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METHODOLOGY FOR UNDERGROUND MINING METHOD SELECTION

Stojance MIJALKOVSKI[1]*, Dragi PELTECHKI[2], Zoran DESPODOV[1], Dejan MIRAKOVSKI[1], Vancho ADJISKI[1], Nikolinka DONEVA[1]

[1] Faculty of Natural and Technical Sciences, Mining Engineering, "Goce Delchev" University, PO Box 201, 2000 Shtip, Macedonia
[2] Rudplan DOOEL, Karaman Atanas 36, 2400 Strumica, Macedonia

Abstract: The mining method selection for underground mining is one of the most important decisions when designing a mine. This selection depends on the mining-geological, mining-technical and economic factors. The mining method selection for underground mining can be described as a multi-criteria decision-making process, as several factors are involved in the selection process. In this paper, a methodology for rational and optimal mining method selection for underground mining of metallic mineral resources has been developed. First, a rational selection of the four best-ranked mining methods for underground mining is performed using numerical methods (Nicholas' approach and the modified approach of Nicholas, i.e., UBC selection of mining method). This is followed by the optimal selection of underground mining method using multi-criteria decision-making methods (ELECTRE, PROMETHEE, AHP, and integrated AHP-PROMETHEE) and by comparing the obtained rankings, the optimal mining method is selected.

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

1. INTRODUCTION

Appropriate mining method selection (MMS) for a particular underground mine is of great importance and is a substantial problem. The mining method should provide as little capital and operating costs as possible, i.e., the return on investments should start as soon as possible, and it is also necessary to increase the safety of employees and provide the necessary production (Mijalkovski 2009; Peskens 2013). The mining

* Corresponding author: stojance.mijalkovski@ugd.edu.mk (Stojance Mijalkovski)

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method selection (MMS) depends on a number of factors, which can be qualitative and quantitative, and can be divided into three groups (Bogdanovic 2012):

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

In practice, there are cases where mining and geological factors allow the application of a particular mining method, but its application is not economically justified. There are also cases where a certain mining method allows the application of a certain mechanization, but this is not allowed by the mining-technical factors (Bogdanovic 2012).

Methodologies for mining method selection (MMS) can be divided into three groups: qualitative methods, numerical methods and decision-making methods (Nourali et al. 2012). A comprehensive survey of literature on the first two groups can be found in Namin et al. (2009).

The classification system proposed by Boshkov and Wright (1973) was one of the first qualitative classification schemes attempted for underground mining method selection. It uses general descriptions of the ore thickness, ore dip, strength of the ore, and strength of the walls to identify common methods that have been applied in similar conditions. Later, Morrison (1976), Laubscher (1981), Hamrin (1982; 1998), Hartman (1992), etc. have suggested a series of approaches for mining method selection.

The first numerical approach for mining method selection was suggested by Nicholas (1981; 1992). This methodology numerically ranks deposit characteristics of ore geometry and rock mechanic characteristics of ore zone, footwall and hanging wall. The rankings are then summed together with the higher rankings being the more favorable or likely mining methods. In 1992, Nicholas made some modification to his selection procedure by introducing a weighting factor. The UBC (University of British Columbia) mining method selection algorithm developed by Miller, Pakalnis and Poulin (1995) is a modification to the Nicholas approach, which places more emphasis on stoping methods, thus better representing typical Canadian mining design practices (Miller et al. 1995).

Bandophadhyay and Venkatasubramanian (1987) developed one of the first studies on the implementation of expert system in the mining method selection process (Bakhtavar et al. 2009a; 2009b). Later, expert systems application in mining method selection decision-making was developed and a milling and mining method chosen expert was expressed utilizing a knowledge base that is comprised of alternative methods, experience, intuition, deposit types, mine plans and engineering studies (Camm et al. 1992). Third expert system by Gershon et al. (1995) based on the Nicholas approach (1981) was developed. Due to Basu (1999) efforts to improve practically and technically the Gershon et al. system (1995), a similar expert system was developed (Bakhtavar et al. 2009b). According to the study of Guray et al. (2003) which concerned the Nicholas system (1981) and based on a number of expert systems and one interface agent, a new expert system was achieved. In this system, the intuitive knowledge and judgment of the expert users or in other words "experienced engineers" can be directly added to the databases of the virtual experts.

It is notable that, recently, numerous researches have been done and published in relation to selection of a suitable mining method for an ore deposit using the multi-criteria decision-making (MCDM), such as AHP, ELECTRE, PROMETHEE, TOPSIS, WPM, VIKOR, Fuzzy logic and so on, separately and together. Shahriar et al. (2007) used a new numerical Shahriar and Bakhtavar (Sh and B) approach and the AHP. The method is a combined and modified system of Nicholas, Modified Nicholas and UBC for mining method selection. Alpay et al. (2007) used decision support system and AHP for the selection of underground mining method at Eskisehir–Karaburun chromite mine. Namin et al. (2008) used fuzzy TOPSIS for mining method selection and examined the model for GEG anomaly No. 3 and Chahar Gonbad mine. Ataei et al. (2008b) used the TOPSIS method with 13 criteria to develop a suitable mining method for Golbini No. 8 of Jajarm bauxite mine in Iran. Also, Ataei et al. (2008a) used AHP method to select mining method for the same mine. Namin et al. (2009) used AHP, TOPSIS and PROMETHEE to solve mining method selection problem. Jamshidi et al. (2009) used the AHP to select the optimal underground mining method in the Jajarm bauxite mine. Alpay et al. (2009) have proposed a combination of AHP and fuzzy logic methods for underground mining method selection. Naghadehi et al. (2009) used fuzzy AHP for mining method selection at Jajarm Bauxite mine. Mikaeil et al. (2009) developed a decision support system using Fuzzy AHP and TOPSIS approaches to select the optimum underground mining method. Azadeh et al. (2010) used fuzzy AHP for mining method selection by modifying Nicholas technique for Choghart iron mine. Gupta et al. (2012) developed AHP model for underground mining method selection. Bogdanovic et al. (2012) used the PROMETHEE and AHP methods to select an appropriate mining method in the Coka Marin mine in Serbia. Mijalkovski et al. (2013) used AHP, PROMETHEE and AHP-PROMETHEE integrated method for mining method selection for Sasa mine in Macedonia. Shariati et al. (2013) used fuzzy AHP and TOPSIS for mining method selection for Angouran mine in Iran. Ataei et al. (2013) proposed a Monte Carlo-based AHP (MAHP) technique for mining method selection of Bauxite ore deposit in Iran. Gelvez et al. (2014) applied the AHP and the VIKOR methods to select optimum mining method in the coal mine in Colombia. Yavuz (2015) used AHP and Yager's method for selection of underground mining for Ciftalan lignite mine in Istanbul. Karimnia et al. (2015) used AHP to select the better mining method at a salt mine in Iran. Chen et al. (2015) applied AHP and PROMETHEE methods for selecting the most suitable technique for mechanized mining in a tin coal mine in China. Javanshirgiv et al. (2017) used fuzzy TOPSIS for mining method selection at Kamar Mahdi fluorine mine in Iran. Balusa et al. (2018a) used fuzzy AHP for mining method selection at Tummalapalle and Turamdih uraniums mines in India. Chander et al. (2018) used AHP and VIKOR for the selection of the optimal underground bauxite mining method. Balusa et al. (2018b) used AHP, WPM and PROMETHEE to determine the effective mining method for a bauxite mine. Balusa et al. (2019a) used AHP, TOPSIS, VIKOR, ELECTRE, PROMETHEE, WPM for mining method selection at Tummalapalle uranium mine, India. Balusa et al. (2019b) analyzed the sensitivity in decision-making which results in the selection of the appropriate underground metal mining method using the fuzzy-AHP (FAHP) model. Wang et al. (2019) used Monte Carlo analytic hierarchy process for selection of the longwall mining method in tin coal seams. Bajic et al. (2020) used fuzzy AHP for mining method selection at Borska Reka copper mine, Serbia.

In this paper, the methodology for mining method selection for underground mining of metallic mineral resources will be reviewed. The methodology consists of two phases:

- rational selection of a group of mining methods using numerical methods;
- optimal selection of a mining method using multi-criteria decision-making methods.

2. METHODOLOGY

The working methodology for underground metal mining method selection is shown in Fig. 1. First, we make a rational choice (phase 1), i.e., underground mining methods selection according to mining-geological factors (geometry of deposit, ore variability and rock quality). For that purpose, numerical methods will be used, i.e., Nicholas and UBC mining method selection. Since it is a methodology for mining method selection for underground mining of metallic mineral resources, the open pit mining and longwall mining methods have not been taken into account. After ranking the mining methods according to the mining-geological factors, the four best ranked mining methods will be further taken into account and from them, optimal selection of the mining method will be performed. The optimal choice (phase 2) is the selection of a mining method according to the mining-technical and economic factors, using multi-criteria decision-making methods (ELECTRE, PROMETHEE, AHP and AHP-PROMETHEE integrated method). After ranking the mining methods according to the multi-criteria decision-making methods, the obtained rankings from each multi-criteria method will be compared and the average ranking of the mining methods will be calculated, which is actually the final ranking and optimal selection of mining method.

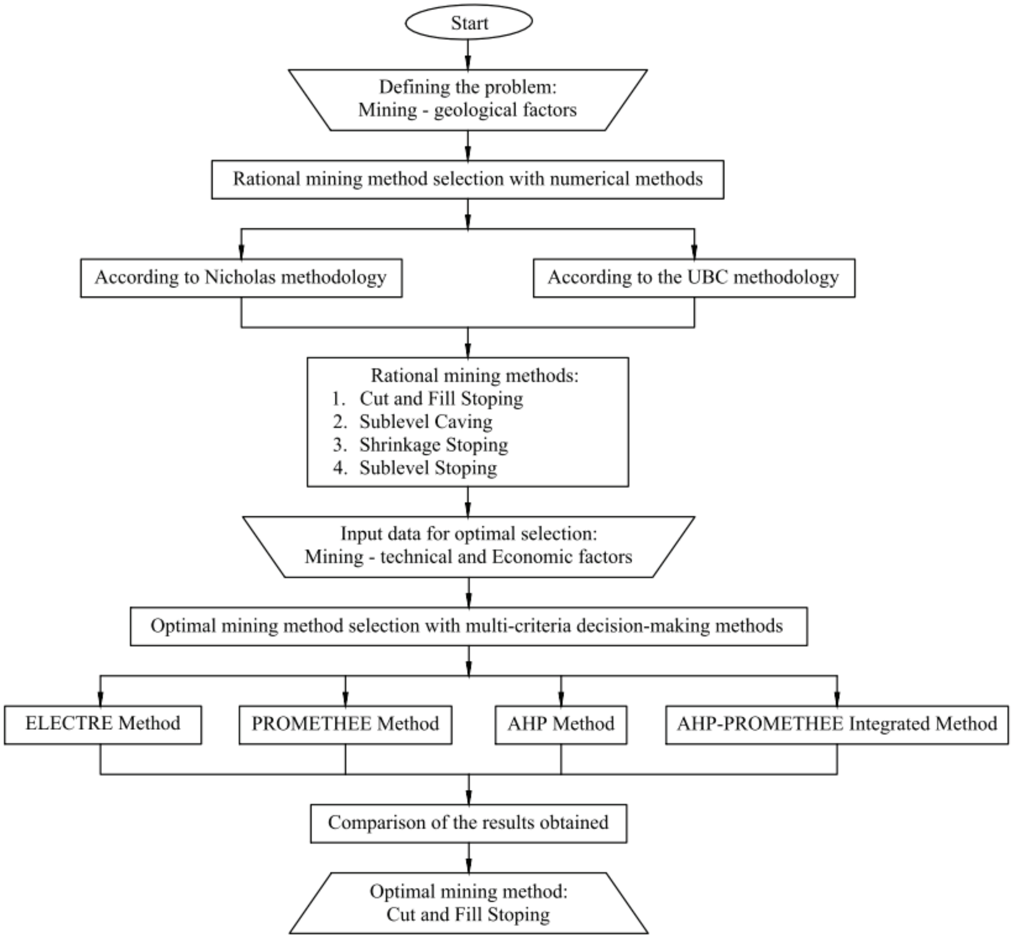

Fig. 1. Methodology for underground metal mining method selection

3. CASE STUDY

To validate the proposed methodology for mining method selection for underground mining of metallic mineral resources, we selected a lead and zinc mine where we will conduct the case study.

3.1. NUMERICAL METHODS

For the mining methods selection according to the mining-geological factors, we will use numerical methods, i.e., Nicholas and UBC mining method selection (Miller et al.

1995; Nicholas 1981; 1992; Shahriar et al. 2007). To rank the mining methods, we will use the following mining-geology factors: deposit geometry and grade distribution (general shape, ore thickness, plunge, depth below surface, grade distribution) and rock mechanics characteristics for ore zone, hanging wall and footwall (rock substance strength, fracture frequency, fracture shear strength). We will compare the obtained rankings from the two methodologies, but we give preference to the UBC methodology, and then we select the four best ranked mining methods for further optimization. The rankings of the mining methods are shown in Table 1.

Table 1. Ranking of underground mining methods

Underground mining method	Nicholas' methodology	UBC methodology
Cut and Fill Stoping	1	1
Sublevel Stoping	8	2
Shrinkage Stoping	3	3
Sublevel Caving	5	4
Room and Pillar Mining	7	5
Block Caving	4	6
Top Slicing	6	7
Square Set Stoping	2	8

3.2. MULTI-CRITERIA DECISION-MAKING METHODS

The optimal selection of mining method will be made from the four best ranked methods according to the numerical methods, i.e., according to UBC methodology, which will actually be alternatives (Table 2). For this purpose, we will use multi-criteria decision-making method, i.e., ELECTRE, PROMETHEE, AHP and AHP-PROMETHEE integrated method (Mardani et al. 2015; Sitorus et al. 2019). For the optimal mining method selection, we will use eight mining-technical and economic factors, which will be the criteria according to which we will compare the alternatives (Table 3). Each criterion has a different weight, i.e., an impact on alternative solutions. In this study, the weights of the criteria were adopted in two ways: by voting (Nourali et al. 2012), i.e., in consultation with a group of 15 experts in the field of underground mining and by using the AHP method, in order to minimize subjectivity in optimization. When comparing the weights obtained in both ways, we can conclude that the ranking of the weights of criteria is almost identical. 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 3). These weights will be used in the ELECTRE I and PROMETHEE II method calculations. Table 3 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 for transformation, and so on. In this study, the interval scale was used to transform qualitative into quantitative values (Table 4). The weights obtained using the AHP method (Table 10) will be used in the calculations with AHP and AHP-PROMETHEE integrated methods.

Table 2. 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 3. Criteria for mining method selection

Criteria	Symbol	Weights of criteria	Goal	Category
Value of mined ore	K_1	0.1900	max	quantitative
Occupational safety and health conditions	K_2	0.1200	max	qualitative
Coefficient of preparation works	K_3	0.1150	min	quantitative
Ore recovery	K_4	0.1400	max	quantitative
Coefficient of ore dilution	K_5	0.0900	min	quantitative
Cost of one ton (1 t) of ore	K_6	0.1850	min	qualitative
Effect of mining	K_7	0.0975	max	quantitative
Terrain degradation and other environmental impacts	K_8	0.0625	min	qualitative

Table 4. 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

3.2.1. DECISION-MAKING ANALYSIS USING ELECTRE MODEL

The ELECTRE was originally created in the 1960s (Benayoun et al. 1966; Roy 1968) as a response to the limitations of existing decision-making methods for resolving the choice problem. Since the introduction of the method, eight further variations have been applied for supporting MCDM problems, namely ELECTRE I, IS, Iv, II, III, IV, III-H and Tri. All these methods were developed on the same fundamental concept but differ in their stages. Each of the ELECTRE family methods has a specific function regarding the type of problem (Sitorus et al. 2019). The ELECTRE I method was used in this study.

After the analysis for evaluation of the individual criteria for each alternative solution, the definition of the multi-criteria model (Table 5) was performed.

Table 5. Input model for ELECTRE I 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	93.3	7	8.65	94	6	9	15	3
A_2	81.6	5	23.9	80	18	7	22	5
A_3	88.2	7	17.55	85	12	7	10	3
A_4	77.3	9	2.56	75	22	3	30	9
Weights of criteria	0.1900	0.1200	0.1150	0.1400	0.0900	0.185	0.0975	0.0625

By solving the given problem, a partial sequence of alternatives is obtained according to the ELECTRE I method (Table 6).

Table 6. Partial sequence of alternatives according to the ELECTRE I method

Alternatives	Prefers	Total prefers	Rank
A_1	A_3, A_4	2	1
A_2	A_3, A_4	2	1
A_3	A_2, A_4	2	1
A_4	does not prefer	0	2

3.2.2. DECISION-MAKING ANALYSIS USING PROMETHEE MODEL

The PROMETHEE method, which was initially proposed by Brans (1982), is another outranking method for a finite set of alternatives that is to be ranked and selected. The original method was further extended by Brans et al. (1985). A finite set of predetermined alternatives are evaluated under multiple criteria. Each independent criterion is weighted, and an appropriate preference function should be selected. The preference function describes the difference between the evaluations of an alternative to another into a preference degree (Brans et al. 1986). Since its introduction, six methods developed within the PROMETHEE family have been applied for solving MCDM problems, namely PROMETHEE I, II, PROSA (an extension of the PROMETHEE II method), III, IV, V and VI.

Similarly to the ELECTRE family, each of the PROMETHEE methods has a specific role with respect to the type of problem (Sitorus et al. 2019). The PROMETHEE II method was used in this study.

The PROMETHEE method uses six generalized criteria to display the preferences of the decision maker for specific criteria, and the types of these criteria are shown in Fig. 2 (Brans et al. 1986).

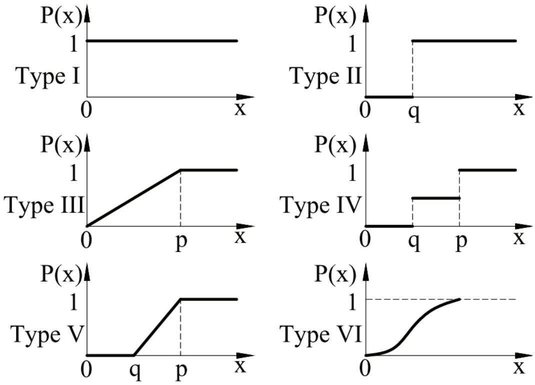

Fig. 2. Type of generalized criteria in PROMETHEE

After the analysis for evaluation of the individual criteria for each alternative solution, and based on the theory, the equations for the PROMETHEE II method and based on our assessment, the types of generalized criteria have been adopted and the definition of the multi-criteria model has been performed (Table 7).

Table 7. Input model for PROMETHEE II 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		93.3	7	8.65	94	6	9	15	3
A_2		81.6	5	23.9	80	18	7	22	5
A_3		88.2	7	17.55	85	12	7	10	3
A_4		77.3	9	2.56	75	22	3	30	9
Criteria features	Weights	0.1900	0.1200	0.1150	0.1400	0.0900	0.1850	0.0975	0.0625
	Type	Linear	Level	Linear	Quasi	Level	Level	Linear	Level
	q	–	2	–	5	4	2	–	2
	p	4.3	4	6.09	–	6	4	5	6

By solving the given problem, a complete ranking of the alternatives according to the PROMETHEE II method (Table 8) is obtained.

Table 8. Complete ranking of alternatives according to the PROMETHEE II method

Alternatives	Positive flow	Negative flow	Net flow	Rank
A_1	0.3960	0.1695	0.2266	1
A_2	0.1021	0.3780	–0.2759	4
A_3	0.2159	0.2177	–0.0018	3
A_4	0.3700	0.3188	0.0511	2

3.2.3. DECISION-MAKING ANALYSIS USING AHP MODEL

The AHP, originally designed by Saaty (1980), provides a systematic process to incorporate factors such as logic, experience or knowledge, emotion, and a sense of optimisation into a decision-making methodology. This method simplifies a multi-criteria complex problem into a hierarchy structure. According to Saaty et al. (2001), hierarchy is defined as a representation of a complex problem in a multi-level structure where the first level is the goal, followed by sub-levels, criteria, and sub-criteria, and down to the last level of the alternatives. With this approach, a complex problem can be deconstructed into sections and then arranged into a form of hierarchy so that the problem will appear more structured and systematic. The AHP method comprises four main stages: structuring the model into a hierarchy; conducting the comparative judgment of the criteria, sub-criteria, and alternatives with respect to their importance through pairwise comparisons; summarising the result of the pairwise comparisons in an evaluation matrix; synthesising the order of preferences of the alternatives that are obtained from the normalised evaluation matrix. AHP has been applied widely in mining for decision-making (Sitorus et al. 2019).

The ANP is a generalization of the AHP that deals with dependencies (Saaty 2008). Many real-life MCDM problems might involve the interaction and dependence between different criteria, as well as between different sub-criteria in the form of internal and external dependencies, or in the form of feedbacks from alternatives to criteria. The ANP method allows modeling all these interactions, dependencies and feedbacks between the aforementioned elements in the network (Saaty 2008).

The input data of the model for further processing are shown in Table 9.

Table 9. Input model for AHP 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	93.3	7	8.65	94	6	9	15	3
A_2	81.6	5	23.9	80	18	7	22	5
A_3	88.2	7	17.55	85	12	7	10	3
A_4	77.3	9	2.56	75	22	3	30	9

The Consistency Ratio of the pairwise comparison matrix is calculated as 0.074 < 0.1. So, the weights are shown to be consistent, and they can be used in the decision-making process (Table 10).

Table 10. Results obtained by comparing first level criteria

Criteria	K_1	K_2	K_3	K_4	K_5	K_6	K_7	K_8
Weights	0.3168	0.0853	0.0747	0.1356	0.0309	0.2956	0.0425	0.0186
Rank	1	4	5	3	7	2	6	8
$\lambda_{max} = 8.7306$		$CI = 0.1044$		$RI = 1.41$		$CR = 0.074 < 0.1$		

By further solving the given problem, a final ranking of the alternatives according to the AHP method (Table 11) is obtained.

Table 11. The ranking of alternatives by AHP method

Alternatives	Score	Rank
A_1	0.5575	1
A_2	0.1376	3
A_3	0.1852	2
A_4	0.1197	4

3.2.4. DECISION-MAKING ANALYSIS USING AHP-PROMETHEE INTEGRATED MODEL

Macharis et al. (2004) have analyzed the strengths and weaknesses of both PROMETHEE and AHP methods. They have made the comparative analysis of the following elements in both methods: the underlying value judgments, the structuring of the problem, the treatment of inconsistencies, the determination of weights, the evaluation elicitation, the management of the rank reversal problem, the support of group decisions, the availability of software packages and the possibility to visualize the problem. Based on this comparative analysis, we have concluded that a number of favorable characteristics of the AHP method could enhance PROMETHEE, namely at the level of structuring the decision problem and determining weights. The criteria weights, obtained by AHP, have a higher level of coherence, correlation, consistency and accuracy than weights determined on the basis of intuition or a domain specialist's knowledge, which is mostly used in the PROMETHEE method (Bogdanovic et al. 2012; Turcksin et al. 2011).

In this combined decision-making methodology, first the calculation of the weights of the criteria according to the AHP method is performed and they are given in Table 10. Further calculation is performed with the PROMETHEE II method. The definition of the multi-criteria model is given in Table 7, only the values for the weights of the criteria have been changed. By further solving the given problem, a ranking of the alternatives is obtained (Table 12).

Table 12. The ranking of alternatives by AHP - PROMETHEE integrated method

Alternatives	Positive flow	Negative flow	Net flow	Rank
A_1	0.3925	0.2011	0.1914	1
A_2	0.0933	0.3600	-0.2667	4
A_3	0.2242	0.1929	0.0313	3
A_4	0.3667	0.3227	0.0441	2

3.2.5. COMPARISON OF RESULTS OBTAINED BY MULTI-CRITERIA DECISION-MAKING METHODS

Table 13 shows the results obtained using the ELECTRE I, PROMETHEE II, AHP and AHP-PROMETHEE methods. By comparing the results and calculating the average value of the rankings, we can conclude that the most acceptable alternative is "A_1", i.e., Cut and Fill Stoping (Fig. 3). The alternative "A_3" is second in rank, followed by the alternative "A_4", and the last ranked alternative is A_2 ($A_1 \rightarrow A_3 \rightarrow A_4 \rightarrow A_2$).

Table 13. Ranking of alternatives according to different multi-criteria methods

Alternatives	ELECTRE I	PROMETHEE II	AHP	AHP – PROMETHEE	Average	Rank
A_1	1	1	1	1	1.00	1.00
A_2	1	4	3	4	3.00	0.33
A_3	1	3	2	3	2.25	0.44
A_4	2	2	4	2	2.50	0.40

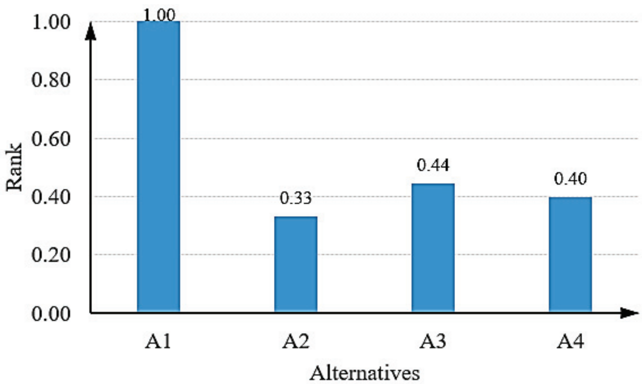

Fig. 3. Overall ranking of alternatives

4. CONCLUSION

Mining method selection for underground mining of metallic mineral resources is one of the most difficult tasks a mining engineer encounters. The mining method selection has a direct impact on the economic operation of the mine, i.e., on its income or losses. The mining method selection depends on many factors, which can be divided into three groups: mining-geological, mining-technical and economic factors.

In this study, the mining method selection for underground mining of metallic mineral resources was performed in two stages: rational selection of a group of mining methods using numerical methods, taking into account only mining-geological factors and optimal selection of a mining method using multi-criteria decision-making methods, taking into account mining-technical and economic factors. After making a rational selection of a group of mining methods with UBC methodology, we selected the four best ranked mining methods, which presented us with alternatives in the further calculation for optimal selection of a mining method using multi-criteria decision-making methods. The selection of the optimal alternative was made according to eight criteria.

For the optimal selection of a mining method, four multi-criteria decision-making methods were used: ELECTRE I, PROMETHEE II, AHP and AHP-PROMETHEE integrated method. By comparing the results obtained from all multi-criteria decision-making methods, we came to the conclusion that the optimal mining method is Cut and Fill Stoping.

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