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THE SELECTION OF AN UNDERGROUND MINING METHOD USING THE FUZZY TOPSIS METHOD: A CASE STUDY IN THE KAMAR MAHDI II FLUORINE MINE

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Abstract: The selection of the mining method is one of the most crucial decisions in the stage of designing mines. This depends on some underlying parameters such as economic, technical and efficiency properties. The parameters may be collected and examined in a wide range of methods including core drilling and developmental planning of an active mine. The process of selecting the mining method can be described as multi-criterion decision-making due to the several factors involved in the evaluation process. Through the multi-criterion decision-making, the structure of problems is analyzed. However, multi-criteria decision-making (MCDM) is often criticized because of its inability to handle uncertain and imprecise problems. Thus, the fuzzy decision-making is proposed as a powerful tool. Therefore in this paper, the fuzzy technique for order performance by similarity to ideal solution (Fuzzy TOPSIS) is used to select the best mining method among square-set stoping, cut-and-fill stoping, shrinkage stoping and sublevel stoping at the Kamar Mahdi fluorine mine based on 14 criteria such as deposit thickness, deposit dip, grade distribution, joint spacing in deposit and hanging wall as well as the cost of mining. Other criteria with the same importance for the four alternatives are neglected. Finally, the alternatives are ranked and the shrinkage stoping is proposed as the optimal mining method for this mine.

Keywords: *mining method selection, the Kamar Mahdi Fluorine Mine, fuzzy TOPSIS, shrinkage stoping.*

INTRODUCTION

Mining method selection underlies every mining operation and is essential for estimating capital and operating costs of alternatives in order to maximize economic return. This selection is an important task for mine management due to its operational

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cost, and also an integral part of mine planning and design. Most importantly, the appropriate mining method increases the safety of employees and secures the production (Peskens, 2013). Mining method selection is not a well-defined process because it involves the interaction of several subjective factors or criteria. In this process, several controllable and uncontrollable parameters should be taken into account (Bakhtavar et al., 2009). Therefore, these parameters should be reached according to scientific and technical studies for each ore deposit (Kahriman et al., 1994; Demirci et al., 1995). Because of the multiplicity of effective factors in selection of an appropriate mining method, this is not a simple problem to deal with. As is true for other deposits, the selection of an exploitation method for fluorine deposit includes modeling the ore deposit followed by examining alternatives for mining and treatment.

Several qualitative and quantitative methods have been developed to evaluate suitable mining methods for an ore deposit based on geometry of deposit (depth, shape, thickness, dip), rock quality (ore zone and host rock competency, i.e. structures, stress, stability), ore variability (ore uniformity, continuity, grade distribution) and economics (ore recovery, ore value and mine recovery, productivity, capital and operating costs). Some of these methods have been presented by Boshkov & Wright (1973), Morrison (1976), Laubscher (1977, 1981), Nicholas (1981, 1992), Tymshore (1981), Hamrin (1982), Brady & Brown(1985), Yun & Huang (1987), Laubscher & Page (1990), Hartman (1992), Adler & Thompson (1992), Kahriman et al. (1994), Demirci et al. (1995), Miller et al. (1995), Clayton et al. (2002), Guray et al. (2003), Bitarafan & Ataei (2004), Shahriar et al (2007), Yavuz & Alpay (2008), Alpay & Yavuz (2009), Zare Naghadehi et al. (2009), Bakhtavar et al. (2009) Azadeh et al. (2010), Ozfırat (2012), Bogdanovic et al. (2012), Ataei et al. (2013), Peskens (2013), Shariati et al. (2013), Rahimi Ghazikalayeh et al. (2014), Ozfirat et al. (2015), Njamba & Mutambo (2016), Dehghani et al. (2017), Javanshirgiv et al. (2017) and Balusa & Singam (2017). These studies were neither enough nor complete. The complexity of the matter stems from some basic facts, especially the absence of a specific formulation for selecting an appropriate mining method (Guray et al., 2003). In this regard, the use of the multi-criterion decision-making (MCDM) has managed to overcome many of the shortcomings of the aforementioned studies. However, the MCDM methods are often criticized because of their inability to handle the uncertain and imprecise problems, so the fuzzy decision-making has been proposed as a powerful tool. The fusion between the MCDM and fuzzy set theory has led to a new decision theory known today as fuzzy multi-criterion decision-making (FMCDM) where we have decision-maker models that can deal with incomplete and uncertain knowledge and information. It should be noted that humans' judgment usually necessitates the use of a natural language in which the words do not have a clear, definite meaning. As a result, we need fuzzy numbers to express linguistic variables, to describe the subjective judgment of a decision maker in a quantitative manner (Nădăban et al., 2016). Fuzzy sets and fuzzy logic are powerful mathematical tools for modeling uncertain systems in industry, nature, and humanity and facilitators for common sense reasoning in decision making in the absence of complete and precise information (Bojadziev & Bojadziev, 1998). Since the selection of the mining method is an MCDM type of problem and for the problems of selection type, fuzzy methods are more common than precise and certain models, in this paper, the fuzzy TOPSIS, one of the FMCDM methods, is used to select the mining method in the Kamar Mahdi Fluorine Mine.

FUZZY TOPSIS METHOD

In the TOPSIS method, accurate and definite values are applied in order to determine criteria and option weights (Mohammadi Farzami & Vafaei, 2013). However, in most cases, human thinking is accompanied with indeterminacy, which influences decision making. Decision-making methods based on fuzzy theory are used for decisions hindered by uncertainty. The fuzzy theory is one of the modern techniques which can deal with the impreciseness of input data and domain knowledge by giving quick, simple and often sufficiently good approximations of the desired solutions (Ko et al., 2010; Kazi, 2012). This theory is able to convert most incorrect and enigmatic concepts, variables and systems into a mathematical form, and set the context for reasoning, deduction and decision-making at uncertainty conditions (Mohammadi Farzami & Vafaei, 2013). When the TOPSIS and Fuzzy theory are used together, they form the FTOPSIS approach which is used in the current study for selecting the appropriate mining method. Instead of using crisp numbers in the TOPSIS, it makes use of fuzzy numbers. These numbers allow for the performance of the computational analysis and rank the alternatives (Rudnik & Kacprzak, 2017). The fuzzy TOPSIS method was first developed by Hwang & Yoon (1981). This method is based on multiple-criteria decision-making (MCDM), and the elements of decision-making matrix or the weights of criteria or both of them are evaluated by lingual variables presented by fuzzy numbers. Thus, the problems could be overcome by the TOPSIS method (Mohammadi Farzami & Vafaei, 2013; Ashrafzadeh et al., 2012). This method is particularly suitable for solving the group decision-making problem under fuzzy environment (Torfi et al., 2010; Safari et al., 2012).

The fuzzy TOPSIS procedure involves the following steps (Wang & Chang, 2007; Safari et al., 2012; Javanshirgiv et al., 2017; Nădăban et al., 2016; Rudnik & Kacprzak, 2017):

Step 1. Identify the evaluation criteria and alternatives.

Step 2. Choose the appropriate linguistic variables.

Triangular fuzzy numbers can be used to represent linguistic variables, which can be used for the importance weight of the criteria (Tab. 1) and the evaluation of alternatives with respect to each criterion (Tab. 2) (Zadeh, 1975).

Tab. 1. Linguistic variables for the importance weight of each criterion

Linguistic variables	Fuzzy triangular
Very Low (VL)	(0 , 0.1 , 0.3)
Low (L)	(0.1 , 0.3 , 0.5)
Medium (M)	(0.3 , 0.5 , 0.7)
High (H)	(0.5 , 0.7 , 0.9)
Very High (VH)	(0.7 , 0.9 , 1)

Tab. 2. Linguistic variables for the ratings

Linguistic variables	Fuzzy triangular
Very poor (VP)	(0 , 1 , 3)
Poor (P)	(1 , 3 , 5)
Fair (F)	(3 , 5 , 7)
Good (G)	(5 , 7 , 9)
Very Good (VG)	(7 , 9 , 10)

Step 3. Define the fuzzy decision matrix.

A fuzzy multi-criteria decision-making problem can be concisely expressed in matrix format like Eq. 1.

$$\tilde{D} = \begin{bmatrix} \tilde{X}_{11} & \dots & \tilde{X}_{1j} & \dots & \tilde{X}_{1n} \\ \vdots & \dots & \vdots & \dots & \vdots \\ \tilde{X}_{i1} & \dots & \tilde{X}_{ij} & \dots & \tilde{X}_{in} \\ \vdots & \dots & \vdots & \dots & \vdots \\ \tilde{X}_{m1} & \dots & \tilde{X}_{mj} & \dots & \tilde{X}_{mn} \end{bmatrix} \tag{1}$$

Where $\tilde{x}_{ij}$ are linguistic variables that can be shown by triangular fuzzy numbers: $\tilde{X}_{ij} = (a_{ij}, b_{ij}, c_{ij})$.

Step 4. Normalize the fuzzy decision matrix $\tilde{\mathrm{R}}$ $([\tilde{\mathrm{r}}_{\mathrm{ij}}])$.

The decision matrix must first be normalized so that the elements become unit-free. The process is to transform different scales and units among various criteria into common measurable units to allow comparisons across the criteria. The vector normalization technique is used for computing element $\tilde{\mathrm{r}}_{\mathrm{ij}}$ of the normalized decision matrix, which is given as the normalized fuzzy decision matrix. Linear scale transformation is used to transform the various criteria scales into a comparable scale. Therefore, it is possible to obtain the normalized fuzzy decision matrix denoted by $\tilde{\mathrm{R}}$:

$$\tilde{R} = [\tilde{r}_{ij}]_{m \times n} \qquad i = 1, 2, \dots, m \;\; ; \; j = 1, 2, \dots, n \tag{2}$$

or

$$\tilde{R} = \begin{bmatrix} \tilde{r}_{11} & \cdots & \tilde{r}_{1j} & \cdots & \tilde{r}_{1n} \\ \vdots & \dots & \vdots & \dots & \vdots \\ \tilde{r}_{i1} & \cdots & \tilde{r}_{ij} & \cdots & \tilde{r}_{in} \\ \vdots & \dots & \vdots & \dots & \vdots \\ \tilde{r}_{m1} & \dots & \tilde{r}_{mj} & \dots & \tilde{r}_{mn} \end{bmatrix} \tag{3}$$

where:

$$\tilde{r}_{ij} = \left(\frac{a_{ij}}{c_j^*}, \frac{b_{ij}}{c_j^*}, \frac{c_{ij}}{c_j^*} \right), \; c_j^* = Max_j \{c_{ij}\} s, \; if \quad j \in B; \tag{4}$$

$$\tilde{r}_{ij} = \left(\frac{a_j^-}{c_{ij}}, \frac{a_j^-}{b_{ij}}, \frac{a_j^-}{a_{ij}} \right), \; a_j^- = Min_i \{a_{ij}\}, \; if \; j \in C. \tag{5}$$

Here, B and C are the sets of benefit and cost criteria. Upon obtaining benefit and cost attributes, the discrimination between maximization or minimization criteria desired to achieve by a decision maker would be possible.

Step 5. Establish criteria weighted matrix.

It cannot be assumed that each evaluation criterion is of equal importance because the evaluation criteria have various meanings.

$$\tilde{W} = [\tilde{w}_1, \tilde{w}_2, ..., \tilde{w}_n] \tag{6}$$

where $\tilde{w}_j$ are linguistic variables that can be shown by triangular fuzzy numbers: $\tilde{w}_j = (w_{j1}, w_{j2}, w_{j3})$.

Step 6. Compute the normalized weighted fuzzy decision matrix.

The determination of the weight of each criterion provides the weighted normalized fuzzy decision matrix as follows:

$$V = \begin{bmatrix} \tilde{v}_{11} & \tilde{v}_{12} & \cdots & \tilde{v}_{1n} \\ \tilde{v}_{21} & \tilde{v}_{22} & \dots & \tilde{v}_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ \tilde{v}_{m1} & \tilde{v}_{m2} & \dots & \tilde{v}_{mn} \end{bmatrix} \tag{7}$$

where: $\tilde{v}_{ij} = \tilde{r}_{ij}.\tilde{w}_{ij}$

Step 7. Compute the fuzzy positive ideal solution (FPIS) and the fuzzy negative ideal solutions (FNIS).

The FPIS indicates the most preferable alternative, and the negative ideal solution indicates the least preferable alternative. So, we can now determine the FPIS (A^+) and FNIS (A^-) as follows (Chen, 2000; Chen et al., 2006):

$$A^* = \{\tilde{v}_1^*, \tilde{v}_2^*, ..., \tilde{v}_n^*\} \ , \tilde{v}_i^* = Max_i\{\tilde{v}_{ij}\} \ , i = 1, 2, ..., m \ , j = 1, 2, ..., n \quad (8)$$

$$A^- = \{\tilde{v}_1^-, \tilde{v}_2^-, ..., \tilde{v}_n^-\} \ , \tilde{v}_i^- = Min_i\{\tilde{v}_{ij}\} \ , i = 1, 2, ..., m \ , j = 1, 2, ..., n \quad (9)$$

Step 8. Compute the distance from each alternative to the FPIS and to the FNIS.

The distance of each alternative from the FPIS and FNIS are calculated using the following equations (Eq. 10-13):

$$S_i^* = \sum d_v(v_{ij}, v_j^*) \ , \ i = 1, 2, ..., m \quad (10)$$

$$S_i^- = \sum d_v(v_{ij}, v_j^-) \ , \ i = 1, 2, ..., m \quad (11)$$

$$d_v(v_{ij}, v_j^*) = \sqrt{\frac{1}{3}(\sum(v_{ij} - v_j^*)^2)} \quad (12)$$

$$d_v(v_{ij}, v_j^-) = \sqrt{\frac{1}{3}(\sum(v_{ij} - v_j^-)^2)} \quad (13)$$

Where d (.,.) is the distance measured between two fuzzy numbers.

Step 9. Compute the closeness coefficient of each alternative.

For each alternative A_i we calculate the closeness coefficient (CC_i) as follows:

$$CC_i = \frac{s_i^-}{s_i^* + s_i^-} \quad , \ i = 1, 2, \ldots, m \quad (14)$$

Step 10. Rank the alternatives.

The alternative with highest closeness coefficient represents the best alternative.

CASE STUDY

The Kamar Mahdi II Fluorine Mine is located on 85 kilometers southwest of Tabas, in the South Khorassan province in the east of Iran. The total proved reserve of the Kamar Mahdi II Fluorine Mine approximates to 284,000 tons, with average grade of 90 to 95 percent of fluorine and an average thickness of 0.4 to 2 meters.

According to low thickness and special characteristics of the deposit including high altitude extending to the depth and increasing thickness in lower depths, this deposit may be mined with maximum recovery and minimal cost by the selection of the appropriate mining method. The most important geometrical characteristics and rock mechanical properties of for this deposit are listed in Tab. 3 and Tab. 4.

Tab. 3. Geometrical characteristics

Grade distribution	Shape	Thickness	Deposit dip
Uniform	Vein	Narrow	85 degree

Tab. 4. Rock Mechanical properties

Parameter	Ore	Hangingwall	Footwall
Rock substance strength (RSS)	Medium	Strong	Medium
RQD	75%	90-100%	75%
Fracture shear strength	Medium	Strong	Strong

ALTERNATIVES

The aim of this paper is to determine the suitable mining method for the Kamar Mahdi II Fluorine ore body. According to the technical characteristics of the Kamar Mahdi II Fluorine ore body such as thickness, slope, shape, the strength of the ore and the rock mass, four mining methods (alternatives) including cut-and-fill stoping (A_1), sublevel stoping (A_2), square-set stoping (A_3) and shrinkage stoping (A_4) methods are executable. These mining methods are explained as follows. The purpose of discussing these methods is not to critique them but simply to present the alternatives available to aid in selecting the most appropriate.

Cut and fill stoping is a method of underground mining used in steeply dipping deposits and in mining high-grade irregular ore bodies (Hamrin, 1980). Where ore and/or wall rocks are weak, and hence both opening size and allowable time between ore removal and filling of the excavation is strictly limited, this method can be applied (Bullock, 2011). A stoping method in which each slice of rock is removed after blasting and replaced with some type of fill material (Fig. 1) (Nicholas, 1992).

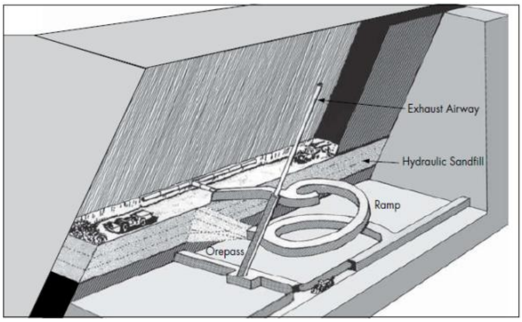

Fig. 1. Cut and fill stoping (Hamrin, 1980)

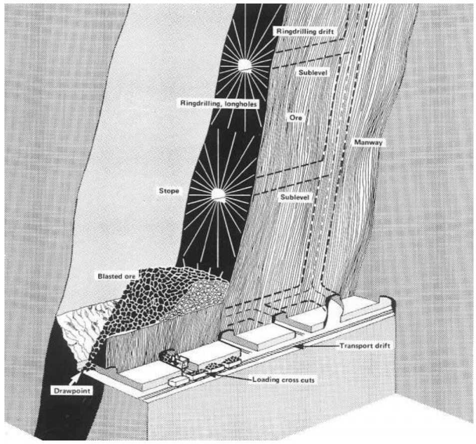

Fig. 2. Sublevel stoping (Hamrin, 1982)

Sublevel stoping is a method of underground mining method that involves vertical mining in a large, open stope that has been created inside an ore vein. The method only applies to vertical or steeply inclined ore bodies. In order to use this method, the hanging wall and the footwall of the ore body must be strong (Hartman & Mutmansky, 2002). This method is an overhand mining method in which the ore is blasted by longholes from sublevels. In this method the deposit is so large or thick that sublevels are required and the blasting requirements approach those of open pit operations. The ore is drawn off as it is blasted, leaving an open stope. The stopes are separated by pillars. The stopes may or may not be filled after mining is completed, and if filled, the pillars are usually recovered using the same method or some type of cut and fill stoping (Fig. 2). The parameters that control this method are an appropriate geometry and competent enough ground to leave open stopes (Nicholas, 1992).

Square set stoping: In square set stoping method, prisms of timber are formed to replace the rock mined and to support the surrounding rock (Fig. 3) (Nicholas, 1992). This method is adapted to mining regular or irregular ore bodies, commonly on dips steeper than about 45°, where the ore and/or walls are too weak to stand even over short spans for more than short time, and where caving and subsidence of overlying rocks must be prevented (Gardner & Vanderburg, 1982).

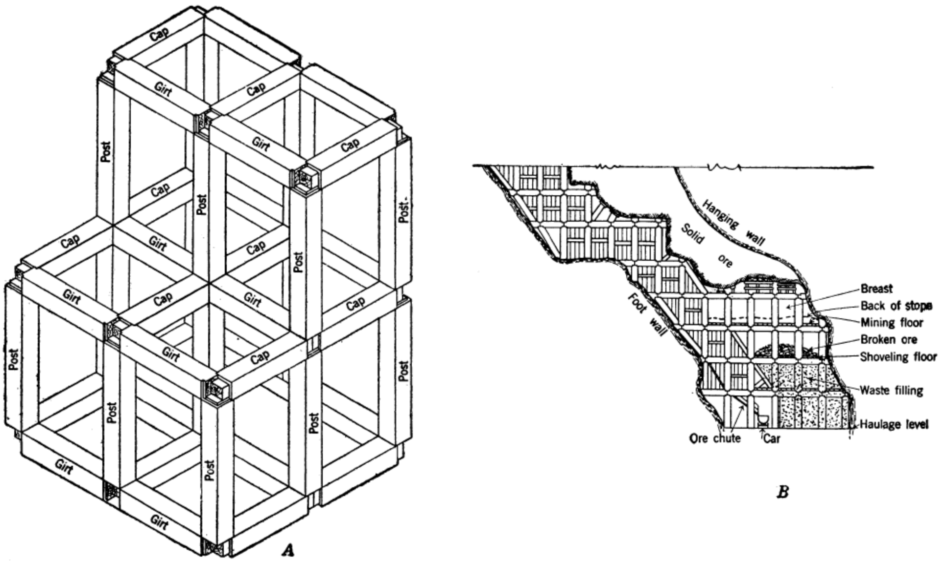

Fig. 3. Square-set stoping. A – Square-set timbering. B – Vertical transverse section through typical square-set stope. (Gardner & Vanderburg, 1982)

Shrinkage stoping: A stoping method in which the ore is blasted, with most of it being left in the stope to accumulate until blasting is completed. The broken ore is then drawn off all at once (Fig. 4). This method is usually used in narrow, steep deposits where the walls are not competent enough to stand without some support, which is provided by the blasted muck (Nicholas, 1992).

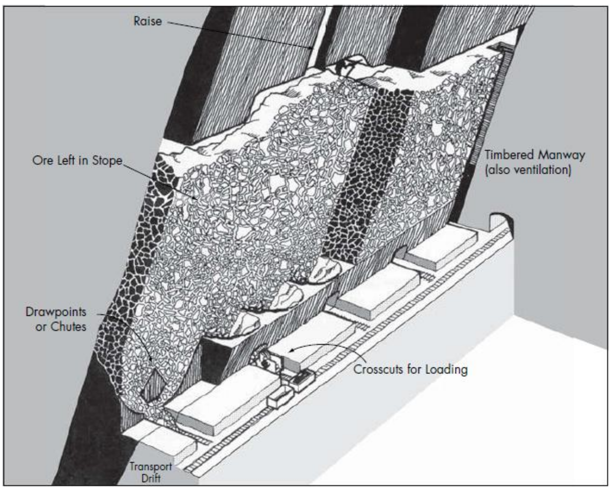

Fig. 4. Shrinkage stoping (Hamrin, 1998)

EFFECTIVE CRITERIA

The selection of a suitable mining method for an ore deposit is dependent on many criteria and variables such as:

- Engineering properties of mineral deposit, hangingwall and footwall (Carter, 2011)
- Geotechnical factors including rock quality (ore zone) and host rock competency (structures, stress, stability) (Peskens, 2013; Carter, 2011)
- Geometry of deposit (depth, shape, thickness, dip, plunge)
- Mining production rate (Peskens, 2013; Carter, 2011)
- Ore variability (ore uniformity, continuity, grade distribution)
- Processing characteristics of the ore
- Economic factors including the capital and operating costs, ore recovery, ore value and mine recovery
- Safety for employees and low environmental impact (Carter, 2011).

In this paper, some criteria such as the mining cost, ore body thickness, ore body shape, grade distribution, the rock substance strength (RSS) and rock quality designation (RQD) of ore, hangingwall and footwall, joint shear stress of ore, hangingwall and footwall and slope are effective in selecting the appropriate mining method at the Kamar Mahdi II Fluorine Mine. These criteria are classified into qualitative and quantitative categories. Some of these criteria are negative and some are positive. For example, the cost of mining is a negative criterion and the grade distribution is a positive one (Tab. 5). It should be mentioned that these criteria are chosen based on comprehensive literature review.

Tab. 5. The classification of criteria

Variable	Criterion	Category
C_1	Ore body thickness	Quantitative
C_2	Ore body shape	Qualitative
C_3	Grade distribution	Qualitative
C_4	RSS of ore	Qualitative
C_5	RSS of hangingwall	Qualitative
C_6	RSS of footwall	Qualitative
C_7	RQD of ore	Quantitative
C_8	RQD of hangingwall	Quantitative
C_9	RQD of footwall	Quantitative
C_{10}	Fracture shear strength of ore	Qualitative
C_{11}	Fracture shear strength of hangingwall	Qualitative
C_{12}	Fracture shear strength of footwall	Qualitative
C_{13}	Deposit dip	Quantitative
C_{14}	Mining costs	Quantitative

Mining cost: Mining costs include capital and operating costs. Estimates of capital and operating costs are necessary for selection of underground mining method. The operating cost of a mine is the cost associated with the production of ore from the primary mining method. The operating cost divided by the number of salable units of production mined creates a metric used to compare efficiency between competing production alternatives – which is $/ton. Initial capital cost is defined as the amount of investment needed before the mine begins to generate revenue (Nieto, 2011).

Ore body thickness: Thickness plays an important role in opening stability and may prevent certain equipment from functioning efficiently or mining methods from being effective (Nieto, 2011). Tab. 6 shows the categories and value ranges for ore body thickness.

Tab. 6. Ore body thickness

Description	Range in Values
Very Narrow	< 3 meters
Narrow	3-10 meters
Intermediate	10-30 meters
Thick	> 30 meters

Shape of ore deposit: This factor is important parameter to consider as they directly influence development requirements and equipment selection. Furthermore, certain deposit geometries are more applicable to certain mining methods than are others (Samimi Namin et al., 2008). According to shape features, ore deposits are classified into three groups as follows:

Massive: A massive deposit may possess any shape. The ore is often distributed in low concentrations over a wide area with varying horizontal and vertical extents. For the purposes of mining method selection, massive deposits are often accompanied by a more specific clause like “massive with large vertical extent.” These additions are necessary because the shape of a massive deposit is variable and may be unsuitable for certain mining methods (Nieto, 2011).

Tabular: A tabular deposit is flat and thin, and has a broad horizontal extent. Most methods designed to exploit tabular deposits may be adapted to mine lenticular ones (Nieto, 2011).

Columnar: A columnar deposit extend in one direction, like; veins, layer, bed, seam, sheet, lenses.

Grade distribution: The grade distribution of the ore in the mineral deposit must be considered, as poor uniformity of grade distribution may render some mining methods unviable. Some mining methods are well suited to flexibility because they can selectively extract specific sections of a deposit without disrupting the overall operation (Carter, 2011). For example, deposits having an erratic grade distribution, with ore grade changing over short intervals, are more faverably mined using more expensive, but more selective techniques, such as cut and fill stoping (Samimi Namin et al., 2008). Ore grade distribution designations are as follows (Nicholas, 1981):

Uniform: The grade at any point in the deposit does not vary significantly from the mean grade for that deposit.

Gradational: Grade values have zonal characteristics, and grades change gradually from one to another.

Erratic: Grade values change radically over short distances and do not exhibit any discernible pattern in their changes.

Rock substance strength (RSS): The parameters such as UCS, vertical stress various with depth, and ratio of horizontal to vertical stress are applied to define the RSS (Samimi Namin et al., 2008). The RSS is a dimentionless parameter defined as the ratio the uniaxial strength of rock mass to the overburden pressure. Tab. 7 summarizes the categories and value ranges for RSS.

Fracture shear strength: The fracture shear strength is an important factor in mining method selection. To execute an appropriate design, this parameter must be understood. The behavior of the hangingwall and footwall can be pivotal in the success of mechanized mining systems. This parameter is categorized as follows (Nicholas, 1981):

Weak: clean joint with a smooth surface or fill with material with strength less than rock substance strength.

Moderate: clean joint rough surface.

Strong: joint is filled with a material that is equal to or stronger than rock substance strength.

Rock quality designation (RQD): Any process intended to aid the selection of an excavation method in for undermining method must consider the RQD. The RQD index was developed by Deere et al. (1967) to provide a quantitative estimate of rock mass quality from drill core logs. RQD is defined as the percentage of intact core pieces longer than 100 mm in the total length of core (Carter, 2011).

Deposit dip: Dip is defined as the angle of inclination of a plane measured downward, perpendicular to the strike direction. The deposit dip is more relevant to tabular ore bodies than massive ones, although it may sometimes be a consideration for the latter. Deposit dips are categorized and defined in Tab. 8. Several methods are highly dependent on gravity for material. Alternatively, low working slopes are a key factor in the application of mechanization for cutting and loading as well as material haulage by rubbertired, rail, or conveyor-belt methods (Nieto, 2011). Therefor this factor is important to mining method selection.

Finally, to select an appropriate mining method for Kamar Mahdi II fluorine mine, investigation was carried out to assess the importance of the criteria to be incorporated in the fuzzy TOPSIS model. The most important criteria (14 criteria) relating to the mining method selection are listed as a questionnaire and respondents were asked to rate each factor according to five-point scale and evaluate each alternative based on each criterion.

Tab. 7. Rock substance strength (Nicholas, 1981)

Description	Range in Values
Weak	< 8
Moderate	8-15
Strong	> 15

Tab. 8. Deposit orientation definitions

Inclination Category	Dip Angle, degrees
Low	0–5
Moderate	5–25
Fairly steep	25–45
Steep	45–90

NUMERICAL EXAMPLE

For determination of the best mining method among four proposed alternatives the fuzzy TOPSIS method involves the following items:

In the first step of the Fuzzy TOPSIS analysis, the decision makers use the linguistic variables (according to Tabs.1 and 2) to evaluate the relative importance or weights of criteria and the ratings of alternatives for various attributes. Final results on the outcome of decision makers' views are presented in the fuzzy decision matrix (Tab. 9) and the criteria weight matrix (Tab. 10).

Tab. 9. Fuzzy decision matrix

Criteria	A_1	A_2	A_3	A_4
C_1	VP	VP	VG	VG
C_2	F	P	P	VG
C_3	G	P	P	G
C_4	F	VG	G	P
C_5	F	VG	P	F
C_6	F	F	P	F
C_7	G	VP	P	VG
C_8	F	VG	VP	F
C_9	F	F	G	F
C_{10}	G	F	F	G
C_{11}	F	VG	VP	F
C_{12}	F	VG	G	F
C_{13}	VG	VG	VG	G
C_{14}	G	P	VG	F

It should be mentioned that the paired comparison matrix was used to determine the weights of the criteria. Next, using the special vector method, the weighted criteria matrix was calculated and the values of this matrix were turned into equivalent fuzzy values. In order to validate the entropy calculations, the degree of deviation and the weight of each criterion were calculated using Shannon entropy method, and they were compared to the results obtained from the special vector method, which showed similar results.

Then, in order to remove a dimension by using Eqs. 2 to 5, the decision matrix is normalized, the corresponding matrix is presented in Tab. 11.

Tab. 10. Criteria weight matrix

Variable	Criterion	Weight
C_1	Ore body thickness	(0.7,0.9,1)
C_2	Ore body shape	(0.5,0.7,0.9)
C_3	Grade distribution	(0.7,0.9,1)
C_4	RSS of ore	(0.5,0.7,0.9)
C_5	RSS of hangingwall	(0.7,0.9,1)
C_6	RSS of footwall	(0.7,0.9,1)
C_7	RQD of ore	(0.5,0.7,0.9)
C_8	RQD of hangingwall	(0.5,0.7,0.9)
C_9	RQD of footwall	(0.5,0.7,0.9)
C_{10}	Fracture shear strength of ore	(0.5,0.7,0.9)
C_{11}	Fracture shear strength of hangingwall	(0.5,0.7,0.9)
C_{12}	Fracture shear strength of footwall	(0.5,0.7,0.9)
C_{13}	Deposit dip	(0.7,0.9,1)
C_{14}	Mining costs	(0.7,0.9,1)

Tab. 11. Normalized fuzzy decision matrix

Criteria	A_1	A_2	A_3	A_4
C_1	(0,0.1,0.3)	(0,0.1,0.3)	(0.7,0.9,1)	(0.7,0.9,1)
C_2	(0.3,0.5,0.7)	(0.1,0.3,0.5)	(0.1,0.3,0.5)	(0.7,0.9,1)
C_3	(0.56,0.78,1)	(0.11,0.33,0.56)	(0.11,0.33,0.56)	(0.56,0.78,1)
C_4	(0.3,0.5,0.7)	(0.7,0.9,1)	(0.5,0.7,0.9)	(0,0.1,0.3)
C_5	(0.3,0.5,0.7)	(0.7,0.9,1)	(0.1,0.3,0.5)	(0.3,0.5,0.7)
C_6	(0.33,0.56,0.78)	(0.33,0.56,0.78)	(0.56,0.78,1)	(0.33,0.56,0.78)
C_7	(0.5,0.7,0.9)	(0,0.1,0.3)	(0.1,0.3,0.5)	(0.7,0.9,1)
C_8	(0.3,0.5,0.7)	(0.5,0.7,0.9)	(0,0.1,0.3)	(0.3,0.5,0.7)
C_9	(0.33,0.56,0.78)	(0.33,0.56,0.78)	(0.56,0.78,1)	(0.33,0.56,0.78)
C_{10}	(0.56,0.78,1)	(0.33,0.56,0.78)	(0.33,0.56,0.78)	(0.56,0.78,1)
C_{11}	(0.3,0.5,0.7)	(0.7,0.9,1)	(0,0.1,0.3)	(0.3,0.5,0.7)
C_{12}	(0.3,0.5,0.7)	(0.7,0.9,1)	(0.5,0.7,0.9)	(0.3,0.5,0.7)
C_{13}	(0.5,0.7,0.9)	(0,0.1,0.3)	(0.7,0.9,1)	(0.3,0.5,0.7)
C_{14}	(0.1,0.11,0.14)	(0.1,0.11,0.14)	(0.1,0.11,0.14)	(0.11,0.14,0.2)

Tab. 12. The normalized weighted fuzzy decision matrix

Criteria	A_1	A_2	A_3	A_4
C_1	(0,0.09,0.3)	(0,0.09,0.3)	(0.49,0.81,1)	(0.49,0.81,1)
C_2	(0.15,0.35,0.63)	(0.05,0.21,0.45)	(0.05,0.21,0.45)	(0.35,0.63,0.9)
C_3	(0.39,0.7,1)	(0.08,0.3,56)	(0.08,0.3,56)	(0.39,0.7,1)
C_4	(0.09,0.49,0.9)	(0.35,0.63,0.9)	(0.25,0.49,0.81)	(0.05,0.21,0.45)
C_5	(0.21,0.45,0.7)	(0.49,0.81,1)	(0.07,0.27,0.5)	(0.21,0.45,0.7)
C_6	(0.23,0.5,0.78)	(0.23,0.5,0.78)	(0.39,0.7,1)	(0.23,0.5,0.78)
C_7	(0.25,0.49,0.81)	(0,0.07,0.27)	(0.05,0.21,0.45	(0.35,0.63,0.9)
C_8	(0.15,0.35,0.63)	(0.35,0.63,0.9)	(0,0.07,0.27)	(0.15,0.35,0.63)
C_9	(0.17,0.39,0.7)	(0.17,0.39,0.7)	(0.28,0.54,0.9)	(0.17,0.39,0.7)
C_{10}	(0.28,0.54,0.9)	(0.17,0.39,0.7)	(0.17,0.39,0.7)	(0.28,0.54,0.9)
C_{11}	(0.15,0.35,0.63)	(0.35,0.63,0.9)	(0,0.07,0.27)	(0.15,0.35,0.63)
C_{12}	(0.15,0.35,0.63)	(0.35,0.63,0.9)	(0.25,0.49,0.81)	(0.15,0.35,0.63)
C_{13}	(0.35,0.63,0.9)	(0.07,0.27,0.5)	(0.49,0.81,1)	(0.21,0.45,0.7)
C_{14}	(0.07,0.1,0.14)	(0.07,0.1,0.14)	(0.07,0.1,0.14)	(0.08,0.13,0.2)

Tab. 13. (FPIS) and (FNIS)

Criteria	FPIS	FNIS
C_1	(1,1,1)	(0,0,0)
C_2	(0.9,0.9,0.9)	(0.05,0.05,0.05)
C_3	(1,1,1)	(0.08,0.08,0.08)
C_4	(0.9,0.9,0.9)	(0.05,0.05,0.05)
C_5	(1,1,1)	(0.07,0.07,0.07)
C_6	(1,1,1)	(0.23,0.23,0.23)
C_7	(0.9,0.9,0.9)	(0,0,0)
C_8	(0.9,0.9,0.9)	(0,0,0)
C_9	(0.9,0.9,0.9)	(0.17,0.17,0.17)
C_{10}	(0.9,0.9,0.9)	(0.17,0.17,0.17)
C_{11}	(0.9,0.9,0.9)	(0,0,0)
C_{12}	(0.9,0.9,0.9)	(0.15,0.15,0.15)
C_{13}	(1,1,1)	(0.07,0.07,0.07)
C_{14}	(0.07,0.07,0.07)	(0.2,0.2,0.2)

Tab. 14. Distance of each alternative from the FPIS

	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9	C_{10}	C_{11}	C_{12}	C_{13}	C_{14}	S^+
A_1	0.88	0.56	0.39	0.56	0.58	0.54	0.45	0.56	0.53	0.41	0.56	0.56	0.44	0.05	7.06
A_2	0.88	0.68	0.68	0.35	0.31	0.54	0.79	0.35	0.53	0.53	0.35	0.35	0.74	0.05	7.15
A_3	0.31	0.68	0.68	0.45	0.74	0.39	0.74	0.79	0.41	0.53	0.79	0.45	0.31	0.05	7.34
A_4	0.31	0.35	0.39	0.68	0.58	0.54	0.39	0.56	0.53	0.41	0.56	0.56	0.58	0.08	6.54

Tab. 15. Distance of each alternative from the FNIS

	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9	C_{10}	C_{11}	C_{12}	C_{13}	C_{14}	S^-
A_1	0.18	0.38	0.67	0.38	0.43	0.35	0.57	0.43	0.33	0.48	0.43	0.30	0.60	0.10	5.62
A_2	0.18	0.25	0.30	0.62	0.73	0.35	0.16	0.67	0.33	0.33	0.67	0.53	0.27	0.10	5.49
A_3	0.80	0.25	0.30	0.52	0.27	0.53	0.29	0.16	0.48	0.33	0.16	0.43	0.73	0.10	5.35
A_4	0.80	0.62	0.67	0.25	0.43	0.35	0.67	0.43	0.33	0.48	0.43	0.30	0.43	0.08	6.26

The next, by using Eq. 7, the normalized weighted fuzzy decision matrix is calculated and the result is given in Tab. 12.

The FPIS and the FNIS were determined as Tab. 13. After determining the FPIS and FNIS, the distance of each alternative from the FPIS and FNIS was obtained as Eqs. 10 to 13. The results are presented in Tabs. 14 and 15.

Consequently, the closeness coefficient of each alternative (Fig. 5) can be calculated as shown below:

$$CC_{A_1} = \frac{5.62}{7.06 + 5.62} = 0.44$$

$$CC_{A_2} = \frac{5.49}{5.49 + 7.15} = 0.43$$

$$CC_{A_3} = \frac{5.35}{5.35 + 7.34} = 0.42$$

$$CC_{A_4} = \frac{6.26}{6.26 + 6.54} = 0.49$$

The closeness coefficient clearly shows the ranking order of all alternatives. Based on these values, the ranking of the alternatives are shrinkage stoping (A_4), cut-and-fill stoping (A_1), sublevel stoping (A_2) and square-set stoping (A_3) in descending order. This means that alternative A_4 (shrinkage stoping) has the highest weight, implying that the most suitable mining method for the Kamar Mahdi II fluorine mine is this option.

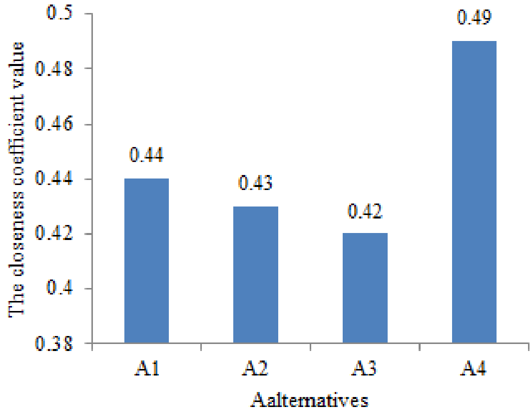

Fig. 5. The closeness coefficient of alternatives

CONCLUSION

One of the most critical and complicated steps in mine design is a selection of the best mining method. The selection of mining method is a multi-criteria decision-making problem which needs to be managed appropriately. Selection Process deals with some factors affecting on selection approach. Since decision-making problems in the field of engineering mining usually bear uncertainty, decision methods employ the fuzzy theory. Therefore, the fuzzy TOPSIS is used for the selection of mining method in the Kamar Mahdi Fluorine Mine. In this regard, 14 criteria are considered. Based on technical characteristics of this ore body such as thickness, slope, shape, strength of the ore and rock mass, four mining methods (alternatives) including cut-and-fill stoping (A_1), sublevel stoping (A_2), square-set stoping (A_3) and shrinkage stoping (A_4) are executable. The alternatives are evaluated according to respective criteria based on technical and experimental experiences as well as decision makers and experts' opinions. Finally, the alternatives are ranked by the fuzzy TOPSIS method, leading to the selection of shrinkage stoping as the best mining method.

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REFERENCES

Adler, L., Thompson, S.D., 1992. *Mining method classification systems*, SME Mining Engineering Handbook, Society for Mining Engineering, Metallurgy and Exploration, Inc. 531-537.

Alpay, S., Yavuz, M., 2009. *Underground Mining Method Selection by Decision Making Tools*, Tunnelling and Underground Space Technology, Vol. 24, No. 2, 173-184.

Ashrafzadeh, M., Mokhatab Rafiei, F., Mollaverdi Isfahani, N., Zare, Z., 2012. *Application of Fuzzy TOPSIS Method for the Selection of Warehouse Location: A Case Study*, Interdisciplinary Journal of Contemporary Research in Business, Vol. 3, No. 9, 655-671.

Ataei, M., Shahsavany, H., Mikaeil, R., 2013. *Monte Carlo Analytic Hierarchy Process (MAHP) Approach to Selection of Optimum Mining Method*, International Journal of Mining Science and Technology, Vol. 23, No. 4, 573–578.

Azadeh, A., Osanloo, M., Ataei, M., 2010. *A new approach to mining method selection based on modifying the Nicholas technique*, Applied Soft Computing, Vol. 10, No. 4, 1040-1061.

Bakhtavar, E., Shahriar, K., Oraee, K., 2009. *Mining Method Selection and Optimization of Transition from Open Pit to Underground in Combined Mining*, Journal of Archives of Mining Sciences, Vol. 54, No. 3, 481–493.

Balusa, B.C., Singam, J., 2017. *Underground Mining Method Selection Using WPM and PROMETHEE*, Journal of the Institution of Engineers (India): Series D, 1–7.

Bitarafan, M.R., Ataei, M., 2004. *Mining Method Selection by Multiple Criteria Decision Making Tools*, The Journal of The South African Institute of Mining and Metallurgy, Vol. 104, No. 9, 493-498.

Bogdanovic, D., Nikolic, D., Ilic, I., 2012, *Mining Method Selection by Integrated AHP and PROMETHEE Method*, Annals of the Brazilian Academy of Sciences, Vol. 84, No. 1, 219-233.

Bojadziev, G., Bojadziev, M., 1998. *Fuzzy Sets and Fuzzy Logic, Applications*, World Scientific Publishing, Singapore.

Boshkov, S.H., Wright, F.D., 1973. *Basic and Parametric Criteria in the Selection, Design and Development of Underground Mining Systems*, SME Mining Engineering Handbook, A.B. Cummins and I.A. Given, (eds.), Vol.1. SME-AIME., New York, 12.2–12.13.

Brady, B.H.G., Brown, E.T., 1985. *Rock Mechanics for Underground Mining*, George Allen and Unwin, London.

Bullock, R.L., 2011, *Comparison of Underground Mining Methods*, In: P. Darling, ed. SME Mining Engineering Handbook. USA: Society for Mining, Metallurgy, and Exploration, Inc., Chapter 6.5, pp: 385-403.

Carter, P.G., 2011. *Selection Process for Hard-Rock Mining*, In: P. Darling, ed. SME Mining Engineering Handbook. USA: Society for Mining, Metallurgy, and Exploration, Inc. Chapter 6.3, 357-376.

Chen, C.T., 2000. *Extensions of the TOPSIS for Group Decision Making Under Fuzzy Environment*, Fuzzy Sets and Systems, Vol. 114, No. 1, 1–9.

Chen, C., Lin, C.T., Huang, S.F., 2006. *A Fuzzy Approach for Supplier Evaluation and Selection in Supply Chain Management*, International Journal of Production Economics, Vol. 102, No. 2, 289–301.

Clayton, C., Pakalnis, R., Meech, J.A., 2002. *A Knowledge-based System for Selecting a Mining Method*, IPPM Conf., Canada, 161–178.

Deere, D.U., Hendron, A.J., Patton, F.D., Cording, E.J., 1967. *Design of Surface and near Surface Construction, In: Fairhurst C, editor. Failure and Breakage of Rock: Proceedings of the 8th U.S. Symposium on Rock Mechanics*. New York: American Institute of Mining, Metallurgical, and Petroleum Engineers, Inc., 237-302.

Dehghani, H., Siami A., Haghi, P., 2017. *A New Model for Mining Method Selection Based on Grey and TODIM Methods*, Journal of Mining and Environment, Vol. 8, No. 1, 2017, 49-60.

Demirci, A., Ceylanoglu, A., Kahriman, A., 1995. *Determined of Optimum Underground Mining Method at Aegean Metal Eskisehir Chrome Enterprise and Projected Studies*, Final Report. Cumhuriyet University, Sivas, Turkey.

Gardner, E.D., Vanderburg, W.O., 1982. *Square-Set System of Mining*,. in Underground Mining Methods Handbook, ed. By W. A. Hustrulid. New York: SME– AIME, Section 3.4.2, 667-729.

Guray, C., Celebi, N., Atalay, V., Pasamehmetoglu, A.G., 2003. *Ore-age: A Hybrid System for Assisting and Teaching Mining Method Selection*, Expert Systems with Applications, Vol. 24, No. 3, 261–271.

Hamrin, H., 1980. Guide to Underground Mining: Methods and Applications. Stockholm, Sweden: Atlas Copco.

Hamrin, H., 1982. *Choosing an Underground Mining Method, Underground Mining Methods Handbook*. ed. By W. A. Hustrulid. New York: SME– AIME, Section 1.6, pp: 88-112.

Hamrin, H., 1998. *Choosing an Underground Mining Method*. In Techniques in Underground Mining. Edited by R.E. Gertsch and R.L. Bullock. Littleton, CO: SME.

Hartman, H.L., 1992. *Selection Procedure*, SME Mining Engineering Handbook. New York: AIME Vol. 2, No. 23.4, 2090-2106.

Hartman, H.L., Mutmansky, J.M., 2002. *Introductory Mining Engineering*, John Wiley and Sons, 344 P.

Hwang, C.L., Yoon, K., 1981. *Multiple Attribute Decision Making Methods and Applications*, Springer – Heidelberg, Berlin.

Javanshirgiv , M., Taheri Moghadder, M., Safari, M., 2017. *The selection of appropriate mining method for the Deh Gheybi Granite Quarry Mine using the FTOPSIS method*, International Journal of Mining and Mineral Engineering, Vol. 8, No. 2, 113-130.

Kahriman, A., Ceylanoğlu, A., Demirci, A., Arpaz, E., Görgülü, K., 1994. *Selection of Optimum Underground Mining Method for Kayseri Pinarbasi-Pulpinar Chromite Ore*, Bulletin of Chamber of Mining Engineers of Turke, Vol. 25, No. 4, 27-41.

Kazi, A.U.Z., 2012. *A Fuzzy TOPSIS Based Multi Criteria Performance Measurement Model for Lean Supply Chain*, MSc thesis, Queensland University of Technology (QUT).

Ko, M., Tiwari, A. Mehnen, J., 2010. *A Review of Soft Computing Applications in Supply Chain Management*, Applied Soft Computing, Vol. 10, No. 3, 661–674.

Laubscher, D.H., 1977. *Geomechanics Classification of Jointed Rock Masses-Mining Applications, Transactions Institute of Minerals and Metals*, Section A., Vol. 86, A1-A7.

Laubscher, D.H., 1981. *Selection of Mass Underground Mining Methods, In: D. Stewart, ed. Design and Operation of Caving and Sublevel Stoping Mines*, New York: SME-AIME, 23-38.

Laubscher, D.H., Page, C.H., 1990. *The Design of Rock Support in High Stress or Weak Rock Environments*, Ottawa, ON, CIM.

Miller, T.L., Pakalnis, R., Poulin, R., 1995. *UBC Mining Method Selection*, University of British Columbia, Vancouver, Canada.

Mohammadi Farzami, S., Vafaei, F., 2013. *Evaluation and Selection of Optimal Contractor to Execute Project Using FTOPSIS Method (Case Study: Kermanshah Gas Company)*, International Research Journal of Applied and Basic Sciences, Vol. 6, No. 4, 450-459.

Morrison, R.G.K., 1976. *A Philosophy of Ground Control*, McGill University, Montreal, Canada, 125–159.

Nădăban, S., Dzitac, S., Dzitac, I., 2016. *Fuzzy TOPSIS: A General View*, Procedia Computer Science, Vol. 91, 823 – 831.

Nicholas, D.E., 1981. *Method Selection—A Numerical Approach, Design and Operation of Caving and Sublevel Stoping Mines*, Chap.4, D. Stewart, (ed.), SME-AIME, New York, 39–53.

Nicholas, D.E., 1992. *Selection method, SME Mining Engineering Handbook*, Howard L. Hartman (ed.), 2nd edition, Society for Mining Engineering, Metallurgy and Exploration, Inc., 2090–2106.

Nieto, A., 2011. *Selection Process for Underground Soft-Rock Mining*, In: P. Darling, ed. SME Mining Engineering Handbook. USA: Society for Mining, Metallurgy, and Exploration, Inc., Chapter 6.4, 377-384.

Njamba, N.M., Mutambo, V., 2016. *Design an Appropriate Mining Method for Extraction of Ore between 330ml and 400ml at Baluba East Upper T- Block*, International Journal of Mining Engineering and Mineral Processing , Vol. 5, No. 1, 16-23.

Peskens, T.W., 2013. *Underground Mining Method Selection and Preliminary Techno-Economic Mine Design for the Wombat Orebody, Kylylahti Deposit*, MSc thesis, Delft University of Technology, Finland.

Ozfirat, M.K., 2012. *A Fuzzy Method for Selecting Underground Coal Mining Method Considering Mechanization Criteria*, Journal of Mining Science, Vol. 48, No. 3, 533-544.

Ozfirat, P.M., Ozfirat, M.K., Malli, T., Kahraman, B., 2015. *Integration of Fuzzy Analytic Hierarchy Process and Multi-Objective Fuzzy Goal Programming for Selection Problems: An Application on Roadheader Selection*, Journal of Intelligent & Fuzzy Systems, Vol. 29, 53–62.

Rahimi Ghazikalayeh, A., Ebrahimabadi, A., Alavi, I., 2014. *Selecting Proper Mining Method Using Fuzzy AHP Approach (Case study: Qaleh-Zari Copper Mine of Iran)*, Journal of Applied Science and Agriculture, Vol. 9, No. 1, 1-10.

Rudnik, K., Kacprzak, D., 2017. *Fuzzy TOPSIS method with ordered fuzzy numbers for flow control in a manufacturing system*, Applied Soft Computing, Vol. 52, 1020-1041.

Safari, M., Kakaei, R., Ataei, M., Karamoozian, M., 2012. *Using Fuzzy TOPSIS Method for Mineral Processing Plant Site Selection. Case study: Sangan Iron Ore Mine (Phase 2)*, Arabian Journal of Geosciences, Vol. 5, No. 5, 1011-1019.

Samimi Namin, F., Shahriar, K., Ataee-pour, M., Dehghani, H., 2008. *A New Model for Mining Method Selection of Mineral Deposit based on Fuzzy Decision Making*, Journal of the Southern African Institute of Mining and Metallurgy, Vol. 108, No. 7, 385-395.

Shahriar, K., Shariati, V., Samimi Namin, F., 2007. *Geomechanical Characteristics Study of Deposit in Underground Mining Method Selection Process*, 11th ISRM Conf., Portugal, 196–199.

Shariati, S., Yazdani-Chamzini, A., Pourghaffari Bashari, B., 2013. *Mining Method Selection by Using an Integrated Model*, International Research Journal of Applied and Basic Sciences, Vol. 6, No. 2, 199-214.

Torfi, F., Zanjirani Farahani, R., Rezapour S., 2010. *Fuzzy AHP to Determine the Relative Weights of Evaluation Criteria and Fuzzy TOPSIS to Rank the Alternatives*, Applied Soft Computing, Vol. 10 No. 2, 520-528.

Tymshore, I., 1981. *Computer Evaluation of Mining Projects*, Mining Journal, Vol. 2, No. 111.

Wang, T.C., Chang, T.H., 2007. *Application of TOPSIS in Evaluating Initial Training Aircraft Under a Fuzzy Environment*, Expert Systems with Applications, Vol. 33, No. 4, 870-880.

Yavuz, M., Alpay, S., 2008. *Underground Mining Technique Selection by Multicriterion Optimization Methods*, Journal of Mining Science, Vol. 44, No. 4, 391–401.

Yun, Q.X., Huang, G.Q., 1987. *Fuzzy Set Approach to the Selection of Mining Method*, Mining Science and Technology, Vol. 6, 9–16.

Zadeh, L.A., 1975. *The Concept of a Linguistic Variable and Its Application to Approximate Reasoning*, Information Sciences, Vol. 8, No. 3, 99–249 (I); No. 4, 301–357 (II).

Zare Naghadehi, M., Mikaeil, R., Ataei, M., 2009. *The Application of Fuzzy Analytic Hierarchy Process (FAHP) Approach to Selection of Optimum Underground Mining Method for Jajarm Bauxite Mine*, Iran, Expert Systems with Applications, Vol. 36, No. 4, 8218–8226.