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APPLYING THE VIKOR METHOD TO SELECT THE OPTIMAL UNDERGROUND MINING TECHNOLOGY

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Abstract

The selection of the most appropriate underground mining technology is not a simple process because it involves handling of a large amount of information about several potential methods. Multicriteria optimization approaches are proven useful tools for ranking alternatives, especially in cases where multiple complex criteria have to be considered simultaneously. An ore deposit is a complex system because of its geology, physical and mechanical properties, and hydrogeological conditions. As such, problem solving requires a heuristic approach and includes tasks involving expert judgement, intuition, estimation, and experience. Using a heuristic strategy to state a problem means that the analyst is placed in a position to apply past experience to a future situation and existing knowledge to new circumstances, as well as discover new avenues to creative problem solving. A complex algorithm was developed to pave the way to quality management of mining, by using the VIKOR method to rank various mining technologies relative to a set of criteria and select the optimum mining method that will primarily ensure profitable and safe mining.

Key words: expert judgement, multicriteria decision making, underground mining methods

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Introduction. The objective of the paper is to present a methodical approach – algorithm – developed and applied to select the most appropriate mining method for an ore deposit whose geological and hydrogeological characteristics are highly complex and subject to continual change. The selection process includes problem solving. The research is based on the “conventional” VIKOR multicriteria optimization method.

Every area of activity involves decision making. In the multicriteria optimization context, decision making is most often seen as a problem where the decision maker must choose one of several alternatives, taking into account all the relevant factors (or criteria). Given that the criteria are as a rule in conflict with each other, the decision maker’s choice will not be the best solution in the traditional sense, but a satisfactory solution where there is no better in a given situation. In the present case, the heuristic approach is applied to select the most suitable underground mining method through problem solving and decision making.

Heuristic modelling involves the creation of a model that represents multiple originals in a single model or, in other words, a model that enables the discovery of new knowledge and develops creativity, requiring some independence of the analyst and recognizing the level of prior knowledge of each analyst in their field of expertise (in this case the selection of an underground copper mining technology, using qualitative assessment to describe pairwise comparisons of criteria, subcriteria and alternatives with a conventional method such as VIKOR).

Problem solving with multicriteria optimization includes the definition of objectives, the selection of criteria to measure the achievement of objectives, specifying of alternatives, transformation of the performance of each alternative relative to various criteria such that their metrics are identical, allocation of weight coefficients to the criteria to identify their relative significance, selection of a suitable multicriteria optimization method to rank the alternatives, and finally selection of the best alternative, or the optimal method in the given case [1].

Figure 1 shows an algorithm and the steps taken to address problems associated with mining. Experience and subjective assessment affect each step of the algorithm. The algorithm models alternative underground mining solutions. The goal is to determine the optimal mining method that will ensure economically viable ore extraction. First the criteria that influence the decision are analyzed and then the VIKOR model used to create a decision matrix. In the end, a series of mathematical optimization calculations are conducted and the final decision made [2].

The VIKOR (multicriteria optimization and compromise solution) method is based on the assumption that a compromise is acceptable for resolving conflicts and that the decision maker is looking for the solution closest to the ideal, where alternatives are evaluated against set criteria [3]. The method was developed to propose alternatives to the decision maker, which represent a tradeoff between wishes and possibilities or a compromise between the interests of various stake-

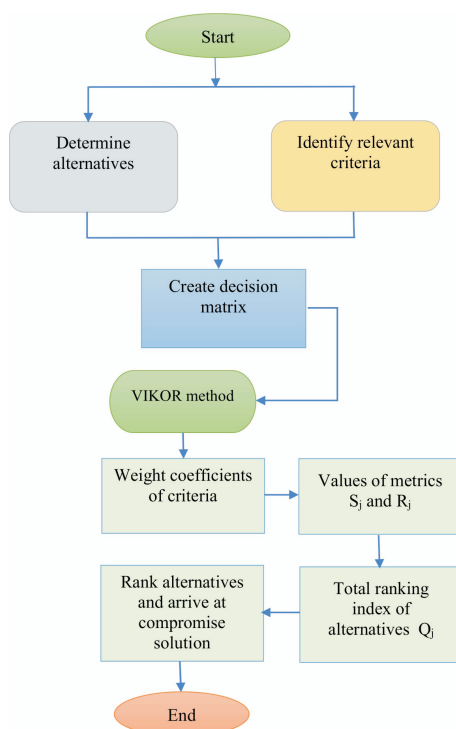


Fig. 1. Algorithm of a holistic approach to the creation of a sustainable mining plan

holders. Here wishes represent criteria and possibilities reflect constraints. The compromise solution is the one closest to the ideal case [4].

VIKOR is applicable to multicriteria decision making, especially in cases where the decision maker is unable or does not know how to express their own weight coefficients of the individual criteria at the beginning of decision matrix design [5].

Study area and geology. The study area is the Borska Reka copper ore deposit in eastern Serbia, which belongs to the Timok Igneous Complex on the northwestern outskirts of the City of Bor, beneath the valley of the Bor River. It is part of an active mine called Jama. The Bor metallogenic zone belongs to the Carpatho-Balkan metallogenic province, which stretches from Romania and the town of Majdanpek in the north, across eastern Serbia and the Bulgarian border in the southeast, to the central Bulgarian highlands. In the north around Majdanpek, this zone tapers out into Paleozoic schists. South of Bučje, igneous and volcanoclastic rocks alternate with sedimentary rocks comprising coal and rare volcanoclastics. To the west, the zone is bounded by the Kučaj-Homolje-Rtanj carbonate complex, and to the east by limestone sediments of Mali Krš, Veliki Krš, Rgotski Kamen and Tupižnica, as shown in Fig. 2 [1].

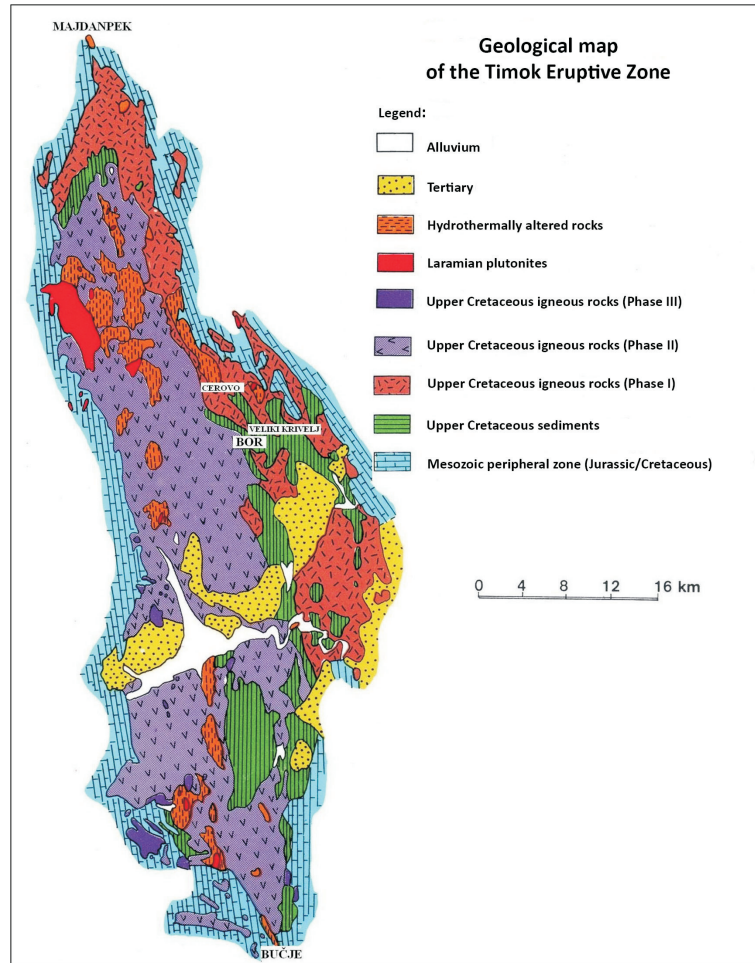


Fig. 2. Geological map of the Timok Eruptive Zone (modified [6])

Methodology. The VIKOR method was applied to a real study area to select the optimal underground mining method.

Step 1. State objective and define evaluation criteria for alternative solutions.

Step 2. Create a decision matrix, according to the following equation:

$$(1) \quad X = [x_{ij}] = \begin{bmatrix} x_{11} & x_{12} & \dots & x_{1n} \\ x_{21} & x_{22} & \dots & x_{2n} \\ \dots & \dots & \dots & \dots \\ x_{m1} & x_{m2} & \dots & x_{mn} \end{bmatrix},$$

where: x_{ij} is the performance of the i -th alternative relative to the j -th criterion, m is the number of alternatives; and n is the number of criteria.

Step 3. Determine the most suitable values of all criteria:

$T = \{T_1, T_2, T_3, \dots, T_j, \dots, T_n\}$ = most desirable element x_{ij} or target value of criterion j .

Step 4. Determine the relative significance of the criteria, in other words the weight coefficients of the criteria for which the following holds true:

$$(2) \quad \sum_{i=1}^n w_i = 1$$

Step 5. Determine weight v . ($v = 0.7$).

Step 6. Values of metrics S_j and R_j .

$$(3) \quad S_j = \sum_{i=1}^n w_i = \frac{f_i^* - f_{ij}}{f_i^* - f_i^-} \quad (p = 0)$$

$$(4) \quad R_j = \max \left(w_i \frac{f_i^* - f_{ij}}{f_i^* - f_i^-} \right), \quad (p = \infty)$$

where: f_i^* and f_i^- are the maximum and minimum values of the criteria function of the alternatives, respectively:

$$f_i^* = \max_j f_{ij} \quad \text{and} \quad f_i^- = \min_j f_{ij} \quad (i = 1, 2, \dots, n).$$

S_j is the deviation metric that expresses the requirement to maximize group utility, and R_j is the deviation metric that expresses the requirement to minimize the longest distance of the alternative from ideal [7].

Step 7. Total alternative ranking index:

$$(5) \quad Q_j = v \frac{S_j - S^*}{S^- - S^*} + (1 - v) \frac{R_j - R^*}{R^- - R^*} \quad (j = 1, 2, \dots, J),$$

where: $S^* = \min_j S_j$, $R^* = \min_j R_j$, $S^- = \max_j S_j$, $R^- = \max_j R_j$, S^* and R^* are the best limits of metrics S_j and R_j , S^- and R^- are the worst limits of metrics S_j and R_j , and v is the weight of the strategy that fulfills most of the criteria [8].

The relation for metric Q_j can also be written as

$$(6) \quad Q_j = vQS_j + (1 - v)QR_j.$$

Step 8. Rank alternatives three times, based on S_j , R_j and Q_j . The best alternative according to the compromise ranking list is the one with the lowest Q_j [9].

The VIKOR method was followed to determine the optimal underground mining method for the Borska Reka copper deposit using the software application Fuzzy-GWCS2, specifically developed for that purpose [1].

Results. Five alternative mining methods were defined: Alternative A1 – sublevel caving; Alternative A2 – cutting and filling; Alternative A3 – shrinkage stoping; Alternative A4 – block caving, and Alternative A5 – vertical crater retreat (VCR) mining. Then the factors that influence the selection of the optimal solution were analyzed. These were the criteria defined based on available information about the ore deposit and the underground mining methods deemed applicable. A working model was constructed to represent a combination of technical criteria (f1 – depth, f2 – thickness and shape of ore body, f3 – value of ore, f4 – slope angle, f5 – rock hardness and stability, f6 – ore body form, f7 – contact with adjacent rocks, and f8 – mineral and chemical composition of ore), production criteria (f9 – productivity of the mining technology and production capacity, f10 – safety at work, f11 – environmental impact, f12 – ore dilution, f13 – ore impoverishment, f14 – ventilation, and f15 – hydrology), and economic criteria (f16 – capital expenditure, f17 – excavation costs, and f18 – maintenance costs) [10].

The analysis was conducted applying the “conventional” VIKOR multicriteria optimization method and following the VIKOR steps described above.

A decision matrix was constructed according to Step 2, Eq. 1. Then the most favourable values of all the criteria (highest maximization and lowest minimization values) were established per Step 3. A fuzzified Saaty scale [11,12] was used to assess the alternatives relative to the criteria, as shown in Table 1. A relative significance scale described the linguistic variables by numerically ranking their significance, as follows: equal (1), equal to moderate (2), moderate (3), moderate to high (4), high (5), high to very high (6), very high (7), very high to extremely high (8), and extremely high (9).

Then according to Step 4, represented by Eq. 2, the weight coefficients of the criteria were determined such that $w_i = 1$, as shown in Table 1. The values of weight v were determined in Step 5. The values of metrics S_j and R_j were established based on Step 6 and Eqs 3 and 4. According to Step 7, Table 2 shows the total ranking index of the alternatives, as the value Q_j that represents a linear combination of metrics S_j and R_j . Q_j was derived from Eq. 5. Past mining experience at Borska Reka favours the sublevel caving method (Swedish approach), primarily for economical reasons. However, this ore deposit is too specific and complex in terms of both geology and geometry. As such, in addition to the economic criteria (f16-f18), which are extremely important, the present research considered numerous other factors/criteria (f1–f15) that cannot be disregarded in the mining process. The alternatives were analyzed and ranked according to the values of S_j , R_j and Q_j , and a compromise solution was proposed. Alternative A_5 was selected as the optimal solution [1].

Conclusion. Many influencing factors need to be considered if decision making about an optimal mining technology is to be effective. The characteristics of the ore deposit are the starting point. The following aspects also need to be addressed: safety at work during mining, minimizing of ore losses, ensuring the re-

T a b l e 1

Quantified decision matrix and intermediate values

Quantified decision matrix and maximum and minimum values of criteria																		
Alter- native	f1	f2	f3	f4	f5	f6	f7	f8	f9	f10	f11	f12	f13	f14	f15	f16	f17	f18
A_1	3	9	9	7	9	5	1	3	7	7	1	3	1	1	1	3	7	9
A_2	9	1	7	1	5	9	7	9	1	5	9	9	9	5	9	1	1	1
A_3	7	5	3	5	1	3	5	1	5	3	5	5	3	9	5	7	5	5
A_4	1	3	1	3	3	1	9	7	3	1	7	1	5	7	7	9	3	3
A_5	5	7	5	9	7	7	3	5	9	9	3	7	7	3	3	5	9	7
Extr	max	max	max	max	max	max	max	max	max	max	max	max	max	max	max	max	max	max
f^*	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9
f^-	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
D	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8

Intermediate values $(f_{i,\max} - f_{ij})/(f_{i,\max} - f_{i,\min}) * w_i$																		
A_1	0.75	0	0	0.25	0	0.5	1	0.75	0.25	0.25	1	0.75	1	1	1	0.75	0.25	0
A_2	0	1	0.25	1	0.5	0	0.25	0	1	0.5	0	0	0	0.5	0	1	1	1
A_3	0.25	0.5	0.75	0.5	1	0.75	0.5	1	0.5	0.75	0.5	0.5	0.75	0	0.5	0.25	0.5	0.5
A_4	1	0.75	1	0.75	0.75	1	0	0.25	0.75	1	0.25	1	0.5	0.25	0.25	0	0.75	0.75
A_5	0.5	0.25	0.5	0	0.25	0.25	0.75	0.5	0	0	0.75	0.25	0.25	0.75	0.75	0.5	0	0.25

T a b l e 2

Values of S_j and R_j , intermediate results (QS_j and QR_j), and ranking of alternatives (Q_j)

Alternative	S_j	R_j	$(S_j - \min S_j) / (\max S_j - \min S_j)$	$(R_j - \min R_j) / (\max R_j - \min R_j)$	Q_j	$v = 0.7$
A_1	9.5	1	0.666667	1	0.766667	
A_2	8	1	0.333333	1	0.533333	
A_3	10	1	0.777778	1	0.844444	
A_4	11	1	1	1	1	
A_5	6.5	0.75	0	0	0	

quired production capacity, and curtailing production costs. Various multicriteria optimization methods are used for efficiency and to simplify the decision making process. One such method is VIKOR, suitable for understanding imprecise and incomplete data.

When a conventional method such as VIKOR is used to select the optimum mining method, a qualitative assessment approach is followed to describe pairwise comparison of criteria, subcriteria and alternatives, or linguistic variables, as reflected in a heuristic approach (expert judgment, intuition, and experience).

Based on the objective and scope of the research, the conclusion is that multicriteria analysis can be applied effectively to solve problems associated with the selection of an optimal mining technology, as demonstrated by an example of the application of the VIKOR method. It should be noted that the weights of criteria functions w_i are set by the decision maker during the process of ranking of alternatives. The values can be varied depending on the emphasis we wish to place on a particular criterion.

The final decision about the optimal underground mining method was made after the criteria, subcriteria and alternatives were evaluated using the VIKOR method. A software application called Fuzzy-GWCS2 was developed specifically for that purpose. Based on the solutions proposed by the VIKOR multicriteria decision-making approach, the conclusion is that the optimal underground mining technology for the Borska Reka copper deposit is A5 (VCR mining). Given that Borska Reka is an ore body with a low copper concentration and features a specific geometry, this approach offers numerous advantages in such a case, including a high production capacity, comparatively minor preparatory work, a high ore utilization coefficient, stability of structural elements during excavation, and miner safety. In view of these facts, the analysis presented in the paper will ensure efficient mining and sustainable ore extraction, resulting in high productivity and market competitiveness.

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