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MINING METHOD SELECTION FOR UNDERGROUND MINING WITH THE APPLICATION OF VIKOR METHOD

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Abstract: Multi-criteria decision making is widely used in mining to solve a variety of problems, as well as to support the mine planning and design process. The choice of the mining method of excavation for underground exploitation is a very complex and responsible matter, and support in the application of multi-criteria decision-making methods are of great importance of making the final decision. This paper will present the scientific methodology for the mining method selection by the application of VIKOR method, which gives the results of compromise alternatives.

Keywords: underground mining method selection, multi-criteria decision-making methods, VIKOR method

1 INTRODUCTION

The choice of the mining method of excavating for a certain underground mine is an essential problem for him, especially if we take into account that the method of excavation should provide safe and healthy working conditions. Also, the fact that the excavation costs cover most of the total costs during the operation of the mine should be constantly taken into account, so the appropriate choice of the method of excavation will largely determine whether the mine will operate with positive financial effects (Mijalkovski et al., 2013).

When deciding which method of mining should be used, several factors should be taken into account, which can be quantitative (can be measured or calculated) or qualitative (cannot be measured and defined by descriptive values, they need to be transformed into numerical values so that they can be used for calculation). Factors influencing the mining method selection can be divided into three groups (Bogdanovic et al., 2012):

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- mining-geological factors, such as: geometry of deposit (general shape, ore thickness, dip, plunge, depth below the surface), rock quality (ore zone, hanging wall and footwall, i.e. rock substance strength, fracture spacing, fracture shear strength, rock quality designation, structures, strength, stress, stability), ore variability (ore boundaries, ore uniformity, continuity, grade distribution), quality of resource, etc.

- mining-technical factors, such as: annual productivity, applied equipment, health and safety, environmental impact, ore dilution, mine recovery, flexibility of methods, machinery and mining rate, and

- economic factors, such as: capital cost, operating cost, mineable ore tons, orebody grades and ore value.

2 METHODOLOGY

The procedure for mining method selection can be divided into two parts (Figure 1):

- Rational mining method selection;

- Optimal mining method selection.

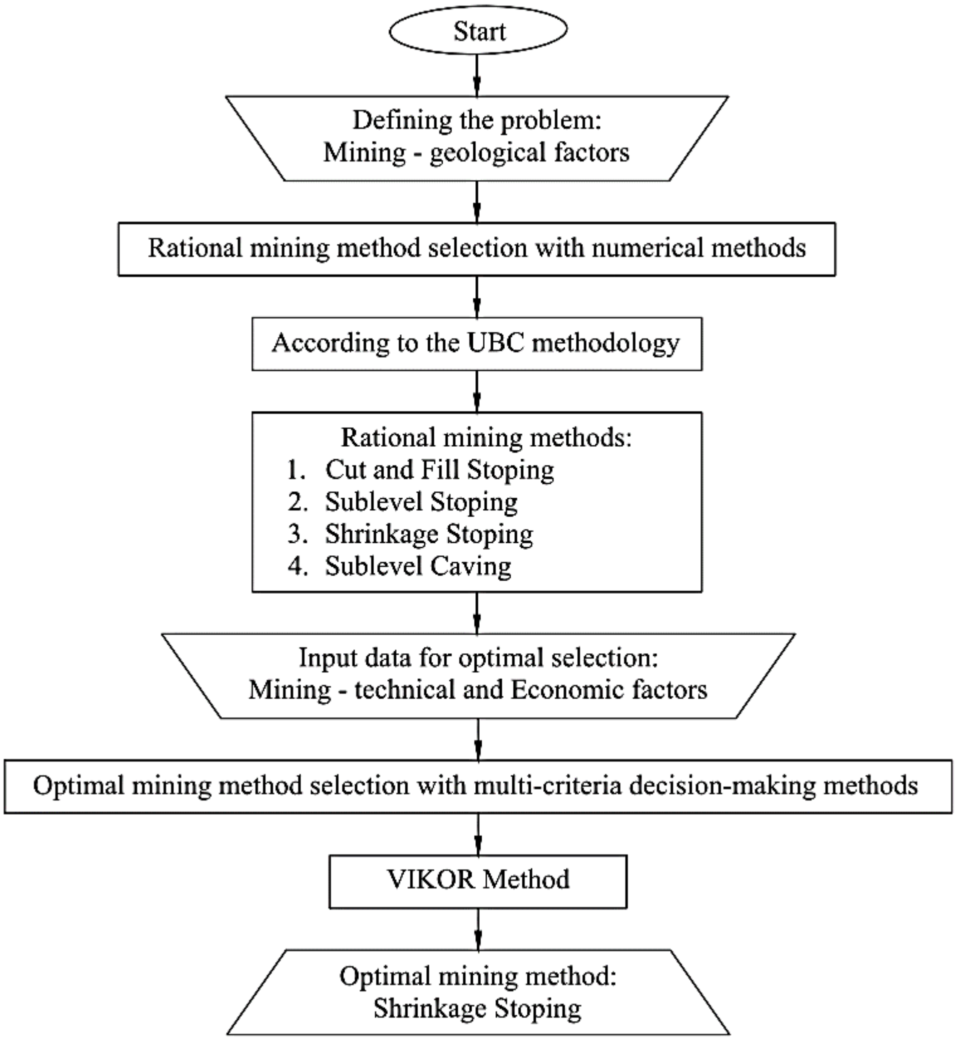

Figure 1 Methodology for underground mining method selection.

In the rational choice of the method of mining excavation, mining methods of excavation are chosen according to the mining-geological factors that influence the choice of the method of mining (geometry of deposit, rock quality, ore variability) (Mijalkovski et al., 2012). The purpose of this choice is to reduce the number of mining methods of excavation for further calculations.

There are several procedures for mining methods selection by mining-geological factors, such as: Boshkov's and Wright's procedure, Morrison's procedure, Nicholas's procedure, Laubscher's procedure, Hartman's procedure, UBC procedure and other. For the rational selection of the method of mine excavation, this paper uses the procedure according to UBC (Miller et al., 1995) and singles out the four best ranked mining methods of excavation (Cut and Fill Stoping, Sublevel Stoping, Shrinkage Stoping and Sublevel Caving), which are alternatives in multi-criteria decision making.

After rational mining methods selection and separation, the most acceptable mining methods according to mining-geological factors (top four highest ranked mining methods), follows optimal choice, i.e., selecting the separated mining methods according to mining-technical and economic factors that influence when choosing mining method.

For the optimal selection of the mining excavation method, multi-criteria optimization methods can be used, such as: AHP, PROMETHEE, ELECTRE, TOPSIS, VIKOR and others. In this case, the VIKOR method will be used.

The successful application of VIKOR has extended to many fields such as manufacturing, material selection, marketing, construction, risk and financial management, supply chain, health-care, performance evaluation and many other areas. In the mining industry, there has been limited application of VIKOR. Baloyi and Meyer researched the development of a mining method selection model through a detailed assessment of multi-criteria decision methods (Baloyi and Meyer, 2020). Sitorus et al. researched Multi-criteria decision making for the choice problem in mining and mineral processing: Applications and trends (Sitorus et al., 2019). Mahase et al. identified two areas dealing with mine planning and related studies to have applied this method (Mahase et al., 2016). Romero-Gelvez et al. researched Compromise solutions in mining method selection - case study in colombian coal mining (Romero-Gelvez et al., 2015). Azimi et al. researched evaluating the strategies of the Iranian mining sector using a integrated model (Azimi et al., 2011). Bazzazi et al. researched deriving preference order of open pit mines equipment through MADM methods: Application of modified VIKOR method (Bazzazi et al., 2011).

3 VIKOR METHOD

VIKOR is a Serbian phrase that means “VIsekriterijumskog KOmpromisnog Rangiranja”, which means “Multi-Criteria Optimization and Compromise Solution”. The VIKOR method, was proposed by Opricovic in 1998 to select an alternative as a compromised solution from a list of alternatives in order to make a final decision. According to the method, the closest valid solution to the ideal solution is the compromise solution (Baloyi and Meyer, 2020; Sitorus et al., 2019). This method focuses on ranking and selection of a set of alternatives in the presence of multiply criteria. It introduces the multi-criteria ranking index based on the particular measure of ‘closeness’ to the ‘ideal’ solution (distance-to-target) (Gao et al., 2019). The VIKOR method ranks alternative according to three scalar quantities (Si, Ri and Qi) which are independently evaluated against the criteria. An in depth description of the procedure used on the VIKOR methods was presented by Opricovic and Tzeng (Opricovic and Tzeng, 2004).

The compromise ranking algorithm of VIKOR encompasses the following steps (Gao et al., 2019; Opricovic and Tzeng, 2004):

Step 1: Determine the best f_i^+ and the worst f_i^- values of all criteria, *i=1, 2, ..., n*. If the *i*th criterion represents a benefit (as larger as better) then:

$$f_i^+ = max_j f_{ij} \text{ and } f_i^- = min_j f_{ij} \tag{1}$$

If the *i*th criterion represents a cost (as smaller as better) then:

$$f_i^+ = min_j f_{ij} \text{ and } f_i^- = max_j f_{ij} \tag{2}$$

Step 2: Computer the values S_j and R_j, *j=1, 2, ..., J,* by the relations:

$$S_j = \sum_{i=1}^{n} w_i\left(f_i^+ - f_{ij}\right)/(f_i^+ - f_i^-) \tag{3}$$

$$R_j = max_i\left[w_i\left(f_i^+ - f_{ij}\right)/(f_i^+ - f_i^-)\right] \tag{4}$$

Where S_j and R_j represent the utility measure and the regret measure, respectively and w_i is the weight of the *i*th criterion, expressing their relative importance.

Step 3: Compute the value Q_j, *j=1, 2, ..., J,* by the relation:

$$Q_j = \frac{v\left(S_j - S^+\right)}{(S^- - S^+)} + (1-v)\frac{\left(R_j - R^+\right)}{(R^- - R^+)} \tag{5}$$

where

$$S^+ = min_j S_j\ ;\ \ S^- = max_j S_j\ ;\ \ R^+ = min_j R_j\ ;\ \ R^- = max_j R_j\ ; \tag{6}$$

and v is introduced as weight of strategy of “the majority of criteria” (or “the maximum group utility”), here $v = 0{,}5$.

Step 4: Rank the alternatives, sorting by the values S, R and Q, in decreasing order. The results are three ranking lists.

Step 5: Propose as a compromise solution the alternative (*A'*) which is ranked the best by the measure Q (minimum) if the following two conditions are satisfied:

Condition 1: “Acceptable advantage”:

$$Q(A") - Q(A') \geq DQ \tag{7}$$

where *A"* is the alternative with second position in the ranking list by Q.

$$DQ = \frac{1}{J - 1} \tag{8}$$

where J is the number of alternatives.

Condition 2: "Acceptable stability in decision making":

Alternative A' must also be the best ranked by S or/and R. This compromise solution is stable within a decision making process, which could be: "voting by majority rule" (when $v > 0{,}5$ is needed), or "by consensus" $v \approx 0{,}5$, or "with veto" ($v < 0{,}5$). Here, v is the weight of the decision making strategy "the majority of criteria" (or "the maximum group utility").

If one of the conditions is not satisfied, then a set of compromise solutions is proposed, which consists of:

- Alternatives A' and A'' if only condition 2 is not satisfied;
- Alternatives $A', A'', \ldots, A^m$ if condition 1 is not satisfied; A^m is determined by the relation $Q(A^m) - Q(A') < DQ$ for maximum M (the positions of these alternatives are ''in closeness'').

The best alternative, ranked by Q, is the one with the minimum value of Q. The main ranking result is the compromise ranking list of alternatives, and the compromise solution with the "advantage rate".

4 CASE STUDY

This paper discusses the active underground lead and zinc mine, where a new part is opened and it is necessary to choose the appropriate mining method. In the work of the mine so far, four methods of mining excavation have been applied, which were obtained as the best ranked according to the UBC procedure, i.e., according to the rational choice (selection according to mining - geological factors), and will be alternatives for mining method selection (Table 1). Since these mining methods were used to excavate some parts of this ore deposit, there are orientation parameters for these mining methods. For the optimal choice of mining method of excavation, we will use the multi-criteria decision-making method, i.e., the VIKOR method (Romero-Gelvez et al., 2015). For that purpose, we will use eight mining-technical and economic factors, which will be the criteria according to which we will compare alternatives (Table 2). Each criterion has a different weight, i.e., an impact on alternative solutions. In this paper, the weights of the criteria were adopted by voting, i.e., in consultation with a group of 15 experts in the field of underground mining, in order to minimize subjectivity in optimization. Defining weights in consultation with experts is done in such a way that each expert has given their opinion on the weights of the criteria, and for further calculations a mean value is taken (Table 2). These weights will be used in the VIKOR method calculations. Table 2 also sets the goal tendency of the criteria (max or min) and the category of classification (quantitative or qualitative). Some criteria are classified in the category of quantitative (can be measured or calculated), and some criteria are classified as qualitative (cannot be measured). Qualitative criteria are defined by descriptive scores, so in order for them to be used for further calculations, they need to be transformed into numerical values. This transformation can be done in several ways, such as with the help of an interval scale, a qualitative scale, a bipolar scale, a linear scale of transformation, and so on. In this paper, the interval scale was used to transform qualitative in quantitative values (Table 3).

Table 1 Alternatives for mining method selection

Alternatives	Symbol
Cut and Fill Stoping	A_1
Sublevel Stoping	A_2
Shrinkage Stoping	A_3
Sublevel Caving	A_4

Table 2 Criteria for mining method selection

Criteria	Symbol	Weights of criteria	Definition
Value of mined ore	K_1	0,1900	This criterion is quantitative and tends to the maximum. The value of mined ore is the net value of the useful component contained in 1 t of ore, after flotation and metallurgical processing, reduced by the costs of metallurgical processing. The values for this criterion are obtained by a separate calculation for each alternative.
Occupational safety and health conditions	K_2	0,1200	This criterion tends to the maximum. This criterion is qualitative, so for each alternative it is assigned qualitative grades.
Coefficient of preparation works	K_3	0,1150	This criterion is quantitative and tends to the minimum. The value for this criterion is taken from the literature, according to each alternative.
Ore recovery	K_4	0,1400	This criterion is quantitative and tends to the maximum. The ore recovery coefficient is the ratio of the excavated ore from the deposit and the total amount of ore in the deposit. The value for this criterion is taken from the literature, according to each alternative.
Coefficient of ore dilution	K_5	0,0900	This criterion is quantitative and tends to the minimum. The coefficient of ore dilution is the ratio of unplanned ore and

Criteria	Symbol	Weights of criteria	Definition
			tailings mixed with ore and the total amount of run of mine ore. The value for this criterion is taken from the literature, according to each alternative.
Cost of one ton (1 t) of ore	K_6	0,1850	This criterion is qualitative and tends to the minimum. The total cost of producing one ton of ore is called the "cost price". Thus, the term cost of ore production means the sum of all costs of production and flotation processing of ore.
Effect of mining	K_7	0,0975	This criterion is quantitative and tends to the maximum. The effect of mining represents the productivity of the worker in the excavation process. The value for this criterion is taken from the literature, according to each alternative.
Terrain degradation and other environmental impacts	K_8	0,0625	This criterion tends to the minimum. This criterion is qualitative, so for each alternative it is assigned qualitative grades.

Table 3 Interval scale

Qualitative value	Very poor	Poor	Average	High	Very high	Type of criterion
Quantitative value	1	3	5	7	9	max
	9	7	5	3	1	min

After the analysis for the evaluation of individual criteria for each alternative solution, and based on the theory and on the basis of our evaluation, the definition of a multicultural model was performed (Table 4).

Table 4 Input model for VIKOR method

Alternatives	Criteria							
	K_1	K_2	K_3	K_4	K_5	K_6	K_7	K_8
Goal	max	max	min	max	min	min	max	min
A_1	93.300	7.000	8.650	94.000	6.000	9.000	15.000	3.000
A_2	81.600	5.000	23.900	80.000	18.000	7.000	22.000	5.000
A_3	88.200	7.000	17.550	85.000	12.000	7.000	10.000	3.000
A_4	77.300	9.000	2.560	75.000	22.000	3.000	30.000	9.000
Weights of criteria	0.1900	0.1200	0.1150	0.1400	0.0900	0.1850	0.0975	0.0625

Table 5 Determination of Best and Worst value

Alternatives	Criteria							
	K_1	**K_2**	**K_3**	**K_4**	**K_5**	**K_6**	**K_7**	**K_8**
Goal	max	max	min	max	min	min	max	min
A_1	93.300	7.000	8.650	94.000	6.000	9.000	15.000	3.000
A_2	81.600	5.000	23.900	80.000	18.000	7.000	22.000	5.000
A_3	88.200	7.000	17.550	85.000	12.000	7.000	10.000	3.000
A_4	77.300	9.000	2.560	75.000	22.000	3.000	30.000	9.000
Weights of criteria	0.1900	0.1200	0.1150	0.1400	0.0900	0.1850	0.0975	0.0625
Best (f_i^+)	93.300	9.000	2.560	94.000	6.000	3.000	30.000	3.000
Worst (f_i^-)	77.300	5.000	23.900	75.000	22.000	9.000	10.000	9.000

Table 6 Computation of S_j, R_j, Q_j

Alternatives	**S_j**	**R_j**	**Q_j**
A_1	0.3509	0.1850	0.4625
A_2	0.7278	0.1389	0.6170
A_3	0.5222	0.1233	0.2273
A_4	0.4825	0.1900	0.6746
S^+, R^+	0.3509	0.1233	
S^-, R^-	0.7278	0.1900	

Table 7 Ranking of alternatives

Alternatives	**S_j**	**R_j**	**Q_j**	**Rank**
A_1	0.3509	0.1850	0.4625	2
A_2	0.7278	0.1389	0.6170	3
A_3	0.5222	0.1233	0.2273	1
A_4	0.4825	0.1900	0.6746	4

The proposed compromise solution for alternatives, according to the ranking of minimum values for “Q”, does not meet the first condition, so we take the next alternative that satisfies the condition. The second condition is met.

Condition 1: “Acceptable advantage” (Eq. 7 and Eq. 8):

$$Q(A'') - Q(A') \geq DQ$$

$$0.4625 - 0.2273 = 0.2352 < 0.3333$$

$$DQ = \frac{1}{4-1} = \frac{1}{3} = 0.3333$$

$$Q(A''') - Q(A') \geq DQ$$

$$0.6170 - 0.2273 = 0.3897 > 0.3333$$

Condition 2: **“**Acceptable stability in decision making”:

Alternative A’ is the best ranked by R_j. This compromise solution is stable within a decision making process.

From Table 7 and Figure 2 it can be seen that the lowest value has an alternative A_3 (Shrinkage Stoping) and that it was chosen as the most acceptable.

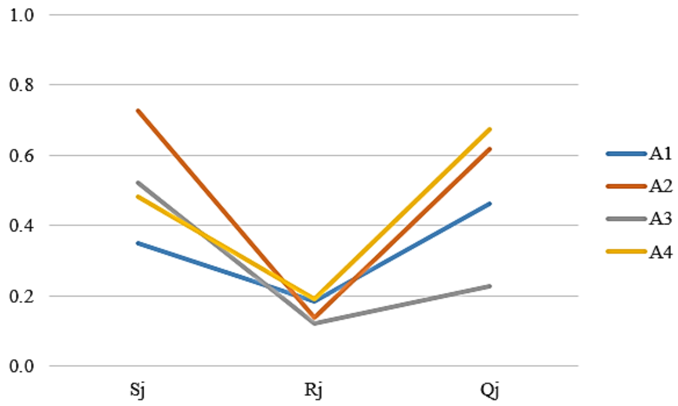

Figure 2 Ranking of alternatives

5 CONCLUSION

The correct choice of the method of mining excavation for underground exploitation has a very large impact on the working effect, the cost of ore mining, the size of losses and dilution of ore, as well as the financial effects that are achieved.

Due to the great importance for the correct choice of mining method, this issue has been studied by numerous authors. As a common phase of the procedures proposed by some authors, two phases can be distinguished: rational choice of mining method and optimal choice of the mining method.

When making the decision about which mining method will apply should take into account many factors that influence on the mining method selection. The selected mining method will be more suited to specific mining-geological, mining-technical and economic conditions if a number of relevant factors and included.

Multi-criteria optimization methods allow the selection of the best alternative, taking into account a number of influential criteria. In this paper, the VIKOR method was used to select the method of mining excavation during which several influencing factors were taken into account and it was concluded that the most acceptable way of excavating the mine is Shrinkage Stoping.

VIKOR is a helpful tool in multicriteria decision making, particularly in a situation where the decision maker is not able, or does not know to express his/her preference at the beginning of system design. The obtained compromise solution could be accepted by the decision makers because it provides a maximum "group utility" of the "majority", and a minimum of the individual regret of the "opponent". The compromise solutions could be the basis for negotiations, involving the decision maker's preference criteria weights.

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