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Multiple Criteria Approach in the Mining Method Selection[4]

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***Abstract**: Underground mining method selection is a very complex task for the mining engineers because the chosen method should fulfill the technical, economic and production requirements. Combining the criteria that cover different aspects of the mining operation and group decision-making increases the reliability of the decisions and minimize its subjectivity. The main objective of this paper is to propose the methodology for the underground mining method selection based on the Extended Pivot Pairwise Relative Criteria Importance Assessment (PIPRECIA-E) and group decision-making. The applicability of the proposed methodology is demonstrated by using the numerical example inclusive of 3 main criteria, 18 sub-criteria and 5 alternative underground mining methods pointed to the exploitation of the Upper Zone of the Čukaru Peki deposit in Serbia.*

***Keywords**: Multiple-Criteria Decision-Making, PIPRECIA-E, group decision-making, underground mining method selection, Čukaru Peki.*

Višekriterijumski pristup izboru metode rudarenja

***Apstrakt**: Izbor metode za podzemnu eksploataciju predstavlja veoma kompleksan zadatak za rudarske inženjere zato što izabrana metoda treba ispuniti tehničke, ekonomske i proizvodne zahteve. Uključivanje više*

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kriterijuma koji uzimaju u obzir različite aspekte rudarske proizvodnje kao i grupno odlučivanje doprinosi povećanju pouzdanosti odluka i smanjenju subjektivnosti. Osnovni cilj ovog rada je predlaganje metodologije za izbor metode podzemne eksploatacije bazirane na PIPRECIA-E metodi (Extended Pivot Pairwise Relative Criteria Importance Assessment) i grupnom odlučivanju. Primenljivost predložene metodologije prikazana je pomoću numeričkog primera koji uključuje 3 osnovna kriterijuma, 18 podkriterijuma i 5 alternativnih metoda podzemne eksploatacije planiranih za primenu u Gornjoj zoni ležišta Čukaru Peki u Srbiji.

***Ključne reči**: Višekriterijumsko odlučivanje, PIPRECIA-E, grupno odlučivanje, izbor metode rudarenja, Čukaru Peki.*

1. Introduction

One of the most important and requiring decisions that mining engineers have to make is certainly a selection of the underground mining method. The ore production, lost rate, safety and overall production productivity (Liu, Dong, & Dong, 2010) depend on the chosen mining method. Decisions connected to this kind of problem are characterized by a lack of geological information and uncertainty which complicates the decision-making process and leads to the final decisions that are often subjective.

Ensuring the optimal use of underground resources is the main goal of the mining method selection (Alpay & Yavuz, 2007). Besides, the selected method should enable the obtaining of the maximum profit, low excavation cost, and safe working conditions for the miners (Ataei, Jamshidi, Sereshki, & Jalali, 2008; Bogdanovic, Nikolic, & Ilic, 2012). Generally, each of the available methods is followed by certain issues and the one which brings the least number of problems could be considered the optimal method.

In order to obtain an optimal decision, all relevant criteria should be involved in the underground mining method selection process. The greater number of criteria important for the evaluation will certainly complicate the decision-making but gained results would be more accurate and reliable (Naghadehi, Mikaeil, & Ataei, 2009). Basing the selection on only one factor or on the intuition of one person would lead to inadequate decisions.

The fact that the underground mining method selection should be based on the greater number of evaluation criteria contributes to the conclusion that the Multiple-Criteria Decision Making (MCDM) methods are suitable for the application in this area. MCDM represents a field of management science and operational research that has significantly developed in recent years and enabled easier resolving of many business problems. A good overview of the introduced MCDM methods could be found in the papers of the following authors: Velasquez & Hester (2013), Zavadskas, Turskis, & Kildienė (2014) and Mardani et al. (2015). Different combinations of these methods are used in resolving various business and optimization problems (Pamučar, Lukovac, Božanić, & Komazec, 2018; Milosavljević, Bursaća, & Tričković, 2018; Vesković, Stević, Stojić, Vasiljević, & Milinković, 2018).

Until today, many scientists dealt with the question of the underground mining method selection by using different MCDM methods. Mahase, Musingwini, & Nhleko, (2016) give a good overview of the MCDM methods applied in the area of mine planning and similar cases. According to the current situation, the Analytic Hierarchy Process – AHP (Saaty, 1980) represents the technique that is very popular and widely used for the mining method selection (Ataei et al., 2008; Alpay & Yavuz 2009; Gupta & Kumar, 2012; Yavuz, 2015a). Also, the combination of the MCDM methods as well as the fuzzy extensions of the methods are very often applied for the same purpose (Bitarafan & Ataei, 2004; Karadogan, Kahriman, & Ozer, 2008; Samimi Namin, Shahriar, Ataee-Pour, & Dehghani, 2008; Bogdanovic et al., 2012; Ataei, Shahsavany, & Mikaeil, 2013; Karimnia & Bagloo, 2015).

The main aim of this paper is to point out the advantages of the PIPRECIA-E method (Stanujkic, Zavadskas, Karabasevic, Smarandache, & Turskis, 2017), which is especially suitable for application in the group decision-making environment. The applicability of the proposed methodology is presented by the numerical example that involves 3 decision-makers (hereinafter marked as DM), 3 main criteria, 18 sub-criteria, and 5 alternative mining methods. The central goal is defining the optimal mining method which will be used for the exploitation of the Upper Zone of the Čukaru Peki deposit.

Except for the Introduction and the Conclusion, the rest of the paper is organized as follows: in the second part the proposed methodology is explained and in the third part the numerical example which contains the application of the proposed methodology is presented, as well as the gained results discussion.

2. Methodology

In this case, for resolving the mining method selection problem PIPRECIA-E technique, introduced by Stanujkic et al. (2017), is proposed. The starting point for the creation of the mentioned method was SWARA method (Keršuliene, Zavadskas, & Turskis, 2010). Namely, the PIPRECIA-E retains the good features of SWARA method and overcomes its deficiencies. The SWARA method is not very suitable for group decision-making because its procedure requires pre-sorting of the considered criteria, that complicates the consolidation and determining of the final results. Besides, SWARA method does not anticipate checking the consistency of gained results, which is a part of the procedure of well-known AHP method (Saaty, 1980).

Contrary to SWARA method, the PIPRECIA-E method does not require the previous sorting of the evaluation criteria, which makes it more suitable for the application in the group decision-making environment. PIPRECIA-E implies consistency testing by applying Pearson's or Spearman's correlation. Additionally, the PIPRECIA-E method predicts the bidirectional approach which includes the evaluation of the considered criteria in both directions, i.e. from first to the last and vice-versa. This way of criteria estimation is somewhat complex, but the obtained results are more reliable because decision-makers must thoughtfully perform the evaluation which also contributes to the consistency of the final results.

Until now, PIPRECIA-E method was used for the assessment of tourism projects (Popović, & Mihajlović, 2018). PIPRECIA method, that is an integral part of the PIPRECIA-E method, is used for evaluation of the websites' quality (Stanujkic, Karabasevic, & Cipriana, 2018), consumer satisfaction of the restaurants services (Stanujkic, Karabasevic, Zavadskas, Smarandache, & Cavallaro, 2019a), and the fuzzy extension of the PIPRECIA method is recently proposed (Stević, Stjepanović, Božičković, Das, & Stanujkić, 2018). All of this indicates that the possibilities of the PIPRECIA-E method are not fully tested yet.

The numerical procedure, used in this paper, relies on that one presented in the paper of Stanujkic et al. (2017) and could be illustrated by the following series of steps.

***Step* 1**. Selection of the evaluation criteria where presorting is not obligatory.

***Step* 2**. Determination of the relative importance s_j that begins from the second criterion as follows:

$$s_j = \begin{Bmatrix} >1 & when & C_j \succ C_{j-1} \\ 1 & when & C_j = C_{j-1} \\ <1 & when & C_j \prec C_{j-1} \end{Bmatrix}. \tag{1}$$

***Step* 3**. Definition of the coefficient k_j in the following way:

$$k_j = \begin{Bmatrix} 1 & j=1 \\ 2-s_j & j>1 \end{Bmatrix}. \tag{2}$$

***Step* 4**. Detection of the recalculated value q_j as follows:

$$q_j = \left\{ \begin{matrix} 1 & j = 1 \\ \dfrac{q_{j-1}}{k_j} & j > 1 \end{matrix} \right\}. \tag{3}$$

***Step* 5**. Determination of the relative weights of the estimated criteria by using the following Eq.:

$$w_j = \frac{q_j}{\sum_{k=1}^{n} q_k}, \tag{4}$$

where w_j represents the relative weight of the criterion j.

***Step* 6**. Definition of the inverse relative importance s'_j starting from the penultimate criterion in the following manner:

$$s'_j = \begin{cases} >1 & when \quad c_j > c_{j+1} \\ 1 & when \quad c_j = c_{j+1} \\ <1 & when \quad c_j < c_{j+1} \end{cases}. \tag{5}$$

***Step* 7.** Determination of the inverse coefficient k'_j by using the following Eg.:

$$k'_j = \begin{cases} 1 & j = n \\ 2 - s'_j & j < 1 \end{cases}. \tag{6}$$

***Step* 8.** Definition of the inverse recalculated weight q'_j as follows:

$$q'_j = \begin{cases} 1 & j = n \\ \dfrac{q'_{j+1}}{k'_j} & j < n \end{cases}. \tag{7}$$

***Step* 9.** Determination of the inverse relative weights of the considered criteria in the following way:

$$w'_j = \frac{q'_j}{\sum_{k=1}^{n} q'_k}, \tag{8}$$

where w'_j is the inverse weight of the criterion j.

***Step* 10.** Verification of the reliability of the obtained results by using the Spearman's rank correlation coefficient:

$$\rho = 1 - \frac{6\sum_{i=1}^{n} d_i^2}{n(n^2-1)}, \tag{9}$$

where ρ represents the correlation coefficient, d_i is a distance between the ranks for every x_i, n denotes the number of elements in each data series and $\rho \in [-1,1]$.

Step* 11*. The overall weight w'' of the criteria is calculated by applying the Eq. (10):

$$w_j'' = \frac{1}{2}(w_j + w_j'), \tag{10}$$

where w_j'' represents the final weight of the criterion j.

***Step* 12.** In the case of group decision-making, the final weights of the criteria are determined in the following manner:

$$w_j^* = \left(\prod_{r=1}^{R} w_j^{nr}\right)^{1/R}, \tag{11}$$

$$w_j = \frac{w_j^*}{\sum_{j=1}^{n} w_j^*}, \tag{12}$$

where w_j^{nr} denotes the weight of the criterion j obtained from the respondent r, R represents the number of the respondents, w_j^* is the group weight of the criterion j before the adjustment in order to fulfill the condition $\sum_{j=1}^{n} w_j = 1$, and the w_j is the final group weight of the criterion j.

3. Case study

As we previously stated, the selection of an appropriate underground mining method is not simply tasked for mining engineers because it requires knowledge, experience, and competence. Besides, the problem additionally complicates the possibility of existence of a few methods that could be convenient for applying in particular case but only one of them would certainly enable maximum usage of the available potential. It is very unlikely that one person would be completely sure which alternative i.e. mining method is optimal for application in present conditions.

The reliability of the selected mining method increases in the case when the decision process involves a greater number of *DM*s. Following that idea, the PIPRECIA-E method is used as a technique which is convenient for applying in the group decision environment. Besides, its procedure that predicts consistency checking in two ways contributes to the assurance that the final choice will be optimal.

The applicability of the proposed model is demonstrated through real case study relative to the Čukaru Peki deposit, situated in the Bor district in Serbia, that includes the Upper Zone of high-sulphidation epithermal mineralization and the Lower Zone of porphyry type of mineralization. The fact that, in this deposit, a probable grade of the Cu amounts 3.25%, Au 2.06% and As 0.17% classifies it in the group of the reachest deposits in the world (Nevsun Resources Ltd, 2018). Until now, the pre-feasibility study for the mine development in the Upper Zone and basic resource assessment for the Lower Zone is done. For the purpose of this work, the optimal mining method for the Upper Zone of the Čukaru Peki will be selected because the more detailed pieces of information are currently available.

The evaluation process is based on 3 groups of criteria that involve 6 sub-criteria. The list of criteria and sub-criteria are formed accordingly to the papers of the: Ataei et al. (2008), Naghadehi et al. (2009), Bogdanovic et al. (2012) and Yazdani-Chamzini, Yakchali, & Zavadskas (2012). Three *DM*s, experienced mining engineers, are involved in the decision process. In order to avoid too complex numerical example, the *DM*s selected 6 sub-criteria from every group and using the domination method formed the final list of sub-criteria. Besides, the *DM*s are familiar with the characteristics of the Upper Zone and, on that base, they estimated the given alternatives. In *Table 1* we presented criteria, sub-criteria and mining methods that will be assessed.

Table 1. Criteria, sub-criteria and mining methods

	Criteria		Sub-criteria		Alternatives
T_1	Technical parameters	T_{11}	Ore body thickness	A_1	Room and pilar
		T_{12}	Ore body shape		
		T_{13}	Ore body dip		
		T_{14}	Ore body size	A_2	Room and pillar with fill
		T_{15}	Ore body RMR		
		T_{16}	Ore body RSS		
P_1	Production parameters	P_{11}	Safety	A_3	Shrinkage stoping
		P_{12}	Environmental impact		
		P_{13}	Technology		
		P_{14}	Expert labour		
		P_{15}	Ventilation		
		P_{16}	Underground water		
E_1	Economic parameters	E_{11}	Operating cost	A_4	Cut and fill
		E_{12}	Capital cost		
		E_{13}	Reclamation cost		
		E_{14}	Mineral value	A_5	Sublevel caving
		E_{15}	Minerable ore tonnes		
		E_{16}	Ore body grades		

Source: Ataei et al. (2008), Naghadehi et al. (2009), Bogdanovic et al. (2012) and Yazdani-Chamzini et al. (2012).

In *Table 2* the local weights of the main criteria defined by the Eqs. (1)-(12) are presented. As can be seen, the responses from the *DM*s are completely consistent and acceptable.

Table 2. The local weights of the main criteria

	w''^{1}_{j}	w''^{2}_{j}	w''^{3}_{j}	w^{*}_{j}	w_j
T_1	0.2817	0.3114	0.3333	0.3081	0.3084
P_1	0.3591	0.3443	0.3333	0.3454	0.3458
E_1	0.3591	0.3443	0.3333	0.3454	0.3458
ρ	1	1	1		

Source: Author's calculations

The obtained results show that considered criteria groups have almost equal importance for the *DM*s.

The local weights of the sub-criteria from the group named „*Technical parameters*“, obtained by using Eqs. (1)-(12), are presented in *Table 3*.

Table 3. The local weights of the sub-criteria - „Technical parameters“

	w''^{1}_{j}	w''^{2}_{j}	w''^{3}_{j}	w^{*}_{j}	w_j
T_{11}	0.1162	0.1695	0.1383	0.1396	0.1420
T_{12}	0.0761	0.1534	0.1529	0.1213	0.1233
T_{13}	0.1083	0.1695	0.1529	0.1411	0.1434
T_{14}	0.1926	0.1534	0.1792	0.1743	0.1771
T_{15}	0.2534	0.1771	0.1884	0.2037	0.2071
T_{16}	0.2534	0.1771	0.1884	0.2037	0.2071
ρ	0.83	0.89	1		

Source: Author’s calculations

In the given case the high degree of the consistency of the responses is evident. As the most important sub-criteria T_{15} - *Ore body RMR* and T_{16} - *Ore body grades* singled out.

Table 4 presents the local weights of the sub-criteria from the group „*Production parameters*“. Given results are obtained in the previously explained way which will be used furthermore.

Table 4. The local weights of the sub-criteria – „Production parameters“

	w''^{1}_{j}	w''^{2}_{j}	w''^{3}_{j}	w^{*}_{j}	w_j
P_{11}	0.1323	0.1759	0.1509	0.1520	0.1537
P_{12}	0.1073	0.1591	0.1231	0.1281	0.1296
P_{13}	0.1004	0.1759	0.1508	0.1386	0.1402
P_{14}	0.2200	0.1523	0.1667	0.1774	0.1795
P_{15}	0.2200	0.1684	0.2042	0.1963	0.1985
P_{16}	0.2200	0.1684	0.2042	0.1963	0.1985
ρ	0.97	0.94	0.94		

Source: Author’s calculations

The consistency rate is again on the satisfying level and the highest local weight has the sub-criteria P_{15} - *Ventilation* and P_{16} - *Underground water*.

Table 5 shows the results for the sub-criteria that belongs to the group „*Economic parameters*“.

Table 5. The local weights of the sub-criteria – „Economic parameters“

	w''^{1}_{j}	w''^{2}_{j}	w''^{3}_{j}	w^{*}_{j}	w_{j}
E_{11}	0.0798	0.1429	0.1334	0.1150	0.1172
E_{12}	0.0894	0.1580	0.1233	0.1203	0.1226
E_{13}	0.0894	0.1580	0.1508	0.1287	0.1311
E_{14}	0.2184	0.1747	0.1975	0.1960	0.1998
E_{15}	0.2100	0.1832	0.1975	0.1966	0.2004
E_{16}	0.3129	0.1832	0.1975	0.2246	0.2288
ρ	0.86	0.89	1		

Source: Author's calculations

The obtained results confirmed that the *DM*s were not contradictory with their decisions. In this case, according to the results, the greatest local weight has the sub-criteria E_{16} - *Ore body grades*.

Table 6 demonstrates the global weights of the considered sub-criteria.

Table 6. The global weights of the sub-criteria

Criteria	Global weight of the criteria	Sub-criteria	Local weight of the sub-criteria	The global weight of the sub-criteria
T_1	0.3084	T_{11}	0.1420	0.0438
		T_{12}	0.1233	0.0380
		T_{13}	0.1434	0.0442
		T_{14}	0.1771	0.0546
		T_{15}	0.2071	0.0639
		T_{16}	0.2071	0.0639
P_1	0.3458	P_{11}	0.1537	0.0532
		P_{12}	0.1296	0.0448
		P_{13}	0.1402	0.0485
		P_{14}	0.1795	0.0621
		P_{15}	0.1985	0.0687
		P_{16}	0.1985	0.0687
E_1	0.3458	E_{11}	0.1172	0.0405
		E_{12}	0.1226	0.0424
		E_{13}	0.1311	0.0453
		E_{14}	0.1998	0.0691
		E_{15}	0.2004	0.0693
		E_{16}	0.2288	0.0791

Source: Author's calculations

Every of the considered alternative is estimated relative to each of the sub-criteria involved in the decision process. Based on that evaluation and on global weights of the sub-criteria, the overall importance of the underground mining methods is calculated regarding every separate group of the sub-criteria. The results are shown in the *Table 7*, *8* and *9*, respectively.

Table 7. The overall importance of each mining method according to the sub-criteria - „Technical parameters“

	T_1	T_2	T_3	T_4	T_5	T_6
A_1	0.0094	0.0077	0.0092	0.0107	0.0130	0.0134
A_2	0.0101	0.0085	0.0100	0.0122	0.0134	0.0144
A_3	0.0096	0.0083	0.0096	0.0122	0.0146	0.0146
A_4	0.0101	0.0091	0.0101	0.0127	0.0146	0.0146
A_5	0.0099	0.0090	0.0107	0.0134	0.0161	0.0146

Source: Author's calculations

Table 8. The overall importance of each mining method according to the sub-criteria - „Production parameters“

	P_1	P_2	P_3	P_4	P_5	P_6
A_1	0.0103	0.0078	0.0084	0.0117	0.0128	0.0135
A_2	0.0110	0.0093	0.0098	0.0121	0.0137	0.0140
A_3	0.0107	0.0091	0.0094	0.0125	0.0138	0.0135
A_4	0.0107	0.0096	0.0099	0.0125	0.0138	0.0131
A_5	0.0104	0.0090	0.0110	0.0134	0.0146	0.0145

Source: Author's calculations

Table 9. The overall importance of each mining method according to the sub-criteria - „Economic parameters“

	E_1	E_2	E_3	E_4	E_5	E_6
A_1	0.0079	0.0087	0.0091	0.0138	0.0125	0.0157
A_2	0.0076	0.0086	0.0091	0.0147	0.0129	0.0159
A_3	0.0079	0.0081	0.0091	0.0139	0.0139	0.0157
A_4	0.0091	0.0087	0.0091	0.0139	0.0155	0.0161
A_5	0.0080	0.0083	0.0091	0.0128	0.0145	0.0158

Source: Author's calculations

The overall results and final ranking of the considered mining methods are presented in *Table 10*.

Table 10. The final rank of the mining methods

Mining method	Priority	Rank
A_1	0.1956	5
A_2	0.2072	3
A_3	0.2062	4
A_4	0.2132	2
A_5	0.2150	1

Source: Author's calculations

As the final results show, the best-ranked alternative is A_5 - *Sublevel caving*. Noting the characteristics of the Upper Zone of the Čukaru Peki, this choice is totally justified. Aforementioned mining method will enable access to the higher grades of the mineralization and better use of the available metals in the given deposit.

3. Conclusion

An extremely important decision for the mining engineers is the selection of the appropriate mining method because it seriously affects the future performance of a certain mine. The threat of involving overly subjectivity could be overcome by introducing group decision-making. Besides, relying on the selection procedure of the greater number of criteria increases the chance of making an optimal decision.

In this paper, the PIPRECIA-E method in the group decision environment is applied for the underground method selection. In order to present the applicability of the proposed methodology, we used the illustrative example connected to the mining method selection for the exploitation of the Čukaru Peki Upper Zone. Three *DM*s estimated 5 mining methods against 3 groups of criteria and 18 sub-criteria in total. The obtained results are in lieu with given conditions of considered deposit and they are entirely reliable and justified.

The PIPRECIA-E method proved that it is very convenient for applying in cases when there are several *DM*s. The reliability of received responses is checked in two ways: (1) by a bidirectional approach in the evaluation of the given set of criteria; (2) and by using Spearman's correlation. Thereby, by checking the consistency of the obtained responses twice, the possibility of wrong decisions decreases. This is the advantage of the PIPRECIA-E method relative to the SWARA method. Also, by predicting the reliability checking, this method could be considered equally reliable as widely well-known AHP method. Besides, it has advanced relative to the AHP because the procedure is somewhat simpler than in the AHP method.

As we earlier stated, the selection of the appropriate set of criteria is a very important phase in the decision-making process. In this case, the list of the evaluation criteria is formed on the base of the sets proposed in the papers that considered same topic (Ataei et al., 2008; Naghadehi et al., 2009; Bogdanovic et al., 2012; Yazdani-Chamzini et al., 2012). The main criteria groups are pointed to the: technical, production and economic parameters. Involving a different kind of criteria will give a complete and clear picture to *DM*s about aspects important for the optimal mining method selection.

The main deficiency of this paper reflects through neglecting of uncertainty. Some authors, that examined the problem of mining method selection, proposed the application of the extensions of the MCDM methods (Karadogan et al., 2008; Namin, Shahriar, Bascetin, & Ghodsypour, 2012; Dehghani, Siami, & Haghi, 2017; Liang, Zhao, & Hong, 2018). By introducing the fuzzy, grey or neutrosophic numbers, the vagueness of the environment would be acknowledged in the higher degree and the possibility of making a wrong decision would be minimized. Also, the procedure of the PIPRECIA-E method could be esteemed as complex because the list of criteria should be evaluated from the first to the last and vice-versa. But, although this fact could not be denied, this kind of procedure leads to trustful results.

The proposed methodology shows that it is quite useful for application in the area of the underground mining method selection. Besides, it could be used for the resolving of other problems in the mine production such as equipment selection (Rahimdel & Karamoozian, 2014; Yavuz, 2015b), grinding circuit selection (Stanujkic, Magdalinovic, Milanovic, Magdalinovic, & Popovic, 2014; Stanujkic, Zavadskas, Karabasevic, Milanovic, & Maksimovic, 2019b) and transportation system selection (Gupta, Mehlawat, Aggarwal, & Charles, 2018). The potentials of the PIPRECIA-E method are not fully examined so there is enough room for testing its possibilities and proposing appropriate extensions.

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