

Volume 20 | Issue 2

Article 1

2021

Selection mining methods via multiple criteria decision analysis using TOPSIS and modification of the UBC method

Author(s) ORCID Identifier: Mahrous Ali Mohamed Ali D 0000-0001-9369-0765 Jong-Gwan Kim D 0000-0002-2131-1946

Follow this and additional works at: https://jsm.gig.eu/journal-of-sustainable-mining

Part of the Mining Engineering Commons

Recommended Citation

Ali, Mahrous Ali Mohamed and Kim, Jong-Gwan (2021) "Selection mining methods via multiple criteria decision analysis using TOPSIS and modification of the UBC method," *Journal of Sustainable Mining*: Vol. 20 : Iss. 2, Article 1.

Available at: https://doi.org/10.46873/2300-3960.1054

This Research Article is brought to you for free and open access by Journal of Sustainable Mining. It has been accepted for inclusion in Journal of Sustainable Mining by an authorized editor of Journal of Sustainable Mining.

Selection mining methods via multiple criteria decision analysis using TOPSIS and modification of the UBC method

Abstract

Mine designers often face difficulties in selecting an appropriate mining method; however, such a method should be selected based on ore and rock characteristics. The selection of mining methods can be considered a type of multi-criteria decision making, and this depends on many factors used in the selection process. The general method used in this field is the University of British Columbia (UBC) method, which determines the criteria of the properties that are compared to determine the best and worst of several mining methods. In this paper we used as new technique which define as Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS). The criteria considered in the UBC method include general shape, ore thickness, ore plunge, and grade distribution, beside the rock quality designation (RQD), and the rock substance strength (RSS). This paper presents an improved TOPSIS method based on experimental design. Additionally, this paper will introduce a modified version of the UBC method that can be employed based on Excel sheet. The best mining methods is cut and fill Stoping and Top slicing with the same rank equal 0.72, and the second-best mining method is Square set Stoping with rank equal 0.65.

Keywords

TOPSIS, UBC method, Mining methods selection, Multiple-criteria decision making

Creative Commons License



This work is licensed under a Creative Commons Attribution 4.0 License.

Cover Page Footnote

The authors convey many thanks to the management of Boleo mine (Mexico) for their support and provide them with data to achievement the paper.

Selection mining methods via multiple criteria decision analysis using TOPSIS and modification of the UBC method

Mahrous A.M. Ali^a, Jong-Gwan Kim^{b,*}

^a Mining and Petroleum Engineering Department, Faculty of Engineering Al-Azhar University, Egypt

^b Department of Energy & Resources Engineering, Chonnam National University, South Korea

Abstract

Mine designers often face difficulties in selecting an appropriate mining method; however, such a method should be selected based on ore and rock characteristics. The selection of mining methods can be considered a type of multi-criteria decision making, and this depends on many factors used in the selection process. The general method used in this field is the University of British Columbia (UBC) method, which determines the criteria of the properties that are compared to determine the best and worst of several mining methods. In this paper we used as new technique which defines as Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS). The criteria considered in the UBC method include general shape, ore thickness, ore plunge, and grade distribution, beside the rock quality designation (RQD), and the rock substance strength (RSS). This paper presents an improved TOPSIS method based on experimental design. Additionally, this paper will introduce a modified version of the UBC method that can be employed based on Excel sheet. The best mining methods is cut and fill stoping and top slicing with the same rank equal 0.72, and the second-best mining method is square set stoping with rank equal 0.65.

Keywords: TOPSIS, UBC method, mining methods selection, multiple-criteria decision making

1. Introduction

re extraction processes are designed with regard to surface or underground mining methods. These techniques depend on the depth, stripping ratio, and other parameters. Furthermore, the optimal use of underground resources is related to the choice of underground mining methods; many factors are taken into consideration in underground mining method; these include safety, mine planning, ventilation system, reduced maintenance costs, and planning production [1,2]. According to the criteria of University of British Columbia (UBC) method for selecting appropriate mining methods, a good selection will be made. Another issue pertains to the manner in which the methodology should be achieve high accuracy and easy used to

application. All results should be aggregated to analyse the decision before it is applied. Many conventional methods consider only a limited number of criteria; therefore, in the decisionmaking process; there is a need for alternative methods, that can consider all known criteria related to selecting underground mining methods. This is because once a mining method is selected, it is nearly impossible to change it owing to the high costs and losses entailed. Thus, it is very important to re-analyse a decision before it is carries out [3,4]. The method that decision makers generally use for this is a sensitivity analysis of the final decision. Mining method selection underlies every mining operation and is essential for estimating the capital and operating costs of alternatives such that economic returns are maximized. This selection is also an important task in

https://doi.org/10.46873/2300-3960.1054 2300-3960/© Central Mining Institute, Katowice, Poland. This is an open-access article under the CC-BY 4.0 license (https://creativecommons.org/licenses/by/4.0/).

Received 4 February 2021; revised 23 April 2021; accepted 23 April 2021. Available online 25 May 2021.

^{*} Corresponding author. E-mail address: kimjg@jnu.ac.kr (J.-G. Kim).

mine management because of its effect on operational cost; it is also an integral part of mine planning and design. Most importantly, using the appropriate mining method increases the safety of employees and secures production [5]. Despite this, mining method selection is not a welldefined process because it involves the interaction of several subjective factors or criteria. In this process, several controllable and uncontrollable parameters should be accounted for [6], and they should be determined according to scientific and technical studies for individual ore deposits [7–10]. The numerous effective factors involved in the selection of an appropriate mining method, complicate this process. The selection method for exploiting fluorine deposits, similar to those used for other deposits, includes modelling followed by examining alternative for mining treatment. Several qualitative and quantitative methods have been developed to evaluate suitable mining methods for ore deposits based on their geometry (depth, shape, thickness, dip), rock quality (ore zone and host rock competency, i.e., structures, stress, stability), ore variability (uniformity, continuity, grade distribution) and related economics factors (ore recovery, ore value and mine recovery, productivity, capital, operating costs) [11–13]. Many citations are provided herein regarding the main sequences employed in all mining methods and the related criteria. This study will focus on the modification of the UBC method using the function in an Excel sheet integrated with the UBC criteria for all mining methods. All criteria indexes from the UBC method will be defined in Excel sheets related to all rock characterizations and mining methods. In this regard [14], the use of multi-criterion decision-making overcomes

10010 1. Chundlerization of tota conclea from the mine sh	Table 1.	Characterization	of rock	collected	from t	the mine site
---	----------	------------------	---------	-----------	--------	---------------

many of the shortcomings of the aforementioned studies [15-19].

In this article we applying the TOPSIS technique, TOPSIS is defined related to the main concept of the best decision making which lead to selected the closed ideal solution and faraway from the nonideal solution as mentioned This technique depends on one that maximum or minimum for the benefit criteria which related to positive or negative ideal solutions. TOPSIS is compare between positive and negative solution to find out the distance between alternative solutions. There are many researchers developed the TOPSIS from Ref. [20]. They are focused on creating the weight for each criterion, scoring normalization for each criterion and estimating the geometric distance between each alternative and the ideal alternative, to a carried out the best value for each criterion.

2. Site investigation and data collection

Geotechnical characterization of the Boleo mine (Mexico) field involved evaluating its various geological structural features and depositional environments. The mineral-bearing zones of interest in the area are bedded clay seams with a slight dip known locally as mantos and an overlying brecciated zone. There are three mines denoted M303, M303S, and M303C, at this site. To circumvent the area of Manto 3, step mining was used to reach the ore body after excavation through its upper interburden. Severe abrasions and pillar damage were caused when conglomerate and repeated grading were supporting the lateral pressure of the mine. Crack displacements and cement injections were measured. In addition, water did not penetrate through cracks during the rainy season. For short wall mining, the main gateway was excavated in the Manto 3 layer; this mine has two panels. One section of panel SW1 was 80 m width and 2.4 m high; currently, it is approximately 90 m length, and thus produces a volume of approximately 17,280 m³ of

Ore property		Description	Magnitude
General shape		T, Tabular	_
Ore thickness, m		N, Narrow	15
Ore plunge, degree		_	70
Grade distribution		G, Gradational	-
Depth below surface, m		SH, Shallow	100
Rock quality designation (RQD, %)	Ore zone	M, Moderate	60
	Hanging wall	VW, very weak	35
	Foot wall	VW, very weak	35
Rock substance strength (RSS)	Ore zone	VW, very weak	35
-	Hanging wall	W, weak	25
	Foot wall	W, weak	35

extracted ore. Table 1 lists the proprieties of the rock in the studied area, including data on ore thickness, shape, ore plunge, grade distribution, depth, and rock mass classification.

3. Methodology

The UBC method was devolved and established and developed by Miller to address the need to improve the Nicholas technique. New additions by Miller include assigning a -10 value a negative weight without completely discarding any alternative. Rock characterizations particularly the mechanical values were also modified. Tomich provides more details as shown in Fig. 1 [15]. We are converted the UBC criteria to weight and rate, the weight depends on the properties to mining methods (highest weight is advantages and lowest is disadvantages corresponding to mining methods) and the rate depends on the real geo-technical geometric, and economic factors related to mine filed investigation, all criteria are presented Tables 2 and 3.

TOPSIS technique assumes that monotonous criteria increase or decrease. Which depends on normalization as a basic factor even though takes in consideration an odd dimension in multi-criteria cases. TOPSIS technique is good method to comparison between criteria as considered poor results in other issue. That results provide us in realistic form of modelling than other methods, take in consideration the alternatives related to include or exclude alternative solutions.

One model uses a total of 36 criteria that were classified into six main groups by Hartman and Mutmansky to analyse an underground mining method selection (UMMS) problem in detail [3]. These criteria are listed in Table 3. However, using this model, also increased the number of pair-wise comparison matrices. The alternatives of the Analytical Hierarchy Processing (AHP) models and the fuzzy multiple attribute decision-making (FMADM) are determined based on the UBC approach used by various researcher [21-34]. The UBC approach is simply a modified version of the Nicholas approach; it numerically ranks the characteristics of the ore geometry and rock mechanics for the ore zone, footwall, and hanging wall of the target deposits. The rankings are then summed where the higher rankings correspond to the more favourable methods. Each ranking consists of a number, such as a number from "0 to 6" or "10, -49". A rank of "-49" corresponds to a mining method that is not feasible and the methods is therefore eliminated; a rank of "0" suggests strongly that a particular characteristic makes given mining method less attractive than others; and a rank of "6" indicates that the corresponding mining methods possesses a very favourable characteristic. To determine the set of valid alternatives, the underground mining method selection (UMMS) uses the final UBC ranking.

4. Modifications to the University of British Columbia (UBC) method

The discussion and illustration of the UBC method in the prior section clarify it before the modifications are discussed in this section. The main criterion for this technique is measuring the stratification of all mechanical and other properties



Fig. 1. All criteria and mining methods. *RQD – rock quality designation, RSS – rock substance strength.

	Param metho	eter/mining ods	Open pit	Block caving	Sublevel stoping	Sublevel caving	longwall	Room and pillar	Shrinkage stopping	Cut and fill stoping	Top slicing	Square set stoping
1	Gener	al shape	0.8	0.8	0.6	0.6	0	0	0	0.2	0.2	0
2	Ore th	nickness, m	0.8	0.8	0.6	0.8	0	0	0	0	0.2	0
3	Grade	distribution	0.6	0.6	0.8	0.6	0.8	0.8	0.6	0.4	0.4	0
4	Depth surfac	below e, m	0.8	0.4	0.6	0.6	0.4	0.6	0.6	0.4	0.4	0.2
5	Plange	2	0.2	0.8	0.8	0.8	0	0	0.8	0.8	0	0.4
6	RQD	Ore zone	0.6	0	0.8	0	0.4	09	0.6	0.6	0	0
7		Hanging wall	0.8	0.4	0.8	0.4	0.6	0.9	0.8	0.6	0.6	0
8		Foot wall	0.8	0.4	0.6	0.6	0	0	0.6	0.4	0.4	0
												00
9	RSS	Ore zone	0.6	0	0.8	0.4	0.2	0.9	0.8	0.6	0	0
10		Hanging wall	0.8	0	0.6	0.250	0.4	0.9	0.8	0.4	0.4	0
11		Foot wall	0.8	0.2	0.6	0.4	0	0	0.6	0.4	0.25	0

Table 3. Assigned ratings to the different ranges of parameters.

Parameter		Kating							
		0	0.4	0.6	0.8	1			
General shape		Irregular	Platy/Tabular W/Depth no exceed 35 m	Platy/Tabular W/Depth no exceed 30 m	Platy/Tabular W/Depth no exceed 25 m	Equal dimensions			
		Very low	low	Medium	High	Very high			
Ore thickr	ness, m	<3	3-10	10-30	30-100	>100			
		Very narrow	Narrow	Intermediate	thick	Very thick			
Plunge		>55	45-55	35-45	20-35	<20			
-		steep	Sami steep	Intermediate	Sami flat	flat			
Depth bel	ow surface,	>600	300-600	150-300	70–150	<70			
m		Deep	Sami deep	Intermediate	Sami shallow	shallow			
Grade dist	tribution,	<50	50-70	70-80	80-99	100			
%		erratic	un Uniformed	Medium	Sami Uniformed	Uniformed			
RQD, %	Ore zone	<20	30-40	40-60	60-80	80-100			
		Very weak	Weak	Moderate	strong	Very strong			
RSS, %	Ore zone	<5	5-10	10-15	15-20	20			
		Very weak	Weak	Moderate	strong	Very strong			

of the bedrock such that can be added to a new Excel sheet and linked with phenomena corresponding to all mining methods by using the TOP-SIS technique, which can easily connect all the characterization bed layers e.g., thickness, plunge, depth, rock mass rating (RMR). The following example shows the manner in which the function and active link to all parameters can be prepared. Table 4 illustrate the weight and rate for every property, the weight mean if this property as advantages or disadvantages for mining methods as mention in UBC method, and the rate mean the actual property based on UBC scheme.

The final value will appear in the next file in the same Excel sheet as shown in Table 6. Decision makers can decide which method is suitable able to decide for a given mine based on the fact that a high value (nearest from 1) is assigned to the most preferred method, less to the next preference, and so on. All methods will be formulated according to the UBC method and linked cell in excel sheet with all properties. MCDM assume that, the issue was obeyed to m alternative, denotes the value assigned to the jth criterion of the ith alternative, x_{ii} is the decision matrix. The equivalent weight of property has mentioned by w₁, w₂,w_n, beside the TOPSIS processes are find out as five steps which follows by equations (1)-(5). Table 4 illustrated transformed approach criteria from UBC criteria all properties were weighted to near from 1. Table 5 is given the calculation normalized matrix according to Equation No. 1. Table 6 summarized the results of variables X multiplied with weighted index for every property. Table 7 illustrated the positive ideal and negative ideal solutions and finally Table 8 is given the final results according to the Euclidean distance from the ideal worst and ranking.

Grade distribution

0.4

0.25

0.6

0.6

0.6

0.8

0.6

0.8

0.8

0.8

0.6

0.8

0.6

				RTICLI
0.8 Depth below surface, m	1 Plunge	0.3 RQD	0.4 RSS	ARCH A
0.6	0.6	0.1	0.1	SE
0.8	0.1	0.1	0.1	RF
0.6	0.8	0.8	0.6	
0.6	0.4	0.6	0.6	
0.8	0.1	0.1	0.8	
0.1	0.4	9	0.6	
0.4	0.6	0.9	0.8	
0.6	0.1	0.1	0.6	
0.4	0.2	0.9	0.8	

0.9

0.8

0.4

Table 4. Conversion the UBC criteria to new approach of weight and rate.

General shape

0.4

0.8

0.8

0.6

0.4

0.8

0.1

0.4

0.4

0.1

0.1

Ore thickness, m

0.1

0.4

0.8

0.6

0.8

0.2

0.6

0.1

0.8

0.6

0.8

Table 5. Normalized matrix.

weights/rates

Block caving

Longwall

Top slicing

Open pit mining

Sublevel stoping

Sublevel caving

Room and pillar

Shrinkage stoping

Cut and fill stoping

Square set stoping

	General shape	Ore thickness, m	Grade distribution	Depth below surface, m	Plunge	RQD	RSS
Open pit mining	0.203858877	0.478947472	0.268328157	0.340092121	0.4341	0.0109	0.0499
Block caving	0.407717753	0.478947472	0.268328157	0.453456161	0.0724	0.0109	0.0499
Sublevel stoping	0.305788315	0.359210604	0.357770876	0.340092121	0.5789	0.087	0.2993
Sublevel caving	0.407717753	0.239473736	0.268328157	0.340092121	0.2894	0.0653	0.2993
Longwall	0.101929438	0.478947472	0.357770876	0.453456161	0.0724	0.0109	0.399
Room and pillar	0.305788315	0.059868434	0.357770876	0.05668202	0.2894	0.9792	0.2993
Shrinkage stoping	0.057259833	0.325515384	0.386694596	0.275208366	0.4835	0.0979	0.4
Cut and fill stoping	0.407717753	0.239473736	0.268328157	0.340092121	0.0724	0.0109	0.2993
Top slicing	0.305788315	0.059868434	0.357770876	0.226728081	0.1447	0.0979	0.399
Square set stoping	0.407717753	0.059868434	0.268328157	0.14170505	0.2894	0.0979	0.399

Table 6. Calculate Normalized Matrix multiplied with rate for every property.

Methods/properties	General shape	Ore thickness, m	Grade distribution	Depth below surface, m	Plunge	RQD	RSS
Open pit mining	0.020385888	0.191578989	0.160996894	0.272073697	0.4341	0.0033	0.02
Block caving	0.040771775	0.191578989	0.160996894	0.362764929	0.0724	0.0033	0.02
Sublevel stoping	0.030578831	0.143684242	0.214662526	0.272073697	0.5789	0.0261	0.1197
Sublevel caving	0.040771775	0.095789494	0.160996894	0.272073697	0.2894	0.0196	0.1197
Longwall	0.010192944	0.191578989	0.214662526	0.362764929	0.0724	0.0033	0.1596
room and pillar	0.030578831	0.023947374	0.214662526	0.045345616	0.2894	0.2938	0.1197
Shrinkage stoping	0.005725983	0.130206153	0.232016757	0.220166693	0.4835	0.0294	0.16
Cut and fill stoping	0.040771775	0.095789494	0.160996894	0.272073697	0.0724	0.0033	0.1197
Top slicing	0.030578831	0.023947374	0.214662526	0.181382464	0.1447	0.0294	0.1596
Square set stoping	0.040771775	0.023947374	0.160996894	0.11336404	0.2894	0.0294	0.1596

Table 7. The positive ideal and negative ideal solutions.

V+	0.005725983	0.023947374	0.160996894	0.045345616	0.0724	0.0033	0.02
V-	0.040771775	0.191578989	0.232016757	0.362764929	0.5789	0.2938	0.16

Table 8. Euclidean distance from the ideal worst and ranking.

Si ⁺	Si ⁻	Pi	Rank	
0.4589	0.3723	0.45	7	Open pit mining
0.3607	0.6046	0.63	3	Block caving
0.5799	0.2902	0.33	9	Sublevel stoping
0.3393	0.4278	0.56	5	Sublevel caving
0.3889	0.585	0.60	4	Longwall
0.3807	0.4633	0.55	6	Room and pillar
0.486	0.323	0.40	8	Shrinkage stoping
0.2603	0.6564	0.72	1	Cut and fill stoping
0.2178	0.5655	0.72	1	Top slicing
0.2705	0.499	0.65	2	Square set stoping

1. Normalize the decision matrix:

$$\overline{X}_{ij} = \frac{X_{ij}}{\sqrt{\sum_{i=1}^{n} X_{ij}^2}} \tag{1}$$

rij = xij - mk = 1 x2 k j, i = 1, ..., m; j = 1, ..., n where ri j denotes the normalized value of jth criterion for the *i*th alternative Ai.

2. Calculate the weighted normalized decision matrix:

$$V_{ij} = \overline{X}_{ij} \times W_j \tag{2}$$

vi j = wj ri j, i = 1, ..., m; j = 1, ..., n (2), where w_j is the weight of the *j*th criterion or attribute.

3. Determine the positive ideal and negative ideal solutions:

$$S_{i}^{+} = \left[\sum_{j=1}^{m} \left(V_{ij} - V_{j}^{+}\right)^{2}\right]^{0.5}$$
(3)

4. Calculate the Euclidean distance from the ideal worst

$$S_{i}^{-} = \left[\sum_{j=1}^{m} \left(V_{ij} - V_{j}^{-}\right)^{2}\right]^{0.5}$$
(4)

5. Calculate Performance Score and ranking

$$P_i = \frac{S_i^-}{S_i^+ + S_i^-}$$
(5)

5. Conclusion

The results showed that, selecting a mining method would depend on many criteria, all of which are related to safety and economic considerations. The modification of the UBC method focused on linking all parameters related to all criteria in a simple manner and obtaining accurate final results. The final results provide indicators using which decision makers can choose between different mining methods based on the total points given to all ore properties. The best mining methods is cut and fill stoping and top slicing with the same rank equal 0.72, and the second-best mining method is square set stoping with rank equal 0.65, the pattern continues as shown in Table 8. This modified method was applied to other case and good results were obtained; further, it is easy input and output all data and solutions.

Ethical statement

The authors state that the research was conducted according to ethical standards.

Funding body

This research received no external funding.

Conflicts of interest

None declared.

Acknowledgement

The authors convey many thanks to the management of Boleo mine (Mexico) for their support and provide them with data to achievement the paper.

References

- Hoek E, Brown ET. Underground excavations in rock. London: Institution of Mining and Metallurgy; 1980. p. 527.
- [2] Harman HL. Introductory mining engineering. New Jersey: John Wiley; 1987.
- [3] Hartman HL, Mutmansky JM. Introductory mining engineering. New Jersey: John Wiley; 2002.
- [4] Alpay Serafettin, Yavuz Mahmut. Underground mining method selection by decision making tools. Tunn Undergr Space Technol 2009;24:173-84.
- [5] Ataei M. Multicriteria selection for alumina-cement plant location in East- Azerbaijan province of Iran. J S Afr Inst Min Metall 2005;105:507–14.
- [6] Peskens TW. Underground mining method selection and preliminary techno-economic mine design for the Wombat orebody, Kylylahti deposit, Finland. Master thesis. Section for Resource Engineering Department of Geoscience & Engineering Delft University of Technology; 2013.
- [7] Bitarafan MR, Ataei M. Mining method selection by multiple criteria decision-making tools. J S Afr Inst Min Metall 2004; 104:493–8.
- [8] Boshkov SH, Wright FD. Basic and parametric criteria in the selection, design and development of underground mining systems. SME Mining Engineering Handbook. New York: SME-AIME; 1973.
- [9] Laubscher DH. Selection of mass underground mining methods. Design and operation of caving and sublevel stoping mines. New York: SME-AIME; 1981.
- [10] Yavuz M, Alpay S. Mining method selection by multiple criteria decision-making tool by M.R. Bitarafan and M. Ataei. J SAIMM 2007;104(9):493–8.
- [11] Karadogan A, Bascetin A, Kahriman A, Gorgun S. A new approach in selection of underground mining method. In: Proceeding of the international conference-modern management of mine producing, geology and environment protection; 2001. p. 171–83.
- [12] Yavuz M, Iphar M, Once G. The optimum support design selection by using AHP method for the main haulage road in WLC Tuncbilek colliery. Tunn Undergr Space Technol 2008; 23:111–9.
- [13] Samanta B, Sarkar B, Murherjee SK. Selection of opencast mining equipment by a multi-criteria decision-making process. Trans Inst Min Metall A 2002;111:A136–42.
- [14] Kahriman A, Ceylanoglu A, Demirci A, Arpaz E, Gorgulu K. Selection of optimum underground mining method for Eskisehir-Karaburun chromite ore (in Turkish). In: Proceeding of the 3rd national rock mechanics symposium; 1996. p. 47–60.
- [15] Miller-Tait L, Panalkis R, Poulin R. UBC mining method selection. In: Proceeding of the mine planning and equipment selection symposium; 1995. p. 163–8.
- [16] Bascetin A, Kesimal A. The study of a fuzzy set theory for the selection of an optimum coal transportation system from pit to the power plant. Int J Surf Min Reclamat Environ 1999;13: 97–101.
- [17] Elevli B, Demirci A. Multicriteria choice of ore transport system for an underground mine: application of PROMETHEE methods. J S Afr Inst Min Metall 2004;104: 251-6.
- [18] Saaty TL. Fundamentals of decision making and priority theory with the analytic Hierarchy process. Pittsburgh: RWS; 2000.

54

- [19] Nicholas DE. Method selection a numerical approach. Design and operation of caving and sublevel stoping mines. New York: SME-AIME; 1981.
- [20] Wang Peng, Zhu Zhouquan, Huang Shuai. The use of improved TOPSIS method based on experimental design and Chebyshev regression in solving MCDM problems. 2014 J Intell Manuf 2017;28:229–43.
- [21] Yavuz M, Alpay S. EQS: a computer software using fuzzy logic for equipment selection in mining engineering. J SAIMM 2006;106(1):63-70. 107, 138.
- [22] Robert Tomich Alexander. An evaluation procedure for new deposits in brownfield underground mines. Master degree. Ontario, Canada: Queen's University Kingston; 2020.
- [23] Acaroglu O, Ergin H, Eskikaya S. Analytical hierarchy process for selection of road headers. J S Afr Inst Min Metall 2006;106:569-75.
- [24] Acaroglu O, Feridunoglu C, Tumac D. Selection of road headers by fuzzy multiple attribute decision making method. Trans Inst Min Metall 2006;115:A91–8.
- [25] Bellman RE, Zadeh LA. Decision making in a fuzzy environment. Manag Sci 1970;17:141-64.
- [26] Bieniawski ZT. Engineering rock mass classification. New York.: John Wiley & Sons; 1989. p. 237.

- [27] Chen C, Klein CM. An efficient approach to solving fuzzy MADM problems. Fuzzy Set Syst 1997;88:51–67.
- [28] Kazakidis VN, Mayer Z, Scoble MJ. Decision making using the analytic hierarchy process in mining engineering. Trans Inst Min Metall 2004;113:A30–42.
- [29] Kesimal A, Bascetin A. Application of fuzzy multiple attribute decision making in mining operations. Miner Resour Eng 2002;11:59–72.
- [30] Riberio RA. Fuzzy multiple attribute decision making: a review and new preference elicitation techniques. Fuzzy Set Syst 1996;78:155-81.
- [31] Saaty TL. The analytic Hierarchy process. Pittsburgh: McGraw-Hill; 1980.
- [32] Triantaphyllou E, Sanchez A. A sensitivity analysis approach for some deterministic multi-criteria decision-making methods. Decis Sci J 1997;28:151–94.
- [33] Yager RR. Fuzzy decision making including unequal objectives. Fuzzy Set Syst 1978;1:87–95.
- [34] Witten IH, Frank E, Hall MA, Pal CJ. Data mining fourth edition: practical machine learning tools and techniques. 2016.