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APPLICATION OF PROMETHEE MATHEMATICAL MODEL FOR CHOOSING A SECONDARY BREAKAGE PROCESS OF THE OVERSIZED BLOCKS IN LIMESTONE QUARRIES

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Abstract: In this paper, the approach consists in selecting the best secondary breakage process of oversize blocks with explosives for the limestone quarries. To solve this problem, we propose the centroid weight method for weighting the selection criteria, and the PROMETHEE model as a multicriteria decision making method. A case study is carried out in the limestone quarry of the cement factory of Hadjar-Soud, Algeria.

***Keywords**: Centroid weight method, Hadjar-Soud quarry, multicriteria analysis, fragmentation.*

INTRODUCTION

At the level of quarries, hard massive limestones undergo a fragmentation by drilling and blasting works. Although it is used for the destruction of rocky materials of any hardness, this method of breakage still does not provide a desired granulometry of the destroyed blocks. It always begets oversize blocks which cannot be loaded or transported neither crushed.

This fact may be explained by uncontrollable factors of the rock mass. Let us quote, inter alia, the complexity of the geological formation of limestone deposits, the

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variation of the structure and texture of the grains forming the limestones, the change of the distribution of cracks and discontinuities in the rock mass, the variation of the physical and mechanical properties of limestones, etc. The oversize blocks, resulting of the primary fragmentation by drilling and blasting works, are object of secondary breakage. In the literature, the secondary breakage processes with explosives, the most suitable for the hard and very hard rocks such as limestones, are as follows:

- The process by superficial charge with hydro-screen (Kovalenko et al., 1986).
- The process by hole charge with sand stemming (Cormon, 1979).
- The process by superficial charge with cumulative effect (Oberemok et al., 1974).
- The process by hole charge with water tamping (Lomonossov, 1971).
- The process by superficial charge with clay stemming (Hermann, 1971).

For solving the problem of choice of a secondary breakage process with explosives in limestone quarries using the PROMETHEE model, we must define the selection criteria. In this research, we define seven criteria as presented in the Table 1.

Tab. 1. Denomination of selection criteria

Criteria C_J	Denomination
C_1	Criterion of maximum radius of rocky particle projection after blasting
C_2	Criterion of labour cost
C_3	Criterion of detonating fuse cost
C_4	Criterion of explosive charge cost
C_5	Criterion of diesel consumption cost (for the compressor)
C_6	Criterion of drilling cost (using the drill hammer)
C_7	Criterion of greasing cost (for the compressor and drill hammer)

Let us look at these criteria in more details: the first is an environmental criterion and the other six are economic criteria. These seven criteria form a coherent family in relation to the durable development of a mining enterprise. In addition, they meet the conditions imposed by (Keeny et al., 1976) which are: exhaustiveness, decomposability, minimality, operability and non-redundancy. For the performance aggregation needs of secondary breakage processes of oversize blocks, according to the PROMETHEE model, the above criteria are weighted by centroid weight method.

In the global context, PROMETHEE model is applied in different fields (see www. Biblio. Promethee-gaia.net). Among recent publications using the PROMETHEE model, we quote (Apriliani et al., 2016; Afful-Dadzie et al., 2015; De Almeida et al., 2014; Anojkumar et al., 2013; Arunkumar et al., 2012; Alencar et al., 2011; Akkaya et al., 2010).

MULTICRITERIA METHODOLOGY OF DECISION MAKING AID

ELICITATION OF CRITERIA WEIGHTS

In the literature, there are several calculus methods for eliciting criteria weights. The most relevant and published methods are:

1. The methods based on ordinal ranking of criteria: a) the geometric weight method (Lootsma, 1999); b) the centroid weight method (Solymosi et al., 1985); c) the rank sum linear weight method (Stillwell et al., 1981); d) the reciprocal weight method (Stillwell et al., 1981); e) the simple ranking method (Kendall ,1970) and f) the ratio method (Von Winterfeldt et al.,1986).
2. The empirical weight method (Alfares et al., 2009).
3. The method of “resistance to change’’ grid (Rogers et al., 1998).
4. The methods of eigenvalues (Klee, 1971; Saaty, 1980).
5. The methods of successive comparisons (Churchman et al., 1954; Knoll et al., 1978).
6. The method of probabilistic evaluation (Rietveld, 1989).
7. The neutral methods: a) the statistical method (Diakoulaki et al., 1992); b) the entropy method (Zeleny, 1982) and c) the standard deviation method (Fleiss, 1981).

Several studies (Noh et al., 2003; Jia et al., 1998; Barron et al., 1996, Srivastava et al., 1995; Edwards et al., 1994; Olsen et al., 1992), concerning the comparison of the methods of criteria weights, have shown that the centroid weight method is practical, easy to use and superior in terms of accuracy compared to the others.

In this article, we retain the centroid weight method due to its benefits.

PRESENTATION OF THE CENTROID WEIGHT METHOD (SOLYMOSI ET AL., 1985)

In this method of elicitation of criteria weights, the unique information, asked to the decision maker, is to rank the considered criteria in descending order of their importances. Then the criterion weight of rank j (W_j) is determined using the following formula:

$$W_j = \frac{100.\sum_{i=j}^{n}\frac{1}{i}}{\sum_{i=1}^{n}\frac{1}{i}} \tag{1}$$

Where: *j* – rank of criterion, *j* = 1, 2, 3, ..., n.
n – number of considered criteria.

Finally, the values of W_j must be normalized and satisfy the constraint below:

$$\sum_{j=1}^{n} W_j = 1 \tag{2}$$

MULTICRITERIA AGGREGATION

In the multicriteria decision making, there are many methods to aggregate the performances (evaluations) of the alternatives and to select the best solution among the alternatives considered.

In the literature, the multicriteria aggregation methods are divided into two categories.

The first category includes the methods with a single criterion of synthesis. Among the most relevant and published, let us mention: the weighted sum method (Timmerman, 1986); the weighted product method (Pomerol et al., 1993); the SMART (Simple Multi-Attribute Rating Technique) method (Edwards, 1971); the AHP (Analytic Hierarchy Process) method (Saaty, 1994) and the TOPSIS (Technique for Order Preference by Similarity to Ideal Solution) method (Lai et al., 1994). The second category includes the methods of alternatives outranking. The most known and published are: the PROMETHEE (Preference Ranking Organization Method for Enrichment Evaluation) method (Brans et al., 2002) and the ELECTRE (Elimination and Choice Translating Reality) method (Roy, 1996).

In this article, we adopt the PROMETHEE method for the following reasons (Brans et al., 2002):

1. It is based on the extension of criterion notion by the introduction of a mathematical function expressing the preference of the decision maker.
2. For each considered criterion, the decision maker is asked to choose one of six forms of criterion curves (usual criterion, quasi criterion, criterion with linear preference, level criterion, criterion with linear preference and indifference, and Gaussian criterion).

The parameters, relating to each curve, represent indifference and/or preference thresholds.

3. It is based on the enrichment of alternative evaluations associated with considered criteria. Which is a special feature compared with other methods.
4. It is partly compensatory.
5. It is not difficult to use.

PROMETHEE MODEL (BRANS ET AL., 2002)

It can be presented as follows:

1. Have decision matrix A, A: = a_{ij}, where a_{ij} is the evaluation (performance) of alternative i (i = 1,…, m) associated with criterion j (j = 1, …, n).

2. Specify for each criterion j, a generalized preference function F_j.

In this article, authors specify usual criterion with a strict preference. Then the preference function F_j, for each pair of evaluations (a_{ij}, a_{kj}), is expressed below:

$$F_j\left(a_{ij}, a_{kj}\right) = \begin{cases} 1 & \text{if} \quad a_{ij} > a_{kj} \\ 0 & \text{if} \quad a_{ij} \leq a_{kj} \end{cases} \qquad i = 1, \dots, m;\ j = 1, \dots, n;\ k \neq i \tag{3}$$

3. Define a vector containing the weights, which are a measure for the relative importance of each criterion, $W^T = [W_1, \dots, W_n]$. If all the criteria are of the same importance in the opinion of the decision maker, all weights can be taken as being equal. The normalization of the weights $\sum_{j=1}^{n} W_j = 1$ is not necessarily required, but facilitates an uniform representation and comparison of different evaluations. No specific approach for the setting of weights is proposed, because the aim of PROMETHEE (and outranking in general) is seen in the explanation of the weighting factors spontaneously expressed by the decision maker.

4. Define, for all the alternatives $a_i, a_k \in A$, the Outranking relation P.

$$P : \begin{cases} A \times A \rightarrow [0, 1] \\ P(a_i, a_k) = \sum_{j=1}^{n} W_j . F_j(a_{ij}, a_{kj}) \end{cases} \tag{4}$$

The preference index $P(a_i, a_k)$ is a measure for the intensity of preference of the decision maker for an alternative a_i in comparison with an alternative a_k for the simultaneous consideration for all criteria. It is basically a weighted average of the preference function $F_j(a_{ij}, a_{kj})$ and can be represented as a valued outranking graph (see Figure 1).

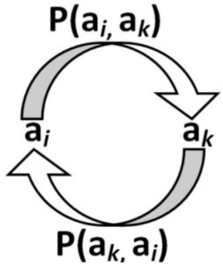

Fig. 1. Outranking graph

5. As a measure for the strength of the alternatives $a_i \in A$, the leaving flow is calculated:

$$\emptyset^{+}(a_i) = \frac{1}{m} \sum P(a_i, a_k) \tag{5}$$

The leaving flow is the sum of the values of the arcs which leave node a_i and therefore yield a measure of the outranking character of a_i. The normalization using the total number of considered alternatives *m* is not a necessary precondition, but both for the leaving and entering flows, the same approach has to be chosen. As through the normalization of the weights, a comparison of different evaluations is made easier.

6. As a measure for the weakness of the alternatives $a_i \in A$, the entering flow is calculated, measuring the outranked character of a_i (analogously to the leaving flow):

$$\emptyset^{-}(a_i) = \frac{1}{m}\sum P\,(a_k, a_i) \tag{6}$$

7. Graphical evaluation of the outranking relation. Basically, the higher the leaving flow and the lower the entering flow, the better the alternative. The PROMETHEE partial preorder is determined by a comparison of the leaving and entering flows by a set intersection in a manner that also allows the representation of weak preferences and incomparabilities of alternatives. In the valued outranking graph, an arc leads from alternatives a_i to a_k, if a_i is preferred to a_k (see Figure 2: e.g. a_4 outranks a_3, a_2 and a_4 are indifferent, a_5 and a_6 are incomparable to each other, but are outranked by (i.e. worse than) a_6).

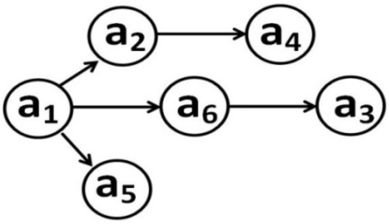

Fig. 2. Partial preorder as an example for a graphical representation of the result on an outranking model

CASE STUDY: THE HADJAR-SOUD LIMESTONE QUARRY, ALGERIA

GEOGRAPHICAL AND GEOLOGICAL OVERVIEWS

The limestone deposit of Hadjar-Soud is located in the North-Eastern of Algeria, in the Wilaya of Skikda, near the locality of Bekkouche Lakhdar (see Figure 3). It is essentially constituted by a thickness of massive crystalline limestone of Lias, presenting a bluish gray color. It is less fractured in the upper part of the deposit. In the lower assizes, limestone is clear, pink or yellowish; it is compact with strong diaclases.

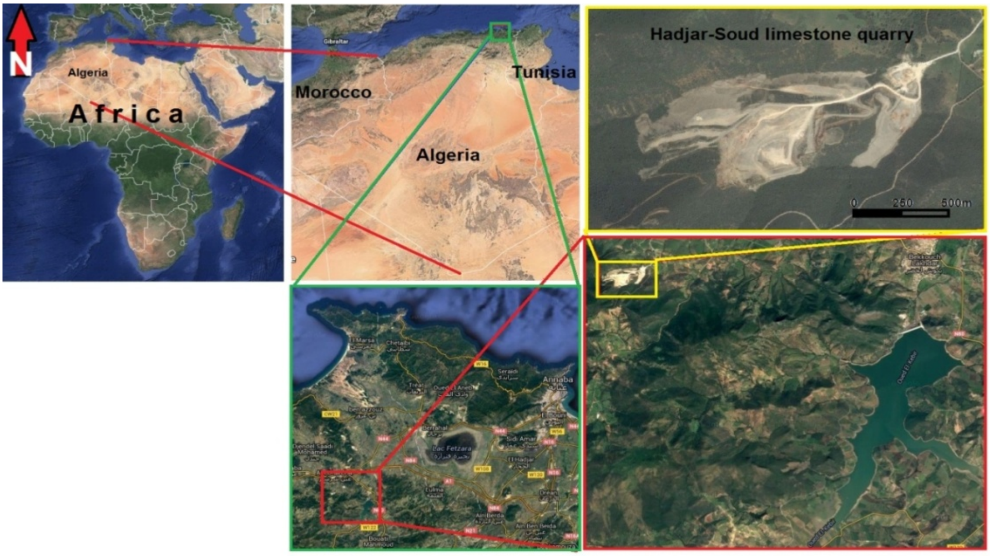

Fig. 3. Satellite location map of the study site

The limestone deposit, which the Hadjar-Soud cement factory exploits, finds in the Djebel-Safia rocky mass. This last, which is the heart of the Alpine chains of the Eastern-Algerian part, is studied by (Vila, 1980).

The limestone deposit is constituted by sandy clay of the Quaternary, and siliceous and carbonate rocks of the Mesozoic. The sides of the Djebel-Safia anticline are covered by a formation of the Cretaceous and are represented by sandstone and schist, and marl and marly limestone.

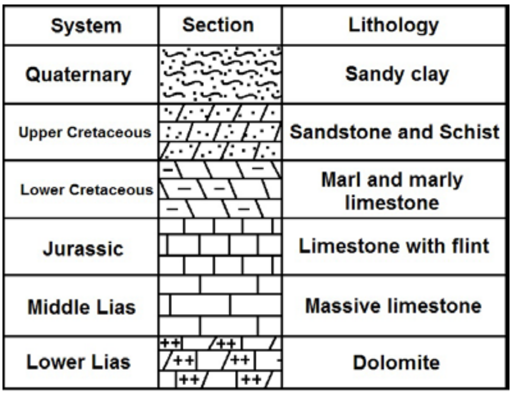

Fig. 4. Litho-stratigraphic overview of the deposit

The limestone with flint belongs to the Jurassic period. In addition, the studied zone corresponds to the termination South-Eastern of the anticline of Djebel-Safia which disappears under the alluvia of the Oued-Kebir in its Western part. The axis of the anticline is formed by compact limestone of Lias. This last is fractured according to a network of breaks of orientation NE-SW.

The formed fractures are filled by argillaceous silts. According to the geological report, the litho-stratigraphic overview of the studied deposit is shown in Figure 4.

In the actual conditions, three levels are exploited by the Hadjar-Soud limestone quarry. The thickness of each level is equal to 13 m. In addition, the three lengths of the exploited levels are respectively equal to 400, 535 and 555 m.

The cement factory of Hadjar-Soud is fed by the massive limestone of Lias whose main properties are presented in Table 2.

Tab. 2. Main properties of limestone

Properties	Values	Units
Density	2.65	t/m^3
Porosity	3.17	%
Humidity	0.77	%
Cracking	0.25	M
Hardness (Protodiakonov)	9.00	-
Uniaxiale compressive strength	90.00	MPa
Drillability index (Rzhevski)	8.47	-
Blastability Index (Rzhevski)	25.80	g/m^3
Swell factor	1.35	-

CRACKING OF THE LIMESTONE DEPOSIT

To analyze the cracking of the limestone in state of exploitation, we have realized some tests based on the observation and photo-planimetric method. The obtained results are:

- Angle of fissure is generally vertical (90°) to subvertical (65°).
- Spacing frequency between two fissures does not constant. On thirty tests, it varies between 0.14 m (minimal value) and 0.35 m (maximal value). The mean value is equal to 0.25 m.
- Starting from obtained results, the studied limestone is meanly fissured according to the classification of (Rzhevski, 1985).

FRAGMENTATION OF LIMESTONE

The Hadjar-Soud quarry limestone is fragmented by drilling and blasting works. The drilling of holes is performed by a rig Atlas Copco brand, model CM 780 D; its parameters are:

- Bench height: $H = 13$ m.
- Sub-drill: $S = 1.65$ m.
- Hole depth: $L = 14.65$ m.
- Hole diameter: $D_h = 0.165$ m
- Hole inclination angle: $\alpha = 70$ degrees

The used explosive is marmanite-I. Its technical characteristics are shown in Table 3. To carry out the priming of explosive, the quarry engineers use the detonating fuse whose technical characteristics are presented in Table 4.

Tab. 3. Explosive characteristics

Explosive used	Coefficient of self-excitation cm	Testing of Trauzl cm^3	Detonation velocity m/s	Density g/cm^3	Water resistance
Marmanite-I	10	395	4 300	0.95	Mean

Tab. 4. Characteristics of detonating fuse

Detonating fuse	Composition	Exterior diameter mm	Detonation velocity m/s	Linear mass g/m	Electrical resistance Ω
-	Penthrite	10	8 000	12	1.6 ÷ 4.2

After each limestone fragmentation of volume equal to 30 000 m^3, it generally results oversize blocks whose rate, estimated by quarry manager, varies between 5 and 10%. A block of limestone is said oversize if it satisfies the following condition:

$$d_b > 0.8\, d, (m) \tag{7}$$

Where: d_b – oversize block dimension, (m).

d – opening dimension of the primary crusher, (m).

The limestone quarry of Hadjar-Soud uses a primary gyratory crusher with cone, model GP 120. Its main parameters are:

- Opening dimension: $d = 1.2$ m.
- Particle size after crushing: $D_p = 0 \div 300$ mm.
- Average productivity: $P = 900$ t/h.
- Reduction ratio: $r = 4$

For the case study, by substituting *d* = 1.2 m in expression (7), we note that any block having $d_b > 0.96$ m is considered as being oversize. To calculate the rate of oversize blocks (T), Doubinine and Troufakine (Doubinine et al.,1971) proposed the empirical formula below:

$$T = \left[K\left(\frac{W}{D_c}\right)^2 - n\right]\frac{f}{15}\ ,(\%) \tag{8}$$

where *K* – coefficient which takes into account the opening dimension of the primary crusher (d). See Table 5.

Tab. 5. Values of *K* versus *d*

K	0.036	0.018	0.011	0.009
d (m)	0.4	0.8	1.0	1.2

W – line of least resistance of the rock, (m).
D_c – diameter of the used explosive cartridge, (m).
n – constant coefficient, n = 5.
f – rock hardness according to Protodiakonov, $0.3 \leq f \leq 20$.

By replacing the values of the Hadjar-Soud quarry {K = 0.009; W = 6.28 m; D_c = 0.165 m; n = 5 and f = 9} in the formula (8), the calculated rate of oversize blocks (T) is equal to 4.82%. As a deduction, we can to say that the rates of oversize blocks, estimated (5÷10%) and calculated (4.82%), are close to the reality. Because the fragmentation of a rock by drilling and blasting works never gives a rate equal to 0%.

DECISION MATRIX FOR CHOOSING A SECONDARY BREAKAGE PROCESS OF OVERSIZE BLOCKS

The data, presented in the decision matrix (see Table 6), are collected from the Hadjar-Soud limestone quarry and established on the basis of an oversize block equal to 1 m^3.

Tab. 6. Decision matrix for choosing a secondary breakage process of oversize blocks

Secondary breakage processes of oversize blocks a_i	Criteria C_i						
	C_1 m	C_2 DA/m^3	C_3 DA/m^3	C_4 DA/m^3	C_5 DA/m^3	C_6 DA/m^3	C_7 DA/m^3
a_1	25	128.00	40.00	26.00	0	0	0
a_2	150	160.00	50.00	13.00	61.65	28.69	9.46
a_3	10	128.00	40.00	39.00	0	0	0
a_4	20	160.00	50.00	40.00	61.65	28.69	9.46
a_5	300	106.66	40.00	52.00	0	0	0

a_1: the process by superficial charge with hydro-screen.
a_2: the process by hole charge with sand stemming.
a_3: the process by superficial charge with cumulative effect.
a_4: the process by hole charge with water tamping.
a_5: the process by superficial charge with clay stemming.
DA: Algerian Dinar (Algeria currency).

RESULTS AND DISCUSSION

WEIGHTS OF CRITERIA

The final results of criteria weights, according to the centroid weight method, are presented in Table 7.

Tab. 7. Results of criteria weights

Criteria C_J	Weights of criteria	
	W_J	Values
C_1	W_1	0.3704
C_2	W_2	0.2276
C_3	W_3	0.1562
C_4	W_4	0.1084
C_5	W_5	0.0728
C_6	W_6	0.0442
C_7	W_7	0.0204

GLOBAL PREFERENCE

The final results of the global preference (degree of outranking), for each pair of secondary breakage processes of oversize blocks a_i and a_k ($i = 1, ..., 5$ and $K \neq i$), are presented in Table 8.

Tab. 8. Results of the global preference (degree of outranking)

$P(a_i, a_k) = \sum W_j . F_j(a_{ij}, a_{kj})$				
	$P(a_1, a_2) = -0.1084$	$P(a_1, a_3) = -0.3704$	$P(a_1, a_4) = -0.3704$	$P(a_1, a_5) = -0.2276$
$P(a_2, a_1) = -0.8916$		$P(a_2, a_3) = -0.8916$	$P(a_2, a_4) = -0.3704$	$P(a_2, a_5) = -0.5212$
$P(a_3, a_1) = -0.1084$	$P(a_3, a_2) = -0.1084$		$P(a_3, a_4) = 0$	$P(a_3, a_5) = -0.2276$
$P(a_4, a_1) = -0.6296$	$P(a_4, a_2) = -0.6296$	$P(a_4, a_3) = -1$		$P(a_4, a_5) = -0.5212$
$P(a_5, a_1) = -0.4788$	$P(a_5, a_2) = -0.4788$	$P(a_5, a_3) = -0.4788$	$P(a_5, a_4) = -0.4788$	

ENTERING AND LEAVING FLOWS

The final results of entering flow $\Phi^{-}(a_i)$ and leaving flow $\Phi^{+}(a_i)$, for each secondary breakage process of oversize blocks, are presented in Table 9.

Tab. 9. Results of entering and leaving flows

Secondary breakage processes of oversize blocks a_i	a_1	a_2	a_3	a_4	a_5	Leaving flows $\Phi^{+}(a_i)$
a_1		–0.1084	–0.3704	–0.3704	–0.2276	–0.2153
a_2	–0.8916		–0.8916	–0.3704	–0.5212	–0.5349
a_3	–0.1084	–0.1084		0	–0.2276	–0.0888
a_4	–0.6296	–0.1084	–1		–0.5212	–0.4518
a_5	–0.4788	–0.4788	–0.4788	–0.4788		–0.3830
Entering flows $\Phi^{-}(a_i)$	–0.4216	–0.1608	–0.5481	–0.2439	–0.2995	

According to Table 9:

- the first partial preorder, in descending order of leaving flows $\Phi^{+}(a_i)$, is derived as follows:

a_3 → a_1 → a_5 → a_4 → a_2
(–0.0888) (–0.2153) (–0.3830) (–0.4518) (–0.5349)

- the second partial preorder, in ascending order of entering flows $\Phi^{-}(a_i)$, is derived as follows:

a_3 → a_1 → a_5 → a_4 → a_2
(–0.5481) (–0.4216) (–0.2995) (–0.2439) (–0.1608)

GRAPH OF THE OUTRANKING RELATIONS

The graph of the outranking relations of secondary breakage processes of oversize blocks, according to PROMETHEE model, is shown in Figure 5.

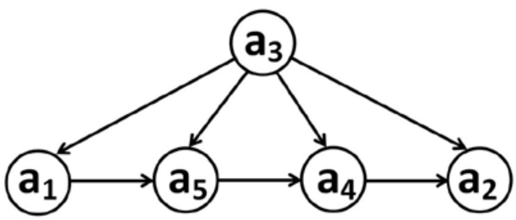

Fig 5. Graph of the outranking relations

According to the graph with an unique core which does not admit cycle nor circuit (see Figure 5), the best secondary breakage process of oversize blocks, selected by the PROMETHEE model for the limestone quarry of Hadjar-Soud (Algeria), is the process by superficial charge with cumulative effect (designated a_3).

CONCLUSION

1. The primary fragmentation of a hard or very hard rock, as limestone, by drilling and blasting works, begets oversize blocks whose rate is never equal to 0%.
2. For the Hadjar-Soud limestone quarry:
   - Any blocks, having d_b > 0.96 m, is considered as being oversize.
   - The rate of oversize blocks, estimated by quarry manager, varies between 5 and 10%, and calculated according to the formula of Doubinine-Troufakine, is equal to 4.82%.
3. To solve the problem of secondary breakage of oversize blocks in the limestone quarries, we propose the multicriteria methodology of decision making aid:
   - The centroid weight method for weighting the selection criteria
   - The PROMETHEE model for outranking the alternatives.
4. The highest weight is allotted to the criterion of maximum radius of rocky particle projection after blasting. It is equal to 0.3704 (see Table 7). According to this result, environmental criterion is preponderant in comparison to the other criteria under consideration.
5. The lower entering flow and the higher leaving flow are: $\Phi^{-}(a_3) = –0.5481$ and $\Phi^{+}(a_3) = –0.0888$ (see Table 9). This means that the alternative a_3 (process by superficial charge with cumulative effect) is preferred to the other alternatives. Because it outranks them (see Figure 5).
6. The best solution for the secondary breakage process of oversize blocks, selected according to PROMETHEE model for the Hadjar-Soud limestone quarry, is the process by superficial charge with cumulative effect.
7. The future extension of this work is to apply the multicriteria methodology presented in this article to other limestone quarries of North-Eastern part of Algeria taking into account the geological and mining characteristics of each quarry.

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