{12}	0.022	4	C_{35}	0.017	8
C_{13}	0.015	10	C_{36}	0.016	9
C_{14}	0.046	1	C_{37}	0.015	11
C_{15}	0.001	22	C_{38}	0.018	7
C_{16}	0.018	7	C_{39}	0.022	4
C_{17}	0.027	2	C_{40}	0.019	6
C_{18}	0.006	19	C_{41}	0.021	5
C_{19}	0.008	17	C_{42}	0.021	5
C_{20}	0.009	16	C_{43}	0.014	11
C_{21}	0.007	18	C_{44}	0.023	3
C_{22}	0.006	19	C_{45}	0.001	22
C_{23}	0.006	19	C_{46}	0.009	16

According to Table 11, criteria with equal rating have the same priority. The criterion of the number of explosions in one stage (C_{14}), with a relative weight of 0.046, is determined as the first blasting operation risk criterion. This criterion belongs to the dimension operational conditions D_3. By controlling the number of explosions and operating conditions, the destructive effects of blasting, such as ground vibration, fly rock, and air vibration, can be prevented.

Therefore, controlling this criterion reduces the risk of blasting operations and also reduces damage to the C_{46} criterion. Two criteria include joints and cracks (C_{15}) and failure to determine the amount of production capacity (low or high) (C_{45}), with a relative weight of 0.001 as the last criteria for blasting operations risk.

8. Conclusions

The process of identifying risk involves identifying the causes and sources of risk as well as events and situations that can have overall outcomes on the goals and nature of the risk, identifying the blasting operation risk, the process of finding the hazards of the blasting operations, and recognizing and recording the blasting risks. To proceed, identifying situations that can affect the achievement of project goals is fundamental. For this purpose, while identifying the blasting operation risk, all the existing controls, such as design specifications, people, processes, and systems, must be identified. Therefore, it should be noted that the risk criteria for blasting operations in a mine project are interdependent. By taking into account all the relevant criteria for blasting operations and incorporating all the dependencies, using techniques that are able to model the interactions of the criteria will provide more accurate results. In this research, the significance and extent of the effectiveness of the criteria and the dimensions of the blasting operation risk on each other, and the determination of the relations of 46 criteria and 10 dimensions affecting the blasting operations risk by the fuzzy DEMATEL method have been investigated. In order to combine the weight of the criteria and dimensions, and to determine the relative weight of the criteria in order to prioritize the risk criteria of the blasting operation, the FDANP method was considered. By using the FDEMATEL technique, each criterion on the criteria of the other levels (same, higher, and lower levels) affects each of them. In this case, the identification of the most effective and most affected criterion and the dimensions of the blasting operations risk are carried out with greater precision. Lack of specialized knowledge (C_1), lack of supervision and technical inspection (C_4) and lack of practical application of specialized knowledge (C_2) were identified as the most influential criteria. Criteria damage to manpower (production of noise and gases from blasting operations) (C_{46}), fly rock (C_{41}) and ground vibration (C_{39}) will be affected the most from other criteria. The criterion implement the explosion plan without respecting the design principles (C_{12}) shows the greatest interaction with other criteria and the criterion failure to determine the amount of production capacity (low or high) (C_{45}) has the least interaction with other criteria. By measuring the dimension of human resources (D_1), which is the most influential dimension, and then natural hazards (D_{10}), which has the greatest interaction with other dimensions, have been affected the most. Dimension production and extraction consideration (D_9) has the least interaction with other dimensions and is less important. According to the FDANP method and the prioritization of the blasting operations risk criteria based on the relative weights of the criteria, number of explosions in one stage (C_{14}) is the first criterion of blasting operations risk. By controlling this criterion and its related dimension, it is possible to prevent the consequences and destructive consequences of blasting operations. Therefore, controlling this criterion reduces the risk of blasting operations and also reduces the damage to the C_{46} criterion. Two criteria for joints and cracks (C_{15}) and failure to determine the amount of production capacity (low or high) (C_{45}) are the latest criteria for the blasting operations risk. Therefore, the identification and control of all criteria for blasting operations is necessary in order to reduce the damage to manpower. With this in mind, reducing the damage to manpower and reducing the risk of blasting operations in mines will take place. In order to reduce the destructive effects of blasting operations, with full knowledge of how to create effective factors, affected factors, and methods of prevention and control of these consequences, two favorable results will be achieved: the reduction of damage caused by undesirable consequences and the assignment of a greater share of the energy of blasting to the desired outcomes.

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Класифікація критеріїв ризику та оцінка вибухових робіт на кар'єрах із використанням методу FDANP (аналітичної мережі нечітких процесів прийняття рішень)

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Мета. Розробка класифікації критеріїв оцінки ризиків на кар'єрах із використанням методу аналітичної мережі нечітких процесів прийняття рішень на основі фактичної інформації та її комплексного аналізу.

Методика. В даному дослідженні були вивчені взаємозв'язки 46 критеріїв і 10 параметрів, що впливають на ризик вибухових робіт, з метою визначення значущості, ефективності, відносної ваги критеріїв та параметрів, а також визначення пріоритетності критеріїв ризику вибухових операцій. Для цього був використаний метод FDANP, який являє собою комбінацію методу FDEMATEL (Fuzzy Decision Making Trial and Evaluation Laboratory) і методу FANP.

Результати. Встановлено, що в оцінці ризиків відсутність спеціалізованих знань (C_1) є найбільш важливим критерієм. Відзначається, що критерій завданих збитків робочій силі (C_{46}) відчуває найбільший вплив з боку інших критеріїв. Критерій виконання плану вибуху без урахування проектних принципів (C_{12}) найбільше взаємодіє з іншими критеріями, а критерій нездатності визначення обсягу виробничої потужності (низький або високий) (C_{45}) взаємодіє з іншими критеріями найменше. Згідно з методом FDANP, кількість вибухів на одній стадії (C_{14}) є першим критерієм ризику вибухових робіт. При порівнянні параметрів виявлено, що людські ресурси (D_1) є найбільш ефективним параметром, а стихійні лиха (D_{10}) найсильніше взаємодіють з іншими параметрами та найбільш схильні до їх впливу. Визначено, що параметр впливу виробництва та видобутку (D_9) менше всього взаємодіє з іншими параметрами і менш важливий.

Наукова новизна. Науково обґрунтовані математичні взаємозв'язки між величинами ризику підривних робіт. Встановлено, що, контролюючи критерій (C_{14}), можна запобігти руйнівним наслідкам вибухових робіт, а управління даним критерієм знижує ризики вибухових робіт, а також зменшує шкоду за критерієм C_{46}.

Практична значимість. Зменшення руйнівного впливу вибухових робіт може призвести до двох сприятливих результатів: скорочення збитку, викликаного небажаними наслідками вибуху, і спрямованому використанню більшої частки енергії вибухових робіт для отримання бажаних результатів

Ключові слова: *оцінка вибухових робіт, вибухові роботи, кар'єр, метод FDANP*

Классификация критериев риска и оценка взрывных работ на карьерах с использованием метода FDANP (аналитической сети нечетких процессов принятия решений)

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Цель. Разработка классификации критериев оценки рисков на карьерах с использованием метода аналитической сети нечетких процессов принятия решений на основе фактической информации и ее комплексного анализа.

Методика. В данном исследовании были изучены взаимосвязи 46 критериев и 10 параметров, влияющих на риск взрывных работ, с целью определения значимости, эффективности, относительного веса критериев и параметров, а также определения приоритетности критериев риска взрывных операций. Для этого был использован метод FDANP, который представляет собой комбинацию метода FDEMATEL (Fuzzy Decision Making Trial and Evaluation Laboratory) и метода FANP.

Результаты. Установлено, что в оценке рисков отсутствие специализированных знаний (C_1) является наиболее важным критерием. Отмечается, что критерий нанесенного ущерба рабочей силе (C_{46}) испытывает наибольшее влияние со стороны других критериев. Критерий выполнения плана взрыва без учета проектных принципов (C_{12}) больше всего взаимодействует с другими критериями, а критерий неспособности определения объема производственной мощности (низкий или высокий) (C_{45}) взаимодействует с другими критериями меньше всего. Согласно методу FDANP, количество взрывов на одной стадии (C_{14}) является первым критерием риска взрывных работ. При сравнении параметров выявлено, что человеческие ресурсы (D_1) являются наиболее эффективным параметром, а стихийные бедствия (D_{10}) сильнее всего взаимодействуют с другими параметрами и наиболее подвержены их влиянию. Определено, что параметр учета производства и добычи (D_9) меньше всего взаимодействует с другими параметрами и менее важен.

Научная новизна. Научно обоснованы математические взаимосвязи между величинами риска взрывных работ. Установлено, что, контролируя критерий (C_{14}), можно предотвратить разрушительные последствия взрывных работ, а управление данным критерием снижает риски взрывных работ, а также уменьшает ущерб по критерию C_{46}.

Практическая значимость. Уменьшение разрушительного воздействия взрывных работ может привести к двум благоприятным результатам: сокращению ущерба, вызванного нежелательными последствиями взрыва, и направленному использованию большей доли энергии взрывных работ для получения желаемых результатов.

Ключевые слова: *оценка взрывных работ, взрывные работы, карьер, метод FDANP*