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Selection of the optimal technology for surface mining by multi-criteria analysis

CVJETKO STOJANOVIC*, DEJAN BOGDANOVIC** AND SNEZANA UROSEVIC***

**Department for Investments, Development and Project Design, Mine and Thermal Power Ugljevik, Ugljevik, Bosnia and Herzegovina, E-mail: cvele.stojanovic@gmail.com*

***Department of Management, University of Belgrade – Technical Faculty in Bor, Bor, Serbia, E-mail: dbogdanovic@tf.bor.ac.rs*

****Department of Management, University of Belgrade – Technical Faculty in Bor, Bor, Serbia, E-mail: surosevic@tf.bor.ac.rs*

Corresponding author email: dbogdanovic@tf.bor.ac.rs

ABSTRACT

The selection of optimal technology for surface mining of mineral deposits is a standard decision-making problem. The aim of this paper is to demonstrate the potential of the combined AHP and ELECTRE methods in selecting the optimal technology using the open pit coal mine “Ugljevik East” (Ugljevik Istok) as an example. In order to resolve the problems encountered, the three types of technologies were taken into consideration with regards to the eight criteria for selecting the optimal solution. The criteria include the most important aspects of selecting the optimal technologies, such as geology and geotechnical engineering, ecology, economy, etc. In addition, AHP is used to analyse the structure of the technology selection process and to determine the significance and impact of certain criteria in the selection process, while ELECTRE method is used for the final ranking of alternatives. The obtained results indicate that the proposed combined method provides extraordinary results and that it can be used to resolve various, even the most complex problems that occur in mining engineering.

Keywords: AHP; decision-making, ELECTRE; surface mining technology.

INTRODUCTION

Significant indicators of surface mining, such as the production efficiency, costs and financial results depend on a number of various factors, where the technology represents one of the most important ones. Of course, the most important goal of the applied mineral resource exploitation technology is to achieve lower operating costs with greater financial gain, taking into account the environmental issues (air and water pollution, area degradation, tailing problems, etc.). The selection of optimal technology for surface mining depends on a number of relevant factors. These factors can be classified into three main groups, namely:

- mining and geological factors (type and characteristics of the work environment, resource thickness, general form of the resource, resource depth, quality of the mineral resources, etc.).
- mining-technical factors (annual production of mineral resources, equipment utilised, environmental protection, mining systems, etc.).
- economic factors (capital investment, operating costs and the value of mineral resource).

Nevertheless, the selection of optimal technology is a long and difficult process that requires extensive knowledge and experience. For the purpose of proper and efficient assessment, the decision maker must be granted access to a large amount of relevant data to be analysed.

Modern approaches perceive the selection of technology for surface mining as a process of multi-criteria decision-making with a finite number of alternatives that must be categorised with respect to many different and conflicting criteria. Multi-criteria decision-making methods represent a beneficial approach to decision making problems, which can evaluate quantitative and qualitative criteria and sort the preferences in order to rank the alternatives and obtain the best solution (best alternative among all the alternatives). The advantage of these methods is that they can simultaneously consider both financial and non-financial factors in the selection process. The best known modern methods are models of assessment, AHP (Analytic Hierarchy Process), ANP (Analytic Network Process), TOPSIS (Technique for Order Preference by Similarity to Ideal Solution), ELECTRE (ELimination Et Choix Traduisant la REalit´e (ELimination and Choice Expressing the REality)) and PROMETHEE (the Preference Ranking Organization METHod for Enrichment of Evaluations). Before selecting and applying the appropriate multiple criteria method for the selection of the optimal resource exploitation technology, it is necessary to discuss in detail the entire scope of the elements and factors related to the specific situation (Bufardi *et al.*, 2004; Mergias *et al.*, 2007).

In the process of multi-criteria decision-making, adequate defining of the criteria importance is crucial. The above-mentioned methods, except AHP method, do not include the procedure for determining the importance of the criteria. Therefore, in order to determine the criteria importance, AHP method is combined with some of the remaining methods in order to perform ranking of the alternatives.

When applied in mining, multi-criteria decision-making methods such as AHP and fuzzy perform evaluations using the same objective function and value scale for the criteria. Bitarafan & Ataei (2004) used various fuzzy methods to group the criteria in decision-making process in the mining industry.

TOPSIS is defined as “an approach to identify an alternative, which is closest to the ideal solution and farthest to the negative ideal solution in a multi-dimensional computing space” (Qin *et al.*, 2008). The advantages of this method are its simplicity and the fact that it maintains the same amount of steps regardless of problem size (Ic, 2012). Disadvantages of the TOPSIS are that it does not consider the correlation of attributes and it is difficult to keep consistency of judgment, especially with additional attributes.

ELECTRE is the multi-criteria decision-making method of selecting the best solution among the alternatives. The author of this method is Roy (1991). It was created as a response to the shortcomings of existing methods for resolving decision-making problems. ELECTRE has progressed through several versions (I to IV). All the versions are based on the same fundamental concept, but differ in steps.

PROMETHEE is an outranking method and similar to ELECTRE. This method includes the PROMETHEE I for partial ranking of the alternatives and the PROMETHEE II for complete ranking of the alternatives. The further development has produced a several new versions of the PROMETHEE methods. For instance, the PROMETHEE III is developed for ranking based on interval. The PROMETHEE IV is made for complete or partial ranking of the alternatives, when the set of viable solutions is continuous. The PROMETHEE V is developed for problems with segmentation constraints, and the PROMETHEE VI for the human brain representation (Behzadian *et al.,* 2010). It is easy to use and it does not require the assumption that the criteria are proportionate. The disadvantages of PROMETHEE are that it does not provide a clear method for weights assignment and it requires the assignment of values, but does not provide a clear method for assignment those values (Velasquez & Hester, 2013).

Also, many authors have combined two different methods for selecting the best alternative in many areas. In mining industry, the combination of Fuzzy AHP and Fuzzy TOPSIS methods is used for selecting the best alternative – shaft sinking method (Yazdani *et al.,* 2010). Also, Bogdanovic *et al.* (2012) has used the integrated AHP and PROMETHEE approach for mining method selection in the “Coka Marin” underground mine in Serbia.

This paper shows the combined AHP – ELECTRE method for selecting the optimal technology in surface mining of mineral deposits. AHP method is used to analyse the structure of selection process regarding surface mining technology and to determine the criteria weight coefficients. ELECTRE method was used later for final ranking of alternatives (applicable technologies).

AHP AND ELECTRE METHODS

AHP method

Analytical Hierarchy Process (AHP) is a method developed by Saaty (1980) as a powerful tool for multi-criteria decision-making.

Lee *et al.* (2001) define the AHP as a quantitative technique that allows the structuring of complex multi-criteria problem as well as the methodology that is widely used in decision-making.

AHP involves the decomposition of a complex problem of multi-criteria decision-making into a multi-dimensional hierarchical structure of objectives, criteria and alternatives. The decomposition is performed on the basis of previous studies, research and empirical experiences. Once the hierarchy is developed, the assessment of criteria effects is performed, followed by the comparison of the alternatives with respect to each criteria and determining of the overall priority of each alternative and the final ranking of alternatives.

The assessment of the relative impact of each criterion and comparing the alternatives with regards to the criteria is performed via a table – comparison matrix. This process includes the following three tasks:

- formation of comparison matrix at each level of the hierarchy, starting from the second level down;
- calculation of weight coefficients for each element of the hierarchy and
- estimation of the consistency level in order to check the consistency of the entire process.

Comparison matrix is formed by a decision maker or an expert, comparing the criteria according to their importance in relation to the ultimate goal decision-making, based on the score scale ranging from 1 to 9 – Table 1.

Table 1. Comparison scale of decision-making elements

Domination	
Description	Rating
Equal	1
Poor domination	3
Intensive domination	5
Very Intensive domination	7
Absolute domination	9
2, 4, 6, 8 represent intermediate values	

After the comparison and formation of the corresponding matrix, the weight coefficients are calculated, which results in a coefficient vector w = [w1, w2,. . . , wn], calculated on the basis of the Saaty procedure, where n represents the number of coefficients (criteria).

After the comparison is performed, the next step is checking of the consistency level. The consistency level should have a value of less than 0.1 (Saaty, 1980). Otherwise, the values entered into the comparison matrix must be re-examined.

Determining the final ranking of the alternatives is made by synthesis of the results obtained at all levels.

ELECTRE method

ELECTRE method compares the actions in pairs. Firstly, the level of compliance between weight coefficients, preferences and paired dominance relations is examined, followed by the non-compliance level by which the weight grade of the individual actions differs. That is the prime reason why ELECTRE method is sometimes referred to as the compliance analysis. It was one of the first methods, which introduced the possibility of quantification into qualitative decision-making. In order to resolve the problem, the first step is to define the alternatives, followed by selecting the criteria important in decision-making. The criteria are awarded different weights, depending on the importance of each criteria, and the number of all weights must be equal to 1. ELECTRE method consists of input, containing the decision-making matrix and criteria weight, as well as the nine steps. The steps in resolving the matter are:

1. Calculating the normalized decision-making matrix
2. Calculating the weighted normalized decision-making matrix
3. Determining the sets of compliance and non-compliance
4. Computing the approval matrix
5. Calculating the disagreement matrix
6. Calculating the matrix of domination by compliance
7. Calculating the matrix of domination by non-compliance
8. Calculating the aggregate dominance matrix
9. Eliminating the weakest alternatives

In the actual process of eliminating the values of less desirable actions, it is necessary to analyse the domination situation for all the possible combinations of action pairs. The action with a higher number of elements (mad = 1) dominates over the others, while in a situation where the number of such elements is not the same, it is not possible to determine the state of domination. The same conclusion on the absence of dominance among individual actions can be made in the case of actions, where all elements are mad = 0. Here, the mad value is obtained in the eighth step of ELECTRE process – calculating the aggregate dominance matrix. Since the situations of being unable to define the domination state by ELECTRE method are common, the method itself therefore belongs to the group of methods used to determine the sequence of partial preferences.

AHP-ELECTRE COMBINED METHOD

Both methods (ELECTRE and AHP) have certain advantages and disadvantages, and both can be independently used to select the optimal technology. The basic idea of this paper is to minimize weaknesses, and to maximize the advantages of these two methods through the process of their integration and combination of their procedures.

After the comparative analysis of the two decision-making methods, it has been concluded that certain characteristics of AHP method can improve the application of ELECTRE method at the level of structuring the decision-making problems and determining weight coefficients. The weight coefficients of the criteria obtained by the AHP method possess higher levels of connectedness, a better correlation, consistency and precision than the coefficients obtained on the basis of intuition and expert knowledge domain, which is mostly used in the ELECTRE method.

The proposed combined AHP-ELECTRE method for the selection of the optimal technology of surface mining contained in this paper, consists of four main phases: (1) data collection, (2) AHP calculations, (3) Electro calculations, (4) decision-making.

In data collection phase, the alternatives (the applicable surface mining technologies) and the criteria that will be used for their evaluation are defined. Likewise, a hierarchy of decision-making is formed at this stage.

In the second stage, AHP calculations are performed in terms of the formation of comparison matrix and determination of the criteria weights. The individual criteria are evaluated using the scale shown in Table 1. Criterium Decision Plus software is used for that purpose.

In the third phase – ELECTRE calculations, priorities of mining methods are defined. In doing so, the appropriate parameters are determined in nine steps, by the author, as required by the method. Within the last stage – decision-making, the best (optimal) surface mining technology is selected based on rankings obtained by the ELECTRE method.

Schematic representation of the proposed approach is shown in Figure 1.

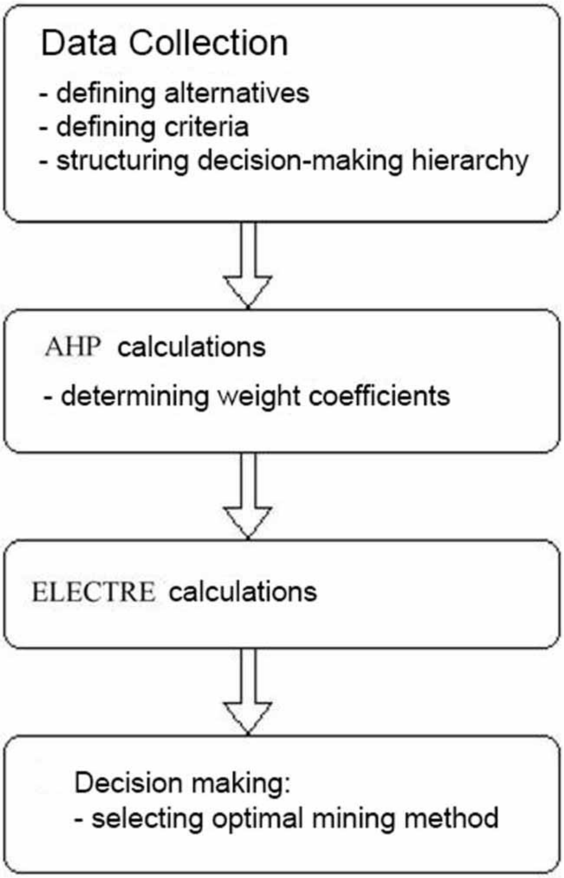

Fig. 1. Schematic representation of the proposed approach

NUMERICAL EXAMPLE

The proposed approach is considered in the selection of optimal technology for surface mining of coal body "Ugljevik East." This deposit is situated about 20 kilometres west of Bijeljina, which is the second largest town in the Republic of Srpska, and 5 km southeast of a nearby small town Ugljevik. For the exploitation purpose of this deposit, a rectangular shape open pit has been designed, being 3 km wide and 1.5 km long. Maximum depth of the open pit coal mine is 210m. Mine optimization has been performed for several variants, with each variant containing different amounts of coal and overburden, which had different economic effects. Optimal exploitation contour of the open pit coal mine "Ugljevik East" includes 55 million tons of coal and 350 million m^3 of overburden. Mine design parameters are determined by a number of factors such as physical-mechanical properties of rock material, coal quality, the intensity of surface mining in the terms of horizontal and vertical aspect and so on.

Vertical division of the open pit was done by 10 meter levels. Final angle of the slopes is within the range of 20-25^o, while the minimum width of floor levels in the final stage is from 20-25 m.

Technical design of opening the pit mine and direction of surface mining both in vertical and horizontal aspect, influences the execution efficiency of the operational plan and mining production aimed at the goals set. The main goal in the open pit coal mine “Ugljevik East” is to ensure a continuous coal supply of a certain quality, in the amount of 1.8 million ton/year.

Table 2. contains physical-mechanical characteristics of the deposit “Ugljevik East”.

Data collection

Based on the optimal contour of the open pit coal mine, location and method of opening, selection of available overburden landfills, as well as the geological, hydrological, physical-mechanical, mining, technical and technological characteristics of the deposit, and of course, the economic factors (Table 2), the following potentially applicable surface exploitation technologies of Ugljevik East open pit coal mine have been discussed, including the following: discontinuous (A_1), combined (A_2) and continuous (A_3). Discontinuous technology involves excavating and loading of coal and overburden utilising hydraulic front loaders, high-capacity lorry transport and disposal of overburden using bulldozers. The combined technology (front loader, lorry, crusher, conveyor, stacker) is reflected in the discontinuous process of excavation and loading overburden and coal into trucks, transport to the crusher plant, crushing to a specific particle size, transport of overburden and coal by belt conveyors and disposal of overburden with the use of stacker. The continuous technology - front loader, conveyor, stacker, includes excavation using bucket-wheel excavators, transportation by belt conveyor and disposal using stacker.

It is known today that continuous technology represents the most cost effective method of integrating the basic production process of digging, loading, transport and disposal. Likewise, it is a fact that the largest capacities of coal and overburden in the world were obtained utilising continuous technology. The main advantages of continuous technology are achievement of greater capacity with lower specific costs of energy, materials, labour, etc. thus, reducing the specific costs per unit of overburden and mineral resource.

Proportionally speaking, transport comprises a major section of the structure of both investment and operating costs, when referring to surface exploitation. Apart from the undeniable advantages of continuous technology, it has a number of disadvantages from the standpoint of reliability of the complex, organizational requirements, and, in particular, restrictions on the introduction and implementation. In fact, this technology requires a number of clearly defined geological and mining-technological conditions, which must be met with little tolerance, in order to be introduced and applied rationally.

Table 2. Physical-mechanical characteristics of the deposit “Ugljevik East”

Parametre	Unit	Coal	Lower coal bed	Hanging wall layer
Volume mass	t/m3	1.35	1.95-2.85	1.8-2.3
Moisture	%	6.7	12-20	5-22
Compressive strength	MPa	45	7	30-100
Tensile strength	MPa	2.5-2.7	0.2-0.3	2.5-5.0
Internal friction angle	degree	35	16	35
Cutting force	kN	17	4-6	8-102
Cutting resistance	kN/cm2	0.085	0.035	0.2-0,60
Cutting resistance	kN/cm1	1.80	0.60-0.85	1.0-8.0
Cohesion	MPa	1.9	0.54	2.0-7.0
Thickness	m	20	10-20	100-180
Slope	degree	25	20-25	25
Depth	m	50-190	70-220	0-180

On the other hand, discontinuous technology has nearly no limits in terms of its application, meaning it is a flexible complex that puts it into the category of more reliable systems. The main drawback of this technology is high level of dependency on weather conditions and relatively high operating costs, which are mainly the result of oil and material prices, maintenance, labour costs, and the relatively large adverse impact onto the environment.

In complex mining - geological conditions, such as the deposit "Ugljevik East", the combined technology of surface mining might present the optimal solution provided that all the aspects are analysed in detail, concerning the application potential, amount of required investment in the procurement procedure, operating costs, etc.

Table 3 presents the criteria, which determine the selection of exploitation technology of deposit "Ugljevik East". These criteria include the most important factors for selecting the appropriate surface mining technology of the coal deposit.

Table 3. Criteria for selecting surface mining technology

Criteria	Title
C_1	Hydrological and hydrogeological characteristics
C_2	Physical and mechanical properties
C_3	Reliability of the system
C_4	Utilization of the resource
C_5	Disposal of overburden
C_6	Coal mining costs
C_7	Operational safety
C_8	Environmental protection

There are three hierarchy levels in decision-making. The first level of the hierarchy is the overall goal of the decision-making process - selecting optimal surface mining technology. The criteria are on the second level, while the alternatives are on the third level of the hierarchy.

The hydrogeological and hydrological conditions have significant influence regarding the selection of technology. The experience in the existing open pit coal mine Bogutovo Selo indicates that the number of non-working days, due to bad climatic conditions, is about 100 days a year.

When referring to physical-mechanical characteristics of a working environment, it is evident that much of the overburden mass cannot be extracted by continuous systems due to increased digging resistance. Likewise, such working environment characteristics cannot present a guarantee in terms of stability, especially of the southern lower coal bed side, which is of great importance, when referring to a continuous system set up, in terms of safety. On the other hand, the abrasiveness of the material contributing to wear and tear of dump truck tires is somewhat relevant as well. So. it is very important to adjust the technology and mineralogical (Alshemari *et al.,* 2013) and physical-mechanical characteristics of coal and overburden.

From the perspective of system reliability, it is evident that the reliability of the discontinuous technology is the highest, followed by the combined and continuous technology.

When it comes to the deposit utilisation, applying the continuous technology has the lowest utilisation level as a result, while having the highest level of losses and dilution.

When it comes to overall operating costs, the lowest cost is in the application of continuous technology, followed by the combined technology, while the discontinuous technology is the most expensive.

When referring to environmental standards, due to the high emissions level resulting from burnt fuel, waste oil and grease, as well as the dust caused by the movement of machinery, and the high noise and vibration level, the discontinuous technology presents, without doubt, the least favourable solution, followed by mixed and discontinuous technology. Also, it must be taken into account the correlation between mining technology and possible indelible mark of mining and its waste on environment (Duane, 2014).

The same is the case, when it comes to operational safety and health of employees.

AHP calculations

Based on the decision-making hierarchy for selecting optimal technology of surface mining, the weight coefficients of the criteria that will be used in the evaluation process shall be determined using AHP method.

With regards to that, the set of technologies applicable for surface mining of "Ugljevik East" deposit, can be marked as $A = \{A_1, A_2, A_3\}$, and a set of selection criteria can be marked as $C = \{C_1, C_2, \ldots, C_8\}$. On that basis, the comparison matrix is using the scale shown in Table 1. Table 4 contains this comparison matrix (size 8x8), obtained on the basis of empirical evaluation of the decision-maker in order to determine the importance of each criterion for selecting the optimal surface mining technology. By using Criterium Decision Plus software, the maximum vector relevant to the criteria has been obtained.

Table 5 contains the results of calculations based on the comparison matrix.

Table 4. Comparison matrix for the criteria

Criteria	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8
C_1	1	1/3	1/3	1/7	1/6	1/7	1/6	1/3
C_2		1	1	1/2	2	1/4	1/3	1/2
C_3			1	1	3	1/3	1/2	1/2
C_4				1	2	1/2	1/3	1
C_5					1	1/3	1/3	1/3
C_6						1	2	2
C_7							1	1
C_8								1

Schematic representation of the contribution (%) of criteria on ranking of alternatives is shown in Figure 2.

Table 5. Results obtained by AHP calculations

Criteria	Weight coefficients	Consistency level
C_1	0.057	0.099
C_2	0.078	
C_3	0.096	
C_4	0.134	
C_5	0.043	
C_6	0.258	
C_7	0.196	
C_8	0.139	

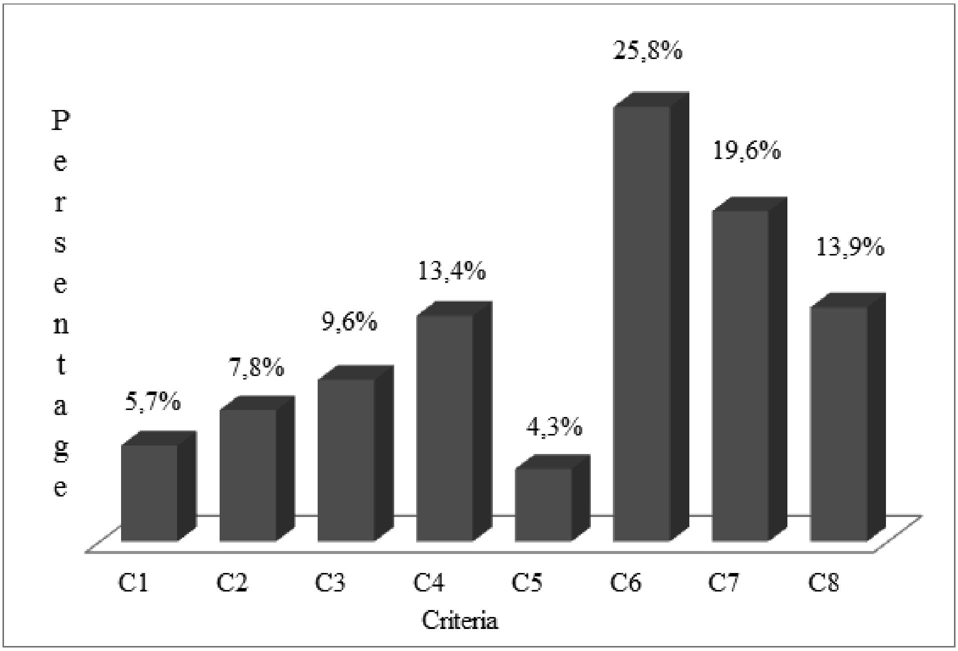

Fig. 2. Contribution (%) of criteria on ranking of alternatives

Table 5 and Figure 2 shows the values for the impact of different criteria on selecting alternatives. The higher value, the higher impact of the criteria onto the selecting process. For example, criteria C_6 (coal mining costs) affects with 0.258, i.e. 25.8% in decision making process, and it is the strongest criteria (the most influencing criteria). Otherwise, criteria C_5 is the weakest criteria as its value is the lowest. Criteria C_5 affects only with 0.043, i.e. 4.3% in decision making process. The reason lies in the fact that the open pit coal mine “Ugljevik East” has sufficient space available for disposal of overburden.

On the basis of AHP calculations performed, it can be seen that the selection of optimal surface mining technology of "Ugljevik East" deposit is influenced mainly by the following criteria: operating costs (C_6), operational safety (C_7), environmental protection (C_8), and the utilization of the resource (C_4). Since the consistency level is 0.099, which is less than 0.1, the results (criteria weight coefficients) can be used in further decision-making process.

ELECTRE calculations

Based on the criteria, an evaluation of exploitation technology is made and the evaluation matrix is formed. In the process, some criteria are of a quantitative structure, while others are of a qualitative or uncertain structure, which cannot be precisely defined and measured. Accordingly, certain criteria (C_4 and C_6) were expressed by a quantitative score, while others are expressed using qualitative assessments. Using quantitative and qualitative assessment ensures that all criteria are treated equally and used in the calculation. Table 6 contains a five-level qualitative scale, as well as the corresponding numerical values for each qualitative assessment.

Table 6. Qualitative scale

Qualitative assessment	Very low	low	medium	high	Very high
Numerical values	1	2	3	4	5

By using interval scale ranging from 1 to 5, a quantified decision-making matrix is obtained – Table 7.

Table 7. Quantified decision-making matrix

	Criteria C_1	Criteria C_2	Criteria C_3	Criteria C_4	Criteria C_5	Criteria C_6	Criteria C_7	Criteria C_8
Criteria type	max	max	max	max	max	min	max	max
Alternative A_1	5	4	5	95	3	1.7	5	4
Alternative A_2	3	4	3	92	4	1.5	4	4
Alternative A_3	3	5	1	90	4	1.3	4	4

In the following, the steps in resolving the matter by ELECTRE are performed by ELECTRE software.

Step I: Calculating normalized decision-making matrix.

Normalized decision-making matrix elements are calculated as follows:

- with max type criteria:

$$n_{ij} = \frac{c_{ij}}{Norma_j} = \frac{c_{ij}}{\sqrt{\sum_{i=1}^{m} c_{ij}^2}} \tag{1}$$

- with min type criteria:

$$n_{ij} = 1 - \frac{c_{ij}}{Norma_j} = 1 - \frac{c_{ij}}{\sqrt{\sum_{i=1}^{m} c_{ij}^2}} \tag{2}$$

Based on the data for this example, a normalized decision-making matrix is obtained – Table 8.

Table 8. Normalized decision-making matrix

	Criteria C_1	Criteria C_2	Criteria C_3	Criteria C_4	Criteria C_5	Criteria C_6	Criteria C_7	Criteria C_8
Alternative A_1	0.7625	0.5298	0.8452	0.5939	0.4685	0.6505	0.6623	0.5774
Alternative A_2	0.4575	0.5298	0.5071	0.5751	0.6247	0.5740	0.5298	0.5774
Alternative A_3	0.4575	0.6623	0.1690	0.5626	0.6247	0.4974	0.5298	0.5774

Step II: Calculation of weighted normalized decision-making matrix.

The matrix of selected weighted coefficients is as follows:

$$TN = N \cdot T \tag{3}$$

where:

$$T = \begin{bmatrix} t_1 & \cdots & \cdots & 0 \\ \cdots & t_2 & \cdots & \cdots \\ \cdots & \cdots & \cdots & \cdots \\ 0 & \cdots & \cdots & t_n \end{bmatrix} \tag{4}$$

and N is the normalized decision-making matrix. The sum of the diagonal matrix elements of the weight assigned to individual attributes (T) must be equal to one, i.e.

$$\sum_{j=1}^{m} t_j = 1 \tag{5}$$

By multiplying the normalized matrix and the matrix of selected weight coefficients, a weighted normalized decision matrix is obtained – Table 9.

Table 9. Weighted normalized decision-making matrix

	Criteria C_1	Criteria C_2	Criteria C_3	Criteria C_4	Criteria C_5	Criteria C_6	Criteria C_7	Criteria C_8
Alternative A_1	0.04346	0.04133	0.08113	0.07958	0.02015	0.16783	0.12980	0.07967
Alternative A_2	0.02608	0.04133	0.04868	0.07707	0.02686	0.14808	0.10384	0.07967
Alternative A_3	0.02608	0.05166	0.01623	0.07539	0.02686	0.12834	0.10384	0.07967

Step III: Determining sets of compliance (S) and non-compliance (NS).

Action pairs are compared in this step. Actions that are being compared are labelled with “p” and “r” (p,r = 1, 2, ..., m and p ≠ r). First, a set of compliance (S_{pr}) is formed, for the actions a_p and a_R, which consists of all the criteria (J = j and j = 1,2, ..., n), for which the action a_p is preferable to the action a_r, i.e.

$$S_{pr} = \left(j \middle| x_{pj} \geq x_{rj}\right) \tag{6}$$

If there is a minimum type criterion, the inequality sign is opposite (≤). Then, a complementary set of non-compliance is formed, for which the following is applied:

$$NS_{pr} = \left(j \middle| x_{pj} \prec x_{rj}\right) = J - S_{pr} \tag{7}$$

If there is a minimum type criterion, the inequality sign is opposite (>).

Step IV: Determining compliance matrix (MS)

Compliance matrix is calculated based on the compliance sets, as calculated in the previous step. The elements of this matrix are composed of compliance indices. Their value is calculated as the sum of preferences (weight coefficients), which correspond to the corresponding elements of compliance sets. The compliance index S_{pr} for the actions a_p and a_r is calculated as:

$$MS_{pr} = \sum_{j \in S_{pr}} t_j \tag{8}$$

S_{pr} value ranges in the interval from 0 to 1. The closer the index value is to number one, the action a_p is more preferable to the action a_r (according to the compliance criteria). The compliance indices form a compliance matrix, which contains elements equal to zero on the main diagonal, since the alternative is not compared to itself. Compliance matrix is given in Table 10.

Table 10. Compliance matrix

Alternative A_1	0	0.69900	0.62100
Alternative A_2	0.51700	0	0.66400
Alternative A_3	0.51700	0.77000	0

Step V: Determining a non-compliance matrix (MNS).

Non-compliance matrix elements consist of non-compliance indices, which are calculated as follows, using the TN matrix (weighted normalized matrix):

$$MNS_{pr} = \frac{\max\limits_{j \in NS_{pr}} \left| t_{pj} - t_{rj} \right|}{\max\limits_{j \in J} \left| t_{pj} - t_{rj} \right|} \tag{9}$$

The non-compliance index ranges from 0 to 1 and indicates how much is the alternative a_r preferable to the alternative a_p. The higher the inconsistency index is (closer to one), according to the non-compliance criterion, the alternative a_p is less desirable than the alternative a_r. The non-compliance indices are calculated based on the weighted normalized decision-making matrix (TN) and the set of non-compliances for the observed alternatives (ns_{pr}). On this basis, the non-compliance matrix is calculated – Table 11.

Table 11. Non-compliance matrix

Alternative A_1	0	0.60863	0.60847
Alternative A_2	1	0	0.60832
Alternative A_3	1	1	0

Step VI: Determining the compliance dominance matrix (MSD).

The elements of this matrix are calculated on the basis of the compliance index threshold. The Compliance index threshold is defined as the average compliance index, calculated by the following formula:

$$PIS = \sum_{\substack{p=1 \\ p \neq r}}^{m} \sum_{\substack{r=1 \\ p \neq r}}^{m} \frac{MS_{pr}}{m(m-1)} \tag{10}$$

Based on the obtained values of the average compliance index, it can be said that the action a_p is likely to be preferable to the action a_r, only if its corresponding compliance index MS_{PR} exceeds the value of an average compliance index. The compliance dominance matrix is based on the following criteria:

$$\begin{aligned} MSD_{pr} &= 1 \quad for \quad MS_{pr} \geq PIS \\ MSD_{pr} &= 0 \quad for \quad MS_{pr} \prec PIS \end{aligned} \tag{11}$$

Compliance dominance matrix for the following example is given in Table 12.

Table 12. Compliance dominance matrix

Alternative A_1	0	1	0
Alternative A_2	0	0	1
Alternative A_3	0	1	0

Step VII: Determining incompatible dominance matrix.

Similar to the previous step, the incompatible dominance matrix is calculated by first calculating the average non-compliance index using the following formula:

$$PINS = \sum_{\substack{p=1 \\ p \neq r}}^{m} \sum_{\substack{r=1 \\ p \neq r}}^{m} \frac{MNS_{pr}}{m(m-1)} \tag{12}$$

Incompatible dominance matrix is formed on the basis of the following criteria – Table 13.

Table 13. Incompatible dominance matrix

Alternative A_1	0	1	1
Alternative A_2	0	0	1
Alternative A_3	0	0	0

Step VIII: Determining aggregate dominance matrix (MAD).

This matrix is obtained as the product of the matrix elements position and the non-compliance dominance matrix (not a conventional matrix calculus) as follows:

$$MAD_{pr} = MSD_{pr} \cdot MNSD_{pr} \tag{13}$$

Aggregate dominance matrix is shown in Table 14.

Table 14. Aggregate dominance matrix

Alternative A_1	1	0
0	Alternative A_2	1
0	0	Alternative A_3

Step IX: Eliminating unwanted actions.

If the MAD_{pr} value = 1, then the action a_p dominates the action A_r, by both criteria (compliance and non-compliance). However, that does not exclude the possibility of having another alternative that dominates the a_p. It is therefore necessary to fulfil another condition:

$MAD_{pr} = 1$ for at least one r, r = 1, 2, ..., m and $p \neq r$

$MAD_{pr} = 0$ for all i, i = 1, 2, ..., m and $p \neq r$ and $i \neq r$

To determine which action is dominant, it is necessary to examine the dominance state of the possible combinations of action pairs. The action with a higher number of elements $MAD_{pr} = 1$, dominates the other actions. In the situation where the number of such elements is the same, it is not possible to determine the dominance state. The conclusion about the absence of dominance between individual actions is made, when all the elements are $MAD_{pr} = 0$ for a certain action. Since the inability to define the dominance state by this method occurs frequently, the ELECTRE method belongs to a group of methods for determining the sequence of partial preferences. The following analysis is performed in the process:

The alternative A_1 dominates the alternative A_2.
The alternative A_2 dominates the alternative A_3.
The alternative A_3 does not dominate over any action.
List of best action: A_1, A_2 and A_3.

The results indicate that the best alternative is the A_1 (discontinuous method), followed by the alternative A_2 (combined method), with the alternative A_3 (continuous method) in the last place.

Decision-making

The use of combined AHP and ELECTRE method, it has been concluded that the best (optimal) method for excavating the deposit "Ugljevik East" is the alternative A_1 (discontinuous method).

CONCLUSION

In this paper, the multi-criteria decision-making method was used in order to select the optimal technology of surface exploitation of the coal deposit "Ugljevik East." The selection of optimal surface exploitation technology is one of the most important decisions in mining project management. The selection process requires considering a number of criteria such as mining-geological, economic and mining-technical factors. Selecting the optimal mining method is based on the comparison of applicable methods in accordance with the relevant criteria.

Accordingly, the paper used the combined method of AHP and ELECTRE decision. The proposed approach differs from the previously used methods used for the selection of the optimal surface exploitation technology for the deposit "Ugljevik East." In this approach, AHP method is used to determine the weight coefficients of criteria for selecting surface exploitation technology for the deposit "Ugljevik East" and ELECTRE method for the complete ranking of the alternatives. The weight coefficients are obtained by AHP calculations used in ELECTRE calculation, so that the ranking of alternatives is done based on these weight coefficients. The operation has shown that the calculation of criteria weight coefficients is essential in the application of ELECTRE method, and that they can change the order of ranking of alternatives.

The proposed combined method can be of great assistance to decision makers, since it allows easy analysis of influential factors and parameters. The advantages of this approach over existing methods are as follows: AHP method allows you to obtain much more precise and more consistent criteria weight coefficients, ELECTRE method uses a certain procedure in nine steps and each criterion is evaluated on a variety of grounds, which helps obtain better results (decisions). In addition, ELECTRE method provides the final ranking of alternatives. All these features are not characterised by the other methods such as AHP, fuzzy AHP, TOPSIS, etc.

Accordingly, on the basis of the results obtained from the combined AHP and ELECTRE methods, the selected surface mining technology of the deposit "Ugljevik East" is a discontinuous method (alternative A_1), with the most influential criteria for the complete ranking of alternatives (mining method) is the criteria C_6 – operating costs and criteria C_7 – operational safety.

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اختيارالتكنولوجيا الأمثل للتعدين السطحي بالتحليل متعدد المعايير

***كفيتكوستويانوفيتش، **ديان بوغدانوفيتش، **وسنيزانا أوروسيفيك**

*إدارة للاستثمارات والتنمية وتصميم المشروع - والأعمال المتعلقة بالألغام ويوليفتش الطاقة الحرارية
-يوليفتش البوسنة والهرسك ، cvele.stojanovic@gmail.com
** إدارة الشؤون الإدارية - جامعةبلغراد - «كليةالتقنية» فيبور- بور- صربيا

خلاصة

اختيار التكنولوجيا المثلى للتعدين السطحي للرواسب المعدنية هي مشكلة قياسية في صنع القرار. الهدف من هذه الورقة لإثبات إمكانية الجمع بين أساليب AHP و الأساليب الكهربائية في اختيار التكنولوجيا الأمثل مع استخدام حفرة الفحم المفتوحة للالغام (الفحم الشرقي) كمثال. من أجل حل المشاكل التي نواجهها، تم اتخاذ ثلاثة أنواع من التقنيات بعين الاعتبار فيما يتعلق بالمعايير الثمانية لاختيار الحل الأمثل. وتشمل المعايير الجوانب الأكثر أهمية لتحديد التكنولوجيات المثلى، مثل الجيولوجيا وميكانيكا التربة، الهندسة، وعلم البيئة، والاقتصاد، إلخ. وبالإضافة إلى ذلك، يتم استخدام AHP لتحليل هيكل عملية اختيار التكنولوجيا، وتحديد أهمية وتأثير معايير معينة في عملية الاختيار، في حين يتم استخدام الأسلوب الكهربائي للترتيب النهائي للبدائل. النتائج التي تم الحصول عليها تشير إلى أن الأسلوب المشترك المقترح يوفر نتائج بدقة غير عادية ، وأنه يمكن استخدامه لحل مختلف المشاكل الأكثر تعقيداً التي تحدث في هندسة التعدين.

الكلمات الرئيسية: AHP ، صناعة القرار؛ تكنولوجيا التعدين السطحي.

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