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A quantitative model for evaluation and classification of blastings in open-pit mines

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Abstract

By evaluation of the blasting results, a proper blast pattern can be presented. It is, therefore, essential to employ a reliable method to evaluate blastings for the effective control and optimization of the main cycle operations. This paper aims to propose a criterion for evaluating the blasting results such as the fragmentation, muckpile condition, back-break, and fly rock, and to make a possible comparison between the blast parameters including the blasting pattern, explosives used, hole depths, and volume of the blasted rocks in the lead and zinc mine in Angouran (Iran). Using the global criterion, making the decision matrix dimensionless, and defining the appropriate conditions for the results obtained, a scalar value is devoted for the blasts, whose larger values denote a larger deviation from the proper blasting conditions and express undesirable blasts regarding the blasting results. By taking into consideration the mining operation conditions and weights of the results obtained, the influence of the results obtained on the mining operation index is also investigated using the genetic algorithm. Furthermore, by composing the weighted decision matrix, the blastings are evaluated and classified. Analyzing the results obtained for blastings in the Angouran mine reveals that the proposed method is an effective approach for evaluation of the blasting results and comparison of the blasts.

Keywords: *Blasting Evaluation, Classification, Blasting Results, Mining Operation Index.*

1. Introduction

Drilling and blasting are two fundamental operations in a mining cycle, and constitute important components of the mining costs. Problems associated with improper drilling and blasting practices may lead to expending high costs. The blasting results such as fragmentation, shape of muckpile, and damage to mine wall affect the other operations [1-5]. Success in exploitation of an open-pit mine is mostly dependent on the machinery efficiency. If blasting is properly implemented and the rocks are appropriately fragmented, the efficiency of loading, haulage, and primary crushing, and consequently, mine production will increase. However, an improper blasting produces vibration, air blast, fly rock, and large boulders, which significantly decrease the production of a loading system. On the other hand, not-moving of rock, not-fracturing of bench floor, and as a result, creation of a toe and an uneven bench floor are the results of an improper blasting of a mine. These issues will impose the cost of a secondary blasting and an extra cost for a dozer to smooth the remaining toe and move the boulders, and will indirectly increase the maintenance and repair costs of the loading system and primary crushing [6].

A number of investigators have studied the possible ways of optimizing blasting operations, arriving at different results. Most of these studies have suggested that the entire process should be modeled. Nevertheless, some of them are still of the opinion that a better understanding of the blasting site matters most in the modeling and design of the drilling and blasting operations [1].

Introducing an optimal plan for drilling and blasting is a difficult work, as several effective parameters are involved, some of which cannot be controlled; and many authors have failed to set a standard practice design in this field. The effective blasting parameters involved are different from one location to another, and optimization of blasting can only be achieved over months or even years by means of trial and error. Therefore, establishing a guide for optimum and cost-effective drilling and blasting operations will surely be of great assistance in this research area [1]. However, in this process, an important and prerequisite matter is to evaluate the blasting conditions, where it is essential to apply a fast and reliable technique for a blasting evaluation due to the effective control and optimization of the main cycle operations. Regarding planning, a blasting evaluation is highly important for a fast and efficient analysis of the results of applying different kinds of explosives and blasting patterns. This fast evaluation should be fulfilled in a simple and uncomplicated way along with the highest efficiency.

Several researches have used various indices for blasting evaluations. Eloranta [7] has used the energy required for crushing, investigating its relation with the specific charge. Moody [8] has related the dig time and crushing speed to the fragmentation. Taqieddin [9] has selected the loading cycle time of the dragline as a criterion for blasting evaluations. In this context, the fragmentation degree has been widely used [10, 11-15], and because of this, many efforts have been devoted to evaluating its performance, determining the fragmentation degree and its impact on the mining operations. However, gaining a proper blasting pattern requires evaluation of all the blasting results. After performing the first blasting, it is required to gather all the results obtained and analyze them; and to achieve a global evaluation, the following aspects must be analyzed [16, 17]:

- Fragmentation and swelling of the muckpile;
- Geometry, height, and displacement of the muckpile;
- State of the remaining rock and bench floor;
- Presence of boulders in the pile;
- Vibrations, fly rock, and air blast produced by the blast.

Therefore, a blasting evaluation is a multi-criteria one. In 2013, Taji [10] has proposed the ODM model, which is based upon scoring the blasting results. This model, however, has been considered to be confusing in the evaluation of the results, especially in the evaluation of the muckpile, back-break, and toe conditions; and evaluation of the results is affected by the individual ideas. Jamshidi et al., Sereshki et al. and Yari et al. have proposed evaluation systems for selecting a proper patterns [18-22] but the effect of blasting on the loading operation has not been taken into account. In this paper, a novel approach is proposed for a blasting evaluation using the multi-criteria decision methods.

Firstly, the field measurements in the Angouran mine are described, and then the blasts in this mine are evaluated using the proposed method.

2. Angouran mine

The Angouran mine is the largest producer of lead and zinc in the Middle-East [23]. Angouran Mine Complex is located in the north of the Zanjan-Tekab road. It is in the region of quadrilateral geology map of Takht-Soleiman. From the constructional viewpoint, it is situated in the Sanandaj-Sirjan area, in the Khoy-Mahabad zone, and in the junction of the constructional zones Alborz-Azarbijan, central Iran, Sanandaj, and Sirjan; and due to this, it has some particular complicated characteristics. The geology of this region includes metamorphic Schist, Marble, Gneiss, and Amphibolites, which are seen from NW to SE. These rocks are covered with Oligocene sediments. The Sanandaj-Sirjan zone along with its unique complexities includes crystalline Limestone and Marl placed on Schist layers and crystalline Schist, where the Limestones are extremely crushed in the extraction pit area, and the main joint system has been filled with Calcite and, sometimes, Clay. In general, the major rock units in the geology map include crystalline Limestone, Schist, Marble, Amphibolite, and Tuff. In some parts, the limy wall is observed as Aragonite [23].

3. Field measurement

The field measurements in this research work were divided into two parts. The first part was related to determining the characteristics of the Angouran mine rocks and blastability of the rock blocks, and the second part included recording drilling and blasting operations, blasting results, and loading time of the blasted rocks. Regarding the purpose of this research work, for evaluation of blasts by means of blasting results, only the stage related to the mining operation before and after blasting is briefly described.

3.1. Before blasting

The information for the drilling operations in the blasting blocks was collected according to the worksheet shown in Figure 1. For each hole, considering the number and length of the employed rods, the penetration speed in different depths was registered by a chronometer, and it was tried to record the stoppings of each driller as well as the stopping reason.

The holes depths, spacings, and burden were measured, and, according to the sheets shown in Figure 2, the other characteristics of the blasting pattern were collected.

3.2. After blasting

According to the worksheet shown in Figure 3, the characteristics of muckpile including the geometry, fly rock, back-break and its spread value, cracks created in bench, and position and number of boulders were recorded.

The parameters corresponding to the geometry of the muckpile are illustrated in Figure 4. Also Figure 5 represents the back-break in blast no. 9 and the shape of its muckpile.

Regarding the shape variability of the muckpile, different sections in specific distances from the muckpile were drawn by geodesy of the pile (Figure 6 is related to the blast no. 12); and the distances of sections along with some descriptions of the pile shape are noted.

For a better usage, the results expressed in the sheets for each block were arranged as tables; a sample table is given in Table 1.

Also for determining the fragmentation using the SplitDesktop software, the blasted rocks were photographed before and during the loading. (Figure 7 is related to the pile resulting from the blasting of block no. 16).

d_{50}, d_{80}, d_{100} (size of screens that, respectively, 50%, 80%, and 100% of the fragmented rocks can pass through them), which were calculated using SplitDesktop, and n (size uniformity of the fragmented rocks), and also X_c (characteristic size) for the blasted piles calculated by experimental relations (1)-(2) (proposed by Sudhakar et. al. [24]) are given in Table 2. The particle size distribution for the blast no. 16 is also illustrated in Figure 8.

$$n = 0.842 / (\mathrm{Ln}\ d_{80} - \mathrm{Ln}\ d_{50}) \tag{1}$$

$$Xc = e^{0.565\times\ln d_{50} + 0.435\times\ln d_{80}} \tag{2}$$

The loading and haulage times of the blasted rocks were registered using a chronometer, according to the worksheet shown in Figure 9, and sometimes by using a video. The loading cycle time and dig time for the recorded blasts are presented in Table 3.

Using the information acquired from the worksheets and the volume of the blasted blocks obtained by counting the number of loading machines, we calculated the specific charge (value of charge for each m^3 of the blasted rock in kg/m^3), specific drilling (drilling length for each m^3 of blasted rock in m/m^3), and specific loading (loading time for each m^3 of the blasted rock in h/m^3) for the blasted blocks in Table 4.

<table>
<tr><th colspan="13">Drilling Daily Report</th></tr>
<tr><td colspan="7">Date:
Level:
Block number:</td><td colspan="6">Page number:
Diameter:
Machine:</td></tr>
<tr><td colspan="13"></td></tr>
<tr><td>Rock type</td><td>Hole no.</td><td>Degree of nclination</td><td>Positioning & collaring</td><td>Rod Number</td><td>Rod length</td><td>Drilling time</td><td>Time to place rod</td><td>Time to remove rod</td><td>Pull-down</td><td>Rotary speed</td><td>Type of bit</td><td>Drilling rate</td></tr>
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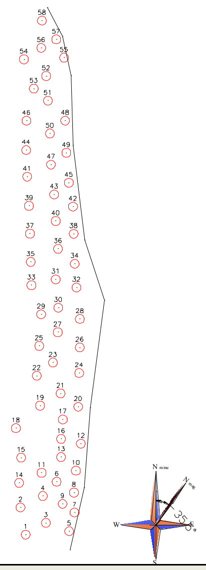
<tr><td colspan="13">Stopping Times</td></tr>
<tr><td colspan="3">Stopping description</td><td colspan="3">Stopping time</td><td colspan="5">Stopping description</td><td colspan="2">Stopping time</td></tr>
<tr><td colspan="3"></td><td colspan="3"></td><td colspan="5"></td><td colspan="2"></td></tr>
<tr><td colspan="3"></td><td colspan="3"></td><td colspan="5"></td><td colspan="2"></td></tr>
<tr><td colspan="6">Total working time</td><td colspan="7">Total stopping time</td></tr>
</table>

Figure 1. Worksheet of drilling information.



Rock type: waste				**Block no. and location: 2960-30W**				
Consumed explosives			Technical characteristics					
ANFO (kg)		4306	Last row		Whole block			
Emolite (kg)			Hole diameter (mm)	127	Block area (m^2)	997	Total drilling length (m)	662.5
Booster	1 pounds	60	Number of holes	5	Approximate block volume (m^3)	9856	drilling network (m)	3.8×4.5
	1.5 pounds							
Cordtex (m)			Average holes depth (m)	11.42	Approximate tonnage of block	26611	Number rows	4
Electric detonator	18m	60	Burden (m)	3.8	Hole diameter (mm)	127	Subdrilling (m)	1.3
	8m							
	5m							
Relay			Vertical slope	0	Number of holes	58	Stemming (m)	3.8
			Distance of the last row to the plan line (m)	6	Average holes depth (m)	11.42	Specific charge (gr/m^3)	437
			Subdrilling (m)	1.3	Minimum holes depth (m)	7.5		
			Stemming (m)	3.8	Maximum holes depth (m)	11.5		

Figure 2. Pattern of blast no. 2.

Date: Level: Rock type: Photographing of pile's shape	Block number: Pile's shape drawing: Photographing of crest:

Row	Component	Value	Comments	
1	Throw			
2	Drop			
3	Spread			
4	Spread angle			
5	Volume of muckpile			
6	Distance of fly rock			
7	Number and size of boulders			
8	Position of boulders in pile			
9	Distance of cracks in crest from the wall			
10	Length of cracks in crest			
11	Fragmentation photography	After blasting (in one horizontal row of pile)	After loading of one-thirds	After loading of two-thirds
	Number			

Figure 3. A sample worksheet of characteristics of muckpile.

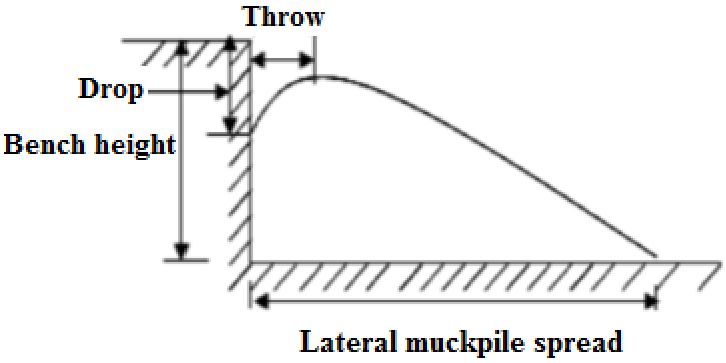


Figure 4. Parameters corresponding to shape of muckpile.

Figure 5. Pile shape and back-break in blast no. 9.

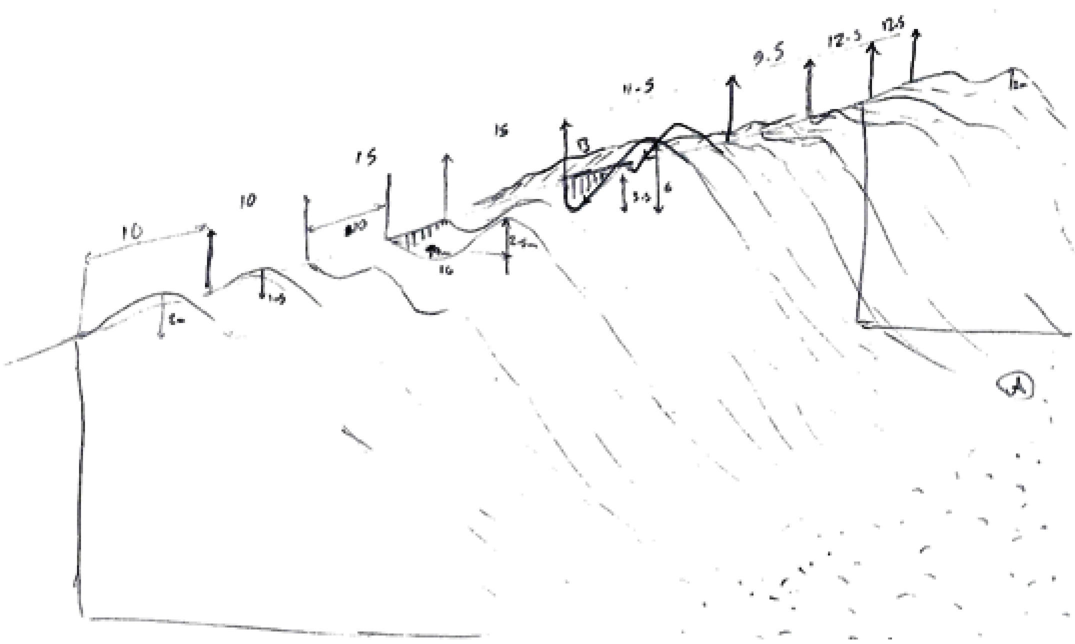


Figure 6. Drawn sections in geodesy of blasted pile in blast no. 12.

Figure 6. Some samples of photography from muckpile in blast no. 16.

Table 1. Information about blasted pile related to blast no. 2.

Block no.	Throw (m)	Drop (m)	Spread (m)	Back-break	Fly rock	Boulder
1	0.21	0.13	20	4 m	60 m	7 boulders of 1.5 m in front of pile
2	0	0	24	5.8 m, cracks are perpendicular to the crest	60 m with maximum size of 30 cm	6 boulders in the middle part with maximum size of 3 m
3	6.1	1.75	33	Does not exist	Does not exist	7 boulders in middle and front parts with maximum size of 1.9 m
4	0	0	22	2 m, with the length up to 12 m	Does not exist	4 boulders in the middle part, and 6 boulders in front with maximum size of 2 m
5	0	0	16	Up to 4 m distance from the crest, with the length of 40 m	Does not exist	4 boulders with maximum size of 1.1 m
6	7.7	3	45	Up to 2.5 m, with length of 13.2 m	75 m	One boulder of 2.5 m in the middle part of pile in its western section
7	1.5	0.51	20	Up to 2 m, with the length of 10 m	40 m	One boulder on top of the pile with the size of 1.7 m
8	8	2	41	Up to 5 m, with length of 54 m	Does not exist	Up to 3 m on top and middle of the bench
9	5.5	2.7	25	Up to 2 m in most cases, with length of 7.5 m, and 4m in one case	Does not exist	On top of the pile with maximum size of 4 m; the block has holes
10	8.5	3.5	60	Does not exist	Does not exist	Up to 6 ones in the middle and front of pile with maximum size of 2.5 m
11	4	1	21	1 m with the length of 10 m	29 m	One boulder in the middle part with the size of 4 m
12	5	0.73	30	2 m with the length of 14 m	40 m	One boulder in the front part with diameter of 3 m
13	4	3.8	28	1.1 m with the length of 10 m	62 m	Was not observed
14	4	1	21	1 m with the length of 10 m	29 m	One boulder with maximum size of 4 m
15	7	5	20	0.5 m with the length of 9 m	Does not exist	One boulder in the front part
16	4	3.8	28	Up to 1 m with the length of 9.6 m	60 m	Was not observed

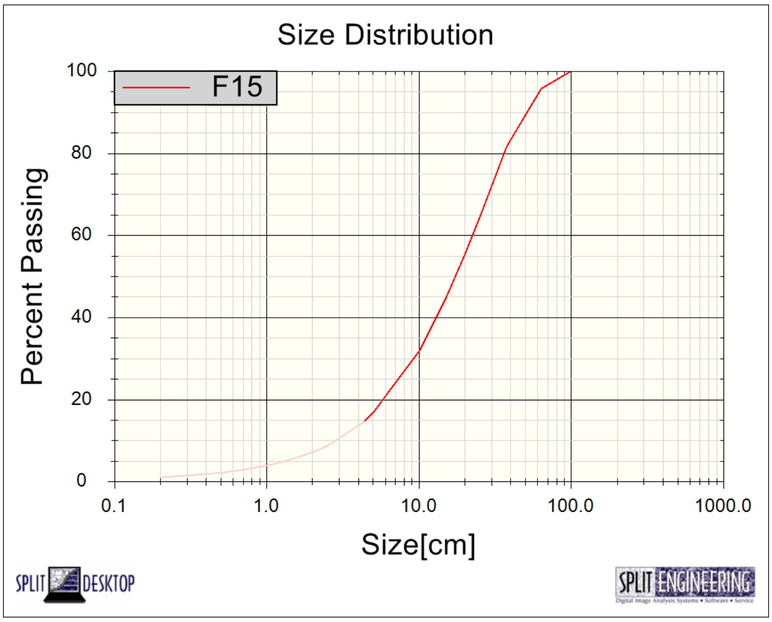


Figure 7. Particle size distribution for fragmented pile in blast no. 16.

Table 2. d50, d80, d100, n, and Xc for blasted piles in Angouran mine.

Blast no.	d_{50} (cm)	d_{80} (cm)	d_{100} (cm)	n	X_c (cm)	Blast no.	d_{50} (cm)	d_{80} (cm)	d_{100} (cm)	n	X_c (cm)
1	25.36	53.14	113.73	1.14	34.99	9	20.37	38.95	98.4	1.3	27
2	20.57	38.9	86.71	1.32	27.14	10	10.75	22.32	51.9	1.15	14.7
3	10.75	22.32	51.91	1.15	14.77	11	12.74	26.26	94.32	1.16	17.45
4	15.14	29.43	84.75	1.27	20.22	12	12.1	29.97	120.9	0.93	17.94
5	24.11	63.99	184.74	0.86	36.86	13	17.59	36.53	99.43	1.15	24.17
6	30.35	62	136.35	1.18	41.41	14	17.61	36.42	100.38	1.16	24.16
7	13	31.76	98.65	0.94	19.19	15	22.1	43.98	175.86	1.22	29.79
8	22.87	44.57	89.79	1.26	30.57	16	17.6	36.5	99.4	1.15	24.2

No. and date: Level: Rock type:	Block no.: Block size:

Row	Loading machine type	Cycle time	Dig time	Hoisting time	Swinging time	Dumping time	Haulage Machine type	Spot time	Number of loading buckets	Haul time	Return time	Dump time

Figure 8. Worksheet for recording loading and haulage operations.

4. Evaluation of blasts

As noted earlier, the researchers have employed various indices for the sake of blasting evaluation, where the most common indices are the fragmentation degree and specific charge. However, to obtain a proper blasting pattern, it is required to evaluate all the blasting results. Therefore, the blasting evaluation is a multi-criteria one.

4.1. Constituting decision matrix

The blasting results were employed as follows, in order to evaluate the blasting and constitute the decision matrix.

- Back-break (Bb in m): Back-break is defined as breakage behind the last row of blast holes, which cause instability in mine walls, falling down the machinery, improper fragmentation, and reduction in efficiency of drilling and difficulties for the placement of drilling machine [25-27].
- Number of boulders (Bo): Any fragment produced by blasting that cannot be handled by the mining equipment is referred to as boulders or oversize [16].
- Fly rock (Fr in m): Fly rock, also called rock throw, is the uncontrolled propelling of

rock fragments beyond a specified boundary by the force of explosion. Fly rock is one of the adverse effects of blasting, which can result in human injuries, fatalities, structure damages; and is the main reason of damage to equipment and constructions [16, 28-31].

- Status of muckpile (S, H): The optimal shape of muckpile is different in each operation, and depends on the loading and haulage machine. For describing the shape of the muckpile, based on Figure 4, two parameters, i.e. Drop and Spread (S), mentioned in the measurements, are used. Drop is used for calculating the ratio of muckpile height to bench height (H).
- Fragmentation (D): The degree of fragmentation is the main output result of the blasting operation. A good fragmentation in a mine is defined as the production of fragmented rocks that the largest particle can be easily loaded within the machine bucket without any need for a secondary blasting [10]. For constitution of decision matrix, regarding the number of boulders, d_{80}, calculated by SplitDesktop, is used.

The decision matrix corresponding to the results of the recorded blasts is according to Table. 5. The columns of the table include the results (Bb: back-break, Bo: number of boulders, Fr: fly rock, S: lateral spread of the blasted rock, H: ratio of muckpile's height to bench's height, D: d_{80}).

Table 3. Average times of loading and dig in blasted piles.

Blast no.	Loading machine type	Loading cycle (average) (s)	Dig time (average) (s)
1	Excavator 800	15.1	7.64
2	Excavator 800	19.01	-
3	Excavator 800	17.75	-
3	Excavator 385	14.29	-
4	Excavator 800	16.92	5.49
5	Excavator 800	18.43	5.33
6	Excavator 800	27.04	5.66
7	Excavator 385	14.79	4.69
8	Excavator 385	15.93	6.58
9	Excavator 800	19.7	6.92
10	Excavator 385	18.83	7.13
11	Excavator 385	13.96	5.31
12	Excavator 385	13.96	5.31
13	Excavator 800	18.73	12.04
14	Excavator 800	18.73	12.04
15	Excavator 800	22.23	14.24
16	Excavator 800	18.73	12.04
Excavator 800 = 5 m^3		**Excavator 385 = 1.75 m^3**	

Table 4. Specific charge, specific drilling, and specific loading.

Blast no.	Specific charge (kg/m^3)	Specific drilling (m/m^3)	specific loading (h/m^3)
1	0.357	0.047	0.05
2	0.392	0.054	0.063
3	0.23	0.034	0.098
4	0.347	0.049	0.056
5	0.397	0.045	0.061
6	0.419	0.057	0.09
7	0.313	0.021	0.141
8	0.426	0.032	0.152
9	0.368	0.065	0.066
10	0.432	0.045	0.179
11	0.418	0.054	0.133
12	0.413	0.05	0.133
13	0.343	0.049	0.062
14	0.45	0.054	0.062
15	0.625	0.076	0.074
16	0.302	0.039	0.062

Table 5. Decision matrix.

Blast no.	Bb	Bo	Fr	S	H	D
1	4	7	60	20	0.99	53.1
2	5.8	6	60	24	1	38.9
3	0	7	0	33	0.83	22.3
4	2	10	0	22	1	29.4
5	4	4	0	16	1	64
6	2.5	1	75	45	0.7	62
7	2	1	40	20	0.95	31.8
8	5	1	0	41	0.8	44.6
9	4	10	0	25	0.73	39
10	0	6	0	60	0.65	22.3
11	1	1	29	21	0.9	26.3
12	2	1	40	30	0.93	30
13	1.1	0	62	28	0.62	36.5
14	1	1	29	21	0.9	36.4
15	0.5	1	0	20	0.5	44
16	1	0	60	28	0.62	36.4

4.2. Making decision matrix as dimensionless

For making the decision matrix dimensionless, the general criterion method was used. In this way, by defining a fitness function for each result, a dimensionless and scalar value was assigned to each result. In this method, the fitness function is defined as the relative deviation of the objective function F_i from its optimal value, and the common objective function is defined as the sum of relative deviations of objective functions (in this work, the sum of squares was used). This method is less influenced by the planner view, and acts based on the normalization of objective functions around the optimal point. The mathematical expression of this method is as (3) [32, 33]:

$$\text{Min}\left\{ F(x) = \sum_{i=1}^{n} \frac{F_i(x) - F_i(x^*)}{F_i(x^{**}) - F_i(x^*)} \right\} \quad (3)$$

where x^* and x^{**} are the solutions to the single-objective optimization problem (relations (4) and (5)). Different functions can be employed for the sake of normalization. In this paper, the average of F_i was chosen for the normalization.

$$MinF_i(x^*), C_i(x^*) \le 0, i = 1,...,n \quad (4)$$

$$MaxF_i(x^{**}), C_i(x^{**}) \le 0, i = 1,...,n \quad (5)$$

The appropriate state for the back-break, fly rock, and number of boulders was non-existence of them. The optimal size of the fragmented rocks (D in m) was calculated using the relation proposed by Rzhevsky in (6) [34] with respect to the bucket capacity of the loading machine (V in m^3).

$$D = 0.127\sqrt[3]{V} \quad (6)$$

According to the explanations given in Table 6 about the shape of muckpile, and considering the type of loading machine, the optimal ratio of the muckpile height to the bench height is set as 2/3 to 1.

Regarding that the loading machine in Angouran mine is of an excavator type, the low degree of lateral spread of the blasted pile is the favorite state, and if this spread is lower, less time will be spent on for cleaning-up the blasted area.

The dimensionless decision matrix was shown in Table 7. The summations of values in the columns corresponding to each blast were also calculated; the larger values represent the larger deviation of blast from the proper blasting, which shows undesirable blasting conditions according to the blasting results.

The result of classification of the blasts using the dimensionless matrix (sum of the value of columns related to each blasting) was illustrated in Figure 10. As it can be seen, the blast no. 15 was the best one. In this blast, the back-break was 50 cm; there is no fly rock; and there is one boulder. The lateral spread of the muckpile after the blast no. 5, in which the pile is not actually moved, is the minimum one among the blasts that minimize the need for cleaning up the area. Also, in this blasting, the size of fragmented rock was just 5 cm, larger than the average size of the rocks in all 16 blasts.

Figure 11 shows the variation in blasting results compared to each other (elements of the dimensionless decision matrix for each blast). As seen, the fairness of the blast no. 15 is due to its relative fairness compared to the other ones. The relatively low fly rock and back-break in the blasts numbers 4 and 9, in spite of high number of boulders in these blasts, increased the fairness of these two blasts compared to the blast no. 2, which had the highest back-break, and also had more fly rock.

Table 6. Description of muckpile state [10].

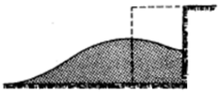
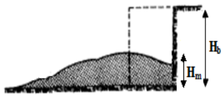
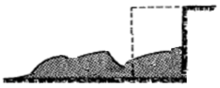
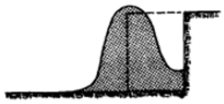
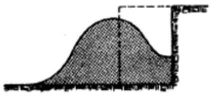
Class	Description		Class	Description	
1	 $H_m = (^1/_3 - ^2/_3)\ H_b$	Wide area requiring cleanup Low efficiency (shovel) Suitable loading security Relatively easy loading operation	4	 $H_m < ^1/_3\ H_b$	High need to cleanup Wide area requiring cleanup Very low efficiency (shovel) Suitable loading security Very good loading security
2	 $H_m = (^1/_3 - ^2/_3)\ H_b$	Irregular section Need to clean up a wide area Low efficiency (shovel) Fair loading security	5	 $H_m > H_b$	Small area requiring cleanup Very good efficiency (shovel) Low loading security (loader)
3	 $H_m = (^2/_3 - 1)\ H_b$	Moderate area requiring cleanup Good efficiency (shovel) Suitable loading security	6	 $H_m > H_b$	Very low movement of pile Difficulty in cleaning operation of wall Low loading security (loader)

Table 7. Dimensionless decision matrix.

Blast no.	Bb	Bo	Fr	S	H	D	Sum
1	3.2	3.86	4.41	0.02	0.05	0.66	12.21
2	6.72	2.84	4.41	0.08	0.06	0.2	14.31
3	0	3.86	0	0.36	0	0	4.22
4	0.8	7.88	0	0.04	0.06	0.04	8.82
5	3.2	1.26	0	0	0.06	1.2	5.72
6	1.25	0.08	6.89	1.04	0.01	1.09	10.37
7	0.8	0.08	1.96	0.02	0.03	0.07	2.96
8	4.99	0.08	0	0.78	0	0.35	6.2
9	3.2	7.88	0	0.1	0.01	0.2	11.38
10	0	2.84	0	2.40	0.03	0	5.27
11	0.2	0.08	1.03	0.03	0.01	0.01	1.37
12	0.8	0.08	1.96	0.24	0.02	0.05	3.15
13	0.2	0	4.71	0.18	0.05	0.15	5.29
14	0.2	0.08	1.03	0.03	0.01	0.15	1.5
15	0.05	0.08	0	0.02	0.13	0.33	0.62
16	0.2	0	4.71	0.18	0.05	0.15	5.29

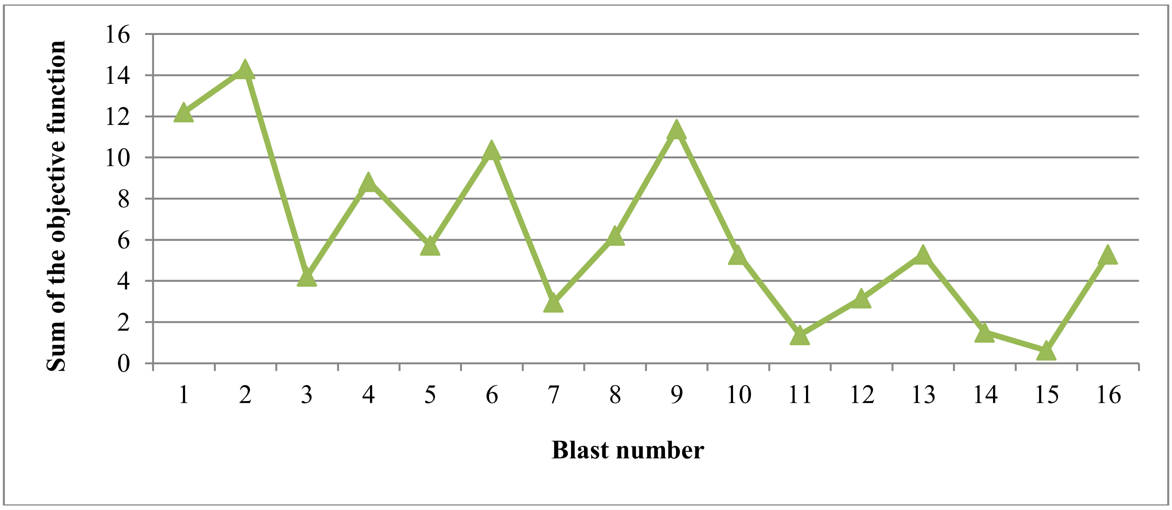


Figure 9. Classification of blasts compared to each other based on dimensionless decision matrix.

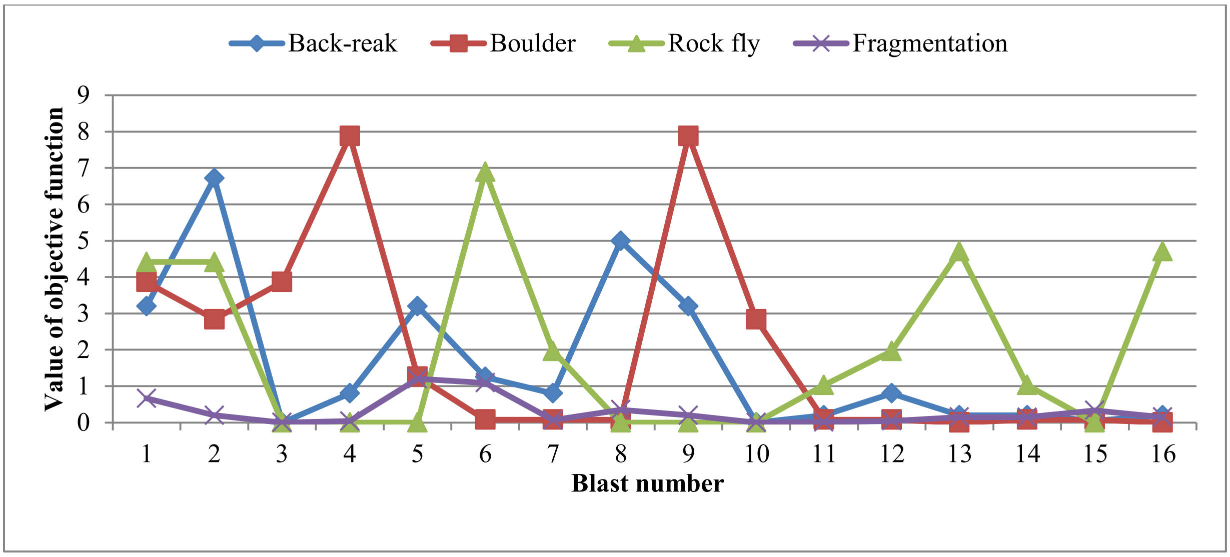


Figure 10. Variations in fragmentation, fly rock, boulder, and back-break in all 16 blasts.

Based on Table 8, the classification and the blast conditions can be determined. The value for *r* was calculated by (7), in which *U* and *L*, respectively, are the maximum and minimum values obtained from summing the columns of dimensionless matrix corresponding to each blasting. The class and condition of the blasts are presented in Table 9.

$$r = (U - L) / 5 \quad (7)$$

Evaluating the results of some blasts (blasts no. 2, 5, 7, 12, and 15) with regards to the dimensionless decision matrix is as follows:

- Blast no. 2 is one of the weakest blasts among the 16 ones. Investigating the results of blast no. 2 indicated that it created the maximum value of back-break, and after the blasts no. 1 and 3, it had the maximum number of boulders. Also a fly rock with a size of 30 cm was recorded for this blast. Compared to other blasts, it is the sixth blast where particles larger than the size of loading bucket in its muckpile existed.
- Regarding that the back-break and the number of boulders of blast no. 5 are lower than those for blast no. 2, and no significant difference was observed in their fragmentations, this blast was regarded as one of the good ones; this can be reasonable, considering the lack of fly rock in this blast, and also regarding the muckpile's shape and its lateral spread, which obtained appropriate conditions for the loading machine.
- The dimensionless decision matrix puts blast no. 7 in a very good class. In comparison with blast no. 2, the back-break, fly rock, and number of boulders in the muckile were lower in this blast; regarding the suitable lateral spread of the muckpile, and considering that the size of fragmented rocks was near the loading bucket, this fact was expected. The same condition was also true for blasts no. 12 and 15, and, additionally, the fly rock was not observed in these blasts, and their back-breaks were also lower than blast no. 7.

Table 8. Classification of blasts and their analysis.

Class	Decision matrix	Condition
I	L to L +r	Very good
II	L+r to L+2r	Good
III	L+2r to L+3r	Relatively weak
IV	L+3r to L+4r	Weak
V	L +4r to L+5r	Very weak

Table 9. Classification of blasts based on dimensionless decision matrix.

Blast no.	Dimensionless decision matrix			Blast no.	Dimensionless decision matrix		
	Value	Class	Condition		Value	Class	Condition
1	12.21	5	Very weak	9	11.38	4	Weak
2	14.31	5	Very weak	10	5.27	2	Good
3	4.22	2	Good	11	1.37	1	Very good
4	8.82	3	Relatively weak	12	3.15	1	Very good
5	5.72	2	Good	13	5.29	2	Good
6	10.37	4	Weak	14	1.5	1	Very good
7	2.96	1	Very good	15	0.62	1	Very good
8	6.2	3	Relatively weak	16	5.29	2	Good

4.3. Determining weight of blast results

For weighting the dimensionless decision matrix, the performance index p_j defined by relations (8) and (9) was utilized. In these relations, Suo_j is the specific mine unit operations index in the j^{th} blasting block (in $\frac{kg.hr}{m^8}$), Scj is the specific charge of the j^{th} blasting block (in $\frac{kg.hr}{m^3}$), Sdj is the specific drilling of the j^{th} blasting block (in $\frac{m}{m^3}$), and Sl_j is the specific loading of the j^{th} blasting block (in $\frac{hr}{m^3}$).

$$Suo_j = Sc_j . Sd_j . Sl_j \tag{8}$$

$$p_j = \frac{Suo_j}{\sum_{j=1}^{m} Suo_j} \qquad j = 1,2,\ldots,m \tag{9}$$

The performance indices for all 16 blasts were tabulated in Table 10. By determining the performance index in each blasting block, an equation as (10), having six unknown variables, was constituted among the dimensionless results of the j^{th} blast and the performance index of the j^{th} block.

$$\begin{aligned} &\alpha_1 \times Bb_j + \alpha_2 \times Bo_j + \alpha_3 \times Fr_j + \\ &\alpha_4 \times S_j + \alpha_5 \times H_j + \alpha_6 \times D_j = P_j \\ &\sum_{j=1}^{6} \alpha_j \times x_j = P_j \end{aligned} \tag{10}$$

For solving 16 equations having 6 unknown variables and finding the best values for α coefficients, the genetic algorithm was employed. The objective function to be minimized in this process was equal to the sum of the squares of relative difference of the above 16 equations as (11). The real and calculated values of performance indices, by applying the coefficients, were compared in Figure 12.

$$min = \frac{\left(\sum_{j=1}^{6} \alpha_j \times x_j - P_j\right)^2}{100 \times P_j^{\,2}} \tag{11}$$

The coefficients of each result, regarded as its weight in this research work (the sextet coefficients are as 0.001, 0.0019, 0.0009, 0.0507, 0.4553, and 0.002), were used to constitute the weighted decision matrix (Table 11). Analyzing the coefficients indicated that the muckpile's condition and its fragmentation had the maximum impacts on the performance index.

Table 10. Performance index of blasts.

Blast no.	Performance index	Blast no.	Performance index
1	0.031	9	0.089
2	0.05	10	0.129
3	0.028	11	0.112
4	0.036	12	0.102
5	0.033	13	0.039
6	0.074	14	0.057
7	0.021	15	0.131
8	0.039	16	0.028

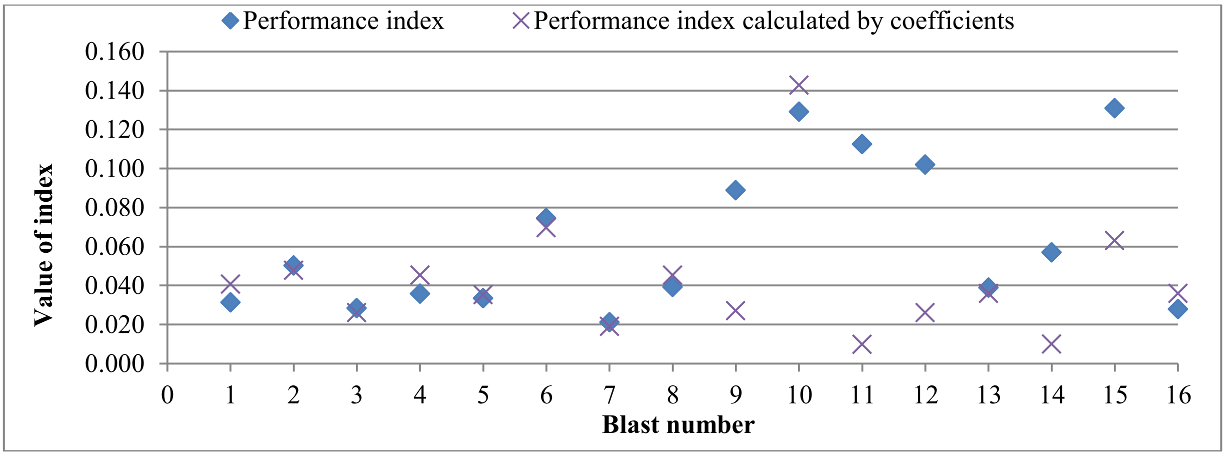


Figure 11. Comparing real and calculated values of performance indices by applying coefficients.

4.4. Analyzing results

The result of classifying the blasts by considering the weight of results was illustrated in Figure 13. Also Table 12 shows the class and condition of the blasts. According to the classification results and the desirable and undesirable blasts, the following points are noteworthy:

- Blast no. 10 was the most undesirable one. It had the worst performance index after blast no. 15 but, regarding the dimensionless decision matrix and the relatively good results of blast no. 15, blast no.10 was located in the category of very weak blasts because it was the third blasting from the viewpoint of having boulders, and also the condition of its muckpile, which had the maximum impact on the performance index was not appropriate due to high spread of the muckpile.
- Blast no. 11 was the most desirable one. The dimensionless decision matrix says that this blast is in the category of a very good blast. This issue and also the good conditions of the muckpile and fragmentation of blast no. 11 which had the maximum effects on the performance index, caused this blast to be located in the category of very good blasts based on the weighted dimensionless decision matrix as well. Blast no. 14, which is the third desirable blast based on the dimensionless decision matrix by having a desirable performance index, was located in the category of very good blasts.

Table 11. Weighted dimensionless decision matrix.

Blast no.	Bb	Bo	Fr	S	H	D
1	0.0032	0.0073	0.0040	0.0010	0.0238	0.0013
2	0.0067	0.0054	0.0040	0.0040	0.0271	0.0004
3	0.0000	0.0073	0.0000	0.0182	0.0004	0.0000
4	0.0008	0.0150	0.0000	0.0023	0.0271	0.0001
5	0.0032	0.0024	0.0000	0.0000	0.0271	0.0024
6	0.0012	0.0001	0.0062	0.0530	0.0068	0.0022
7	0.0008	0.0001	0.0018	0.0010	0.0150	0.0001
8	0.0050	0.0001	0.0000	0.0394	0.0000	0.0007
9	0.0032	0.0150	0.0000	0.0051	0.0033	0.0004
10	0.0000	0.0054	0.0000	0.1219	0.0153	0.0000
11	0.0002	0.0001	0.0009	0.0016	0.0068	0.0000
12	0.0008	0.0001	0.0018	0.0123	0.0109	0.0001
13	0.0002	0.0000	0.0042	0.0091	0.0220	0.0003
14	0.0002	0.0001	0.0009	0.0016	0.0068	0.0003
15	0.0000	0.0001	0.0000	0.0010	0.0611	0.0007
16	0.0002	0.0000	0.0042	0.0091	0.0220	0.0003

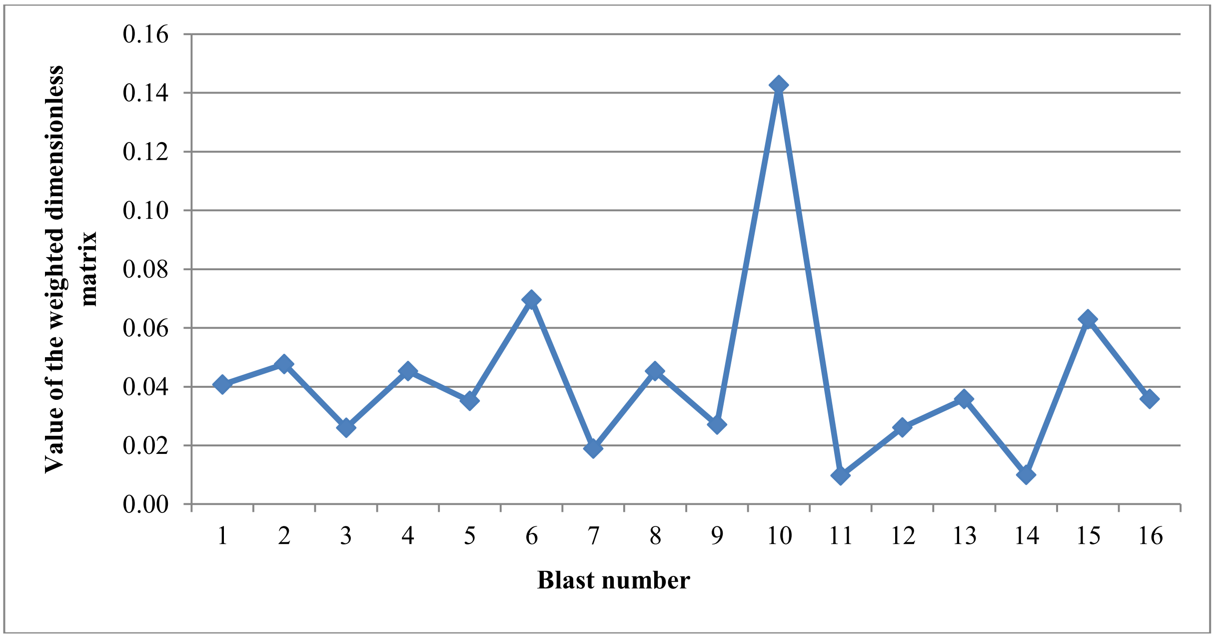


Figure 12. Classification of blasts based on weighted dimensionless decision matrix.

Table 12. Classification of blasts based on weighted dimensionless decision matrix.

Blast no.	Weighted dimensionless decision matrix			Blast no.	Weighted dimensionless decision matrix		
	Value	Class	Condition		Value	Class	Condition
1	0.0407	2	Good	9	0.0270	1	Very Good
2	0.0476	2	Good	10	0.1426	5	Very Weak
3	0.0260	1	Very Good	11	0.0097	1	Very Good
4	0.0453	2	Good	12	0.0261	1	Very Good
5	0.0351	1	Very Good	13	0.0358	1	Very Good
6	0.0695	3	Relatively Weak	14	0.0099	1	Very Good
7	0.0189	1	Very Good	15	0.0629	3	Relatively Weak
8	0.0452	2	Good	16	0.0358	1	Very Good

5. Conclusions

In a blast optimization process, an important and prerequisite matter is to evaluate the current condition of blasting, where it is essential to apply a fast and reliable technique for blasting evaluation due to the effective control and optimization of the main cycle operations. In this research work, a novel approach was presented for blasting evaluation based on the utilization of blasting results. The results of the blastings implemented in the Angouran mine including the fly rock, back-break, muckpile, and fragmentation degree, were used for the blasting evaluation and assigning a scalar and dimensionless value to each blast by employing a general criterion method. The objective functions used in this paper included the blasting results. For weighting the results, the performance index was calculated with regards to the specific charge, specific drilling, and specific loading, and relation of the performance index with each one of the results was investigated using the genetic algorithm; and the weight of each result was determined in terms of its effect on the performance index.

The conclusions drawn from this paper are as follow:

- The proposed method provides an efficient evaluation for the blasting results. By applying this method, the blasts implemented in a mine can be classified in relation to each other.
- This method is less affected by the planner view, and is based on the normalization of objective functions around the optimal point.
- In this method, the blast results and the efficiency of other unit operations are analyzed together.
- Analyzing the blasting results in the Angouran mine verifies that the developed approach is an efficient method for a quantitative comparison of the blasts.
- By employing this method, the results of applying different explosives and blasting patterns can be analyzed in order to control and optimize the main cycle operation.

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ارائه یک مدل کمّی برای ارزیابی و رده‌بندی آتشباری‌های معدن روباز

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چکیده:

با ارزیابی نتیجه انفجار می‌توان الگوی مناسبی برای آتشباری ارائه کرد؛ بنابراین به کار بردن شیوه‌ای قابل اطمینان برای ارزیابی آتشباری به منظور کنترل مؤثر و بهینه‌سازی عملیات چرخه اصلی تولید امری ضروری است. هدف از این تحقیق معرفی معیاری است که بتوان با آن علاوه بر ارزیابی آتشباری با توجه به نتایج آن شامل خردشدگی، وضعیت کپه آتشباری شده، عقب زدگی و پرتاب سنگ، امکان مقایسه پارامترهای انفجارها در معدن سرب و روی انگوران شامل الگوی آتشباری، ماده منفجره مصرفی، عمق چال‌ها و حجم توده آتشباری را نیز با یکدیگر فراهم کرد. با استفاده از روش معیار جامع و بی مقیاس کردن ماتریس تصمیم و تعریف شرایط مناسب برای هر یک از نتایج، به هر انفجار عددی کمّی و بی‌بعد اختصاص داده شد که بیشتر بودن آن بیانگر انحراف بیشتر انفجار از شرایط مناسب آتشباری بوده و نمایانگر شرایط نامطلوب انفجار انجام شده با توجه به نتایج انفجار است. برای لحاظ کردن شرایط عملیات معدنکاری و وزن هر یک از نتایج، تأثیرگذاری نتایج بر شاخص عملیات معدنکاری با استفاده الگوریتم ژنتیک بررسی شد و با تشکیل ماتریس تصمیم وزن‌دار، انفجارها ارزیابی و رده‌بندی شدند. تحلیل نتایج آتشباری ثبت شده در معدن انگوران نشان می‌دهد که روش ارائه شده شیوه‌ای کارا برای ارزیابی آتشباری و مقایسه انفجارها است.

کلمات کلیدی: ارزیابی آتشباری، طبقه‌بندی، نتایج آتشباری، شاخص عملیات معدنکاری.