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USING A INTEGRATED MCDM MODEL FOR MINING METHOD SELECTION IN PRESENCE OF UNCERTAINTY

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The aim objective of this study is to model mining method selection problem for a real world case in Angouran mine which is one of the major zinc producers in Iran. According to many problems of ore body extraction are direct or indirect depend on underground mining method, this issue is one of the most critical decisions in the design stage of mine that should be made. A number of the evaluation criteria that often are in conflicting with each other exist for evaluating feasible mining methods. Therefore, the problem of mining method selection is a multi-criteria decision making (MCDM) issue. On the other hand, according to the sophisticated structure of the problem, imprecise data,less of information, and inherent uncertainty, the usage of the fuzzy sets can be useful. In this paper an integrated model based on fuzzy analytic hierarchy process (FAHP) and fuzzy technique for order preference by similarity to ideal solution (FTOPSIS) is developed. FAHP is applied to determine the relative weights of the evaluation criteria for mining method selection that these weights are inserted to the FTOPSIS technique to rank the alternatives and select the most appropriate alternative. The study was followed by the sensitivity analysis of the results. The results of this study demonstrate the efficiency, capability, and robustness of the proposed model, which can be applied to different types of sophisticated problems in reality.

Keywords:

Mining method selection

MCDM

FTOPSIS

FAHP

Group decision-making

JEL:
C02, C44
C54, D81
M11, M20
L16, L72
P11, P41

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I. INTRODUCTION

Mining, one of the most important activities, is applied in order to extract mineral resources from the earth. This activity has played a much more significant role in the development of civilization (Hartman, 1992). Mining is divided into two main parts, including surface and underground mining. The former is called when the process of mineral extraction is carried out by removing the overburden. The latter is termed when all extractions are accomplished beneath the earth's surface.Both surface and underground mining are fallen into different mining methods.

Underground mining method selection is one of the most critical decisions in the design stage of mine that should be made. Because the ground control on the mining areas, planning the ventilation system, decreasing the maintenance costs of gallery, developing new mining panels and preparing the underground production schedule are also directly related to underground mining method selection, such like geology of deposit (Alpay, Yavuz, 2007, 2009).These issues indicate the importance and complication of mining method selection in mining projects.

This selection is a complex and sophisticated decision making problem because various qualitative and quantitative criteria may affect the decision. Increasing the number of criteria in decision making process makes the decision problem more complex, but the rightness of the decision also increases (Alpay, Yavuz, 2009). According to the complexity of the decision process, many traditional methods take into account only limited number of criteriaand in these methods, the problem is analyzed from quantitative viewpoint (Boshkov, Wright, 1973;Morrison, 1976;Laubscher, 1981;Nicholas,1981; Hartman, 1987; Miller-Tait *et al.* 1995). Therefore, it is a need to use the methods that are able to take into account all effective criteria.

The merit of using multi-criteria decision making (MCDM) methods is their ability to solve complex and multi criteria problems by handling both quantitative and qualitative criteria. The MCDM methods arestrong tools for determining the best alternative among a pool of the feasible alternatives in mining method selection (Table 1).

TABLE 1. MCDM METHODS USED IN MINING METHOD SELECTION

Reference	Method	Considered problem
Leeneer, Pastijn, 2002	PROMETHEE	Selecting land mine detection strategies
Namin,*et al.*, 2009	AHP- PROMETHEE	Selecting of suitable mining method selection
Alpay, Yavuz, 2007	AHP	Underground mining method selection
Alpay, Yavuz, 2009	AHP	Underground mining method selection
Musingwini, 2010	AHP	Techno-Economic Optimization of Level and Raise
Owusu-Mensah, Musingwini, 2011	AHP	Evaluation of ore transport
Bazzaz,*et al.* 2009	AHP-TOPSIS	Optimal Open Pit Mining Equipment Selection
Bazzaz,*et al.* 2011	FAHP	Open pit mines equipment selection
Azadeh,*et al.* 2010	FAHP	Mining method selection
Bangian,*et al.* 2011	FAHP	Post mining land use for pit area
Naghadehi,*et al.* 2009	FAHP	Selection of Optimum Underground Mining Method
Mikaeil, *et al.* 2009	FAHP	Selection of the Optimum Underground Mining Method
Fouladgar, *et al.* 2012	AHP-Fuzzy COPRAS	Maintenance strategy selection
Lashgari, *et al.* 2011	FAHP-FTOPSIS	Model for shaft sinking method selection
Lashgari, *et al.* 2012	AHP- ANP- TOPSIS	Equipment selection
Namin, *et al.* 2008	FTOPSIS	Mining method selection of mineral deposit
Bazzaz,*et al.* 2008	FTOPSIS	Loading-haulage equipment selection in open pit mines
Yazdani-Chamzini, Yakhchali, 2012a	FTOPSIS-AHP	Handling equipment Selection in open pit mines
Yazdani-Chamzini, Yakhchali, 2012b	FAHP-FTOPSIS	Evaluation of tunneling projects
Azimi,*et al.* 2011	SWOT-ANP-VIKOR	Evaluating the strategies of the mining sector

Source: Author's calculation

Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) is one common MCDM method that takes into consider the ideal and the anti-ideal solutions simultaneously. This technique is applied by different researches because of being rational, simple computations, and results are obtained in shorter time than other methods such as AHP (analytical hierarchy process) and ANP (analytic network process) (Fouladgar,*etal.* 2011; Lashgari,*etal.* 2011).

According to the inherent complexity and uncertainty associated with real world problems as well as the vagueness of human feeling, it is difficult for decision makers to express their opinions with precise numerical values for the criteria and alternatives.However, TOPSIS is often criticized for its inability to deal with vague and uncertain problems (Yu,*et al.* 2011), so that; without considering the inherent uncertainty, the results may be unrealistic and unreliable.

On the other hand, fuzzy logic is a powerful mathematical tool that is capable to handle the existing uncertainty. Therefore, TOPSIS is combined with fuzzy logic in order to eliminate the drawbacks of the conventional TOPSIS, which is well-known asFTOPSIS. This technique has been adopted in many different applications, includingservice quality (Büyüközkan, Çifçi, 2012; Awasthi,*et al.* 2011a), strategic management (Ding, 2005; Kahraman, 2004; Kabak, 2012; Fu, 2007; Dağdeviren, 2009; Paksoy,*et al.* 2011; Fouladgar,*et al.* 2011), risk assessment (Braglia,*et al.* 2003; Wang, Elhag, 2006; KarimiAzari *et al.* 2011; Fouladgar, *et al.* 2012), supply chain management (Chen, *etal.* 2006), location selection (Yong, 2006; Anagnostopoulos *et al.* 2008; Montazeri, 2011), service quality (Tseng, 2011; Önüt, 2010), transportation system (Awasthi *et al.* 2011b; Zandi, Tavana, 2011) and in mining method selection (Lashgari, *et al.* 2011; Namin, *et al.* 2008; Bezzazi, *et al.* 2008; Fouladgar, *et al.* 2012; Yazdani-Chamzini, Yakhchali, 2012 a,b).

It is clear that this technique has demonstrated its capability and effectiveness as a practical engineering and problem-solving tool.

On the other hand, AHP (analytical hierarchy process) is widely used to calculate the weights of evaluation criteria. This method use pair-wise comparison for obtaining the relative weights of criteria. AHP is strongly connected to human judgment and pairwise comparisons in AHP may cause evaluator's assessment bias which makes the comparison judgment matrix inconsistent (Aydogan, 2011). Therefore, fuzzy analytical hierarchy process (FAHP) is employed to solve the bias problem in AHP. AFAHP method used in mining method selection (Bezzazi, *et al.* 2011; Azadech, *et al.* 2010; Bagdian, *et al.* 2011; Naghadehi,*et al.* 2009; Mikaeil,*et al.* 2009). FAHP method with FTOPSIS method used in different applications (Torfi,*et al.* 2010; Chen, Yang, 2011; Rostamzadeh,*et al.* 2011; Ic, Yurdakui, 2009; Zouggari, Benyoucef, 2012; Kung,*et al.* 2011; Yazdani-Chamzini, Yakhchali, 2012 a,b; Lashgari, *et al.* 2011).

The main aim of this paper is to develop an integrated model based on FAHP and FTOPSIS methods in order to evaluatemining methodsand select the best alternative inthe Anguran mine.FTOPSIS is employed to select a mining method and the FAHP isapplied to calculate criteria weights.

The rest of this paper is organized as follows. In section 2, a brief review of fuzzy theory is presented, including fuzzy sets, fuzzy numbers, and linguistic variables.Section 3 illustrates the FAHP methodology for calculating the relative weights of evaluation criteria. The procedure of the Fuzzy TOPSIS method is describedin section 4. The proposed model is presented in section 5. Section 6 presents an empirical study of mining method selection. A sensitivity analysis is conducted in section 7. Finally, concluding remarks are discussed in section 8.

II. FUZZY THEORY

Complexity is an important part of most real world decision problems that is due to the existing uncertainty, imprecise knowledge, and less of information. The use of the techniques and tools that allow the available information to be used with the adequate guaranty is desired fordealing with such complexity. Fuzzy logic, introduced by Zadeh (1965), is a powerful tool for facing with this type of problems. Fuzzy numbers may be of almost any shape (though conventionallythey are required to be convex and to have finite area), but frequently they will be triangular (piecewise linear), s-shape (piecewise quadratic) or normal (bell shaped) (Kelemenis *etal.* 2011).

A triangular fuzzy number (TFN) is defined as $\tilde{A} = (a,b,c)$; which *a*, *b*, and *c* are crisp numbers and $a \le b \le c$.

A fuzzy number is defined by its membership function whose values can be any number in the interval [0, 1]. Assume that TFNs start rising from zero at*x*=*a*; reach a maximum of 1 at *x* = *b*; and decline to zero at *x* = *c* as shown in Fig. 1.Then the membership function $\mu_{\tilde{A}}(x)$ of a TFN is given by

$$\mu_{\tilde{A}}(x) = \begin{cases} 0, & x < a \\ (x-a)/(b-a), & a \le x < b \\ (x-c)/(b-c), & b \le x < c \\ 0, & x > c \end{cases} \tag{1}$$

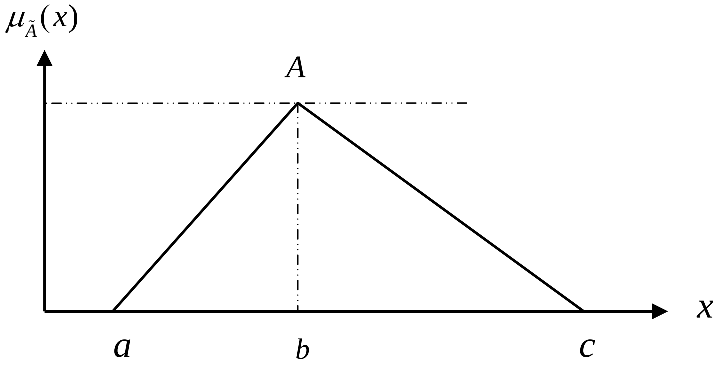

FIGURE .1. TRIANGULAR FUZZY NUMBER

Source: Author's calculation

Let $\tilde{a} = (a_1, b_1, c_1)$ and $\tilde{b} = (a_2, b_2, c_2)$ be two TFNs then the vertex method is defined to compute the distance between them by Eq. (2):

$$d(\tilde{a},\tilde{b}) = \sqrt{\frac{1}{3}\left[(a_1-a_2)^2 + (b_1-b_2)^2 + (c_1-c_2)^2\right]} \tag{2}$$

III. FUZZY AHP

Analytical hierarchy process (AHP), proposed by Saaty (1980),is a popular MCDM method that decomposes a sophisticated problem into ahierarchy. The elements of hierarchy levels are compared in pairs to assess their relative preference with respect to each of the elements at the next higher level(Singh & Benyoucef, 2011). The AHP is widely employed for tackling multi-criteria decision making problems in real world applications. However, in many practical cases the human preference model is uncertain and evaluator might be reluctant or unable to assign crisp values tothe comparison judgments (Chan & Kumar, 2007).The merit of using a fuzzy approach is to determine the relative importance of attributes using fuzzy numbers instead of precise numbers (Önüt, Soner, 2008; Sun, Lin, 2009; Sun, 2010; Kara, 2011).There are many fuzzy AHP methods proposed on the basis of the concepts of the fuzzy set theory and hierarchical structure by various researchers to solve the selection problems in different fields of application (Van Laarhoven and Pedrycz, 1983; Buckley, 1985;Boender et *al.* 1989; Chang, 1996;Cheng, 1996).

In this study, we use Chang's extent analysis method (Chang, 1996) due to its computational simplicity and effectiveness. This method utilizes TFNs for pairwise comparison matrices. Modeling using TFNs has demonstrated to be a successful way for formulating decision making problems where the information available is subjective and imprecise (Dağdeviren & Yüksel, 2008).

Let X = {x_1, x_2, ..., x_n} be an object set and *U* = {u_1, u_2, ..., u_m} be a goal set. According to the method of Chang's extent analysis, each object is taken and extent analysis for each goal, *gi*, is performed, respectively. Therefore, *m* extent analysis values for each object can be obtained, with the following signs: $M_{gi}^1, M_{gi}^2, \ldots, M_{gi}^m$, $i = 1, 2, \ldots, n.$ Where all the M_{gi}^j $(j = 1, 2, \ldots, m)$ are TFNs.

The procedure of Chang's extent analysis is defined in the following steps:

Step 1- The value of fuzzy synthetic extent with respect to *i*th object is calculated as:

(3)

$$S_i = \sum_{j=1}^{m} M_{gi}^j \otimes \left[\sum_{i=1}^{n} \sum_{j=1}^{m} M_{gi}^j \right]^{-1}$$

To obtain $\sum_{j=i}^{m} M_{gi}^j$, perform the fuzzy addition operation of *m* extent analysis values for a particular matrix such that

(4)

$$\sum_{j=1}^{m} M_{gi}^j = \left(\sum_{j=1}^{m} l_i, \sum_{j=1}^{m} m_i, \sum_{j=1}^{m} u_i \right)$$

And to obtain $\left[\sum_{i=1}^{n} \sum_{j=1}^{m} M_{gi}^j \right]^{-1}$, perform the fuzzy addition operation of M_{gi}^j $(j = 1, 2, \ldots, m)$ values such that

$$\sum_{i=1}^{n}\sum_{j=1}^{m} M_{gi}^{j} = \left(\sum_{i=1}^{n} l_i, \sum_{i=1}^{n} m_i, \sum_{i=1}^{n} u_i\right) \tag{5}$$

And then calculate the inverse of the vector in Eq. (6) such that

(6)

$$\left[\sum_{n=1}^{n}\sum_{j=1}^{m} M_{gi}^{j}\right]^{-1} = \left(\frac{1}{\sum_{i=1}^{n} u_i}, \frac{1}{\sum_{i=1}^{n} m_i}, \frac{1}{\sum_{i=1}^{n} l_i}\right)$$

Step 2- The degree of possibility of $M_2 = (l_2, m_2, u_2) \geq M_1 = (l_1, m_1, u_1)$ is assigned as

(7)

$$V(M_2 \geq M_1) = \sup_{y \geq x} \ [\min(\mu_{M1}(x), \mu_{M2}(y))]$$

And can be equivalently expressed as follows:

(8)

$$V(M_2 \geq M_1) = hgt(M_1 \cap M_2) = \ \mu_{M2}(d) = \begin{cases} 1, & \text{if } m_2 \geq m_1 \\ 0, & \text{if } l_1 \geq u_2 \\ \dfrac{l_1 - u_2}{(m_2 - u_2) - (m_1 - l_1)}, & \text{otherwise} \end{cases}$$

Both the values of $V(M_1 \geq M_2)$ and $V(M_2 \geq M_1)$ are needed to compare M_1 and M_2.

Step 3- The degree of possibility for a convex fuzzy number to be greater than *k* convex fuzzy numbers M_i (*i*=1, 2, ... , *k*) can be computed by

(9)

$$\begin{aligned} V(M \geq M_1, M_2, \ \ldots, M_k) &= V[(M \geq M_1) \text{ and } (M \geq M_2) \text{ and ... and } (M \geq M_k)] \\ &= \min \ V(M \geq M_i), \qquad \text{i=1, 2, ... , k} \end{aligned}$$

Assume that

(10)

$$d'(A_i) = \min \ V(S_i \geq S_k)$$

For *k* = 1, 2, ... , *n*; $k \neq i$.

Then the weight vector is obtained by

$$W' = (d'(A_1), d'(A_2), ..., d'(A_n))^T$$

WhereA_i (i=1, 2, … , n) are n elements.

Step 4- The normalized weight vectors are resulted through normalization

$$W = (d(A_1), d(A_2), \ldots, d(A_n))^T \tag{11}$$

Where W is a non-fuzzy number.

IV. FUZZY TOPSIS

The Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) was first introduced by Hwang and Yoon (1981).TOPSIS method is based on the concept that the most appropriate alternative shouldhave the shortest distance from the positive ideal solution (PIS)and the farthest distance from the negative ideal solution (NIS). PIS minimizes the cost criteria and maximizes the benefit criteria, whereas the NIS minimizes the benefit criteria and maximizes the cost criteria (Kelemenis *et al.* 2011). There have been plenty of studies related with the TOPSIS method in the literature (Parkan & Wu, 1999; Gamberini *et al.* 2006; Yu *et al.* 2009; Chen *et al.* 2009; Antuchevičiene*et al.* 2010, 2011;~~Tupenaite et al. 2010;~~ Chang *et al.* 2010). In the TOPSIS method, decision makers' judgments are represented with crisp values. According to the problems associated with determining the precise preference rating to an alternative for the criteria under consideration, decision makers are keen onusing fuzzy numbers instead of precise numbers. For this reason, the fuzzy TOPSIS method is appropriate for solving real world problems under a fuzzy environment (Li, 2007; Chen & Tsao, 2008; Ashtiani et *al.* 2009; Wang et *al.* 2009; Torfi et *al.* 2010; Chen & Hung, 2010; Tupenaite *et al.* 2010; Han&Liu, 2011; Aydogan, 2011; Huang & Peng, 2011; Fouladgar et *al.* 2011; Chen, 2011; Sadi-Nezhad, Damghani, 2011; Kutlu & Ekmekçioğlu, 2012; Awasthi & Chauhan, 2012). The major steps of the FTOPSIS can be described as follows:

Step 1. Choose the linguistic variablesfor the alternatives with respect to the evaluation criteria.The linguistic variables are linguistic terms that express the values by words or sentences. Each linguistic value can be representedby a TFN which can be assigned to amembership function. In this study, we employed TFNs be associated to the linguistic values and scales of five points for the ratings of alternatives (Table 2 and Fig. 2) and ten points for importance weights of the evaluation criteria (Table 3 and Fig. 3).

TABLE 2. LINGUISTIC VARIABLES FOR EACH CRITERION

Linguistic variables	Triangular fuzzy number
Equally preferred (EP)	(1,1,2)
Equally to moderately (EM)	(1,2,3)
Moderately preferred (MP)	(2,3,4)
Moderately to strongly (MS)	(3,4,5)
Strongly preferred (SP)	(4,5,6)
Strongly to very strongly (SVS)	(5,6,7)
Very strongly preferred (VSP)	(6,7,8)
Very strongly to extremely (VSE)	(7,8,9)
Extremely preferred (EXP)	(8,9,10)
Definitely preferred (DP)	(9,10,10)

Source: Author's calculation

TABLE 3. LINGUISTIC VARIABLES FOR THE RATING OF ALTERNATIVES

Linguistic variables	Triangular fuzzy number
Very poor (VP)	(0,0.15,0.3)
Poor (P)	(0.2,0.35,0.5)
Fair (F)	(0.4,0.5,0.6)
Good (G)	(0.5,0.65,0.8)
Very good (VG)	(0.7,0.85,1)

Source: Author's calculation

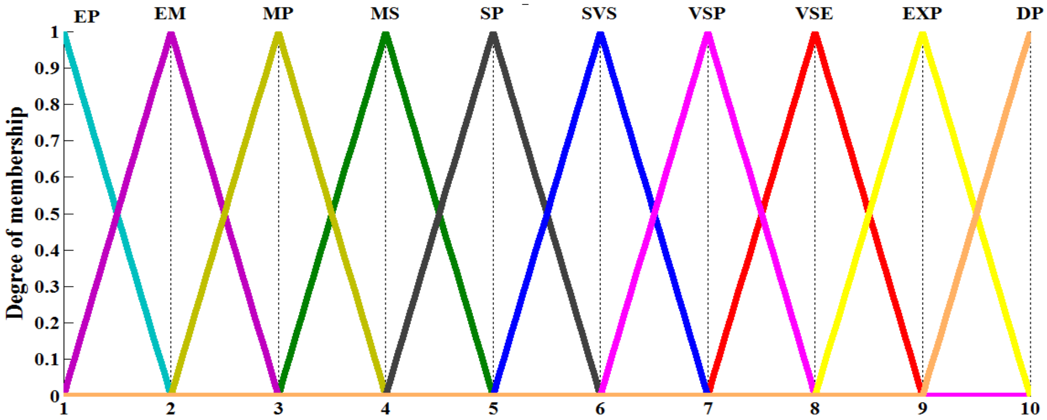

Fig. 2. Membership function of linguistic variables for importance weight

Source: Author's calculation

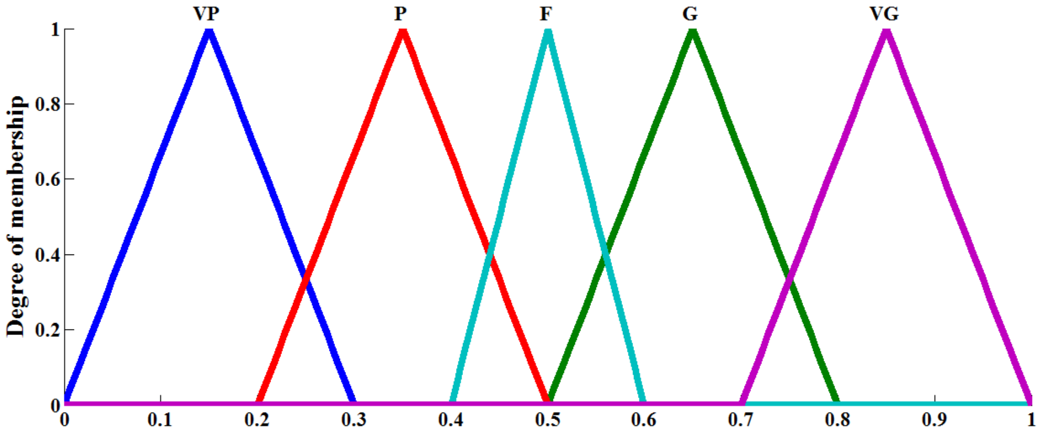

Fig. 3. Membership function of linguistic variables for preference rating

Source: Author's calculation

Step 2. Construct the fuzzy decision matrix.

To calculate the performance of a set of alternatives on a given set of criteria, the decision matrix of $m \times n$ dimension is formed, which m and n are the number of alternatives and criteria respectively.

Step 3. Aggregate the ratings of alternatives respect to each criterion $(\tilde{x}_{ij})$ and fuzzy weights of evaluation criteria $(\tilde{w}_j)$. In order to aggregate the ratings of alternatives versus each criterion and fuzzy weight of each criterion, the arithmetic mean is applied.

Let the fuzzy ratings of all decision makers be TFNs $\tilde{x}_{ijk} = (a_{ijk}, b_{ijk}, c_{ijk})$, $k = 1, 2, \ldots, K$, which $\tilde{x}_{ijk}$ represents the value of the ith alternative respect to the jth criterion by kth decision maker. Then the aggregated fuzzy rating can be defined as

(12)

$$\tilde{x}_{ij} = (a_{ij}, b_{ij}, c_{ij}), \qquad k = 1, 2, \ldots, K$$

Where

$$a_{ij} = \frac{1}{K}\sum_{k=1}^{k} a_{ijk}$$

$$b_{ij} = \frac{1}{K}\sum_{k=1}^{k} b_{ijk}$$

$$c_{ij} = \frac{1}{K}\sum_{k=1}^{k} c_{ijk}$$

Let the fuzzy weights of evaluation criteria be TFNs $\tilde{w}_{jk} = (w_{jk1}, w_{jk2}, w_{jk3})$; *k* =1, 2, . . ., *K*. Then the aggregated fuzzy weight of each criterion can be calculated as

(13)

$$w_j = (w_{j1}, w_{j2}, w_{j3}), \qquad k = 1, 2, ..., K$$

Where

$$w_{j1} = \frac{1}{K}\sum_{k=1}^{k} w_{jk1}$$

$$w_{j2} = \frac{1}{K}\sum_{k=1}^{k} w_{jk2}$$

$$w_{j3} = \frac{1}{K}\sum_{k=1}^{k} w_{jk3}$$

Step 4. Calculate the normalized fuzzy decision matrix.

In order to transform the various criteria scales into a comparable scale, the linear scale transformation is employed. The normalized fuzzy decision matrix can be computed by $\tilde{R}$:

(14)

$$\tilde{R} = [\tilde{r}_{ij}]_{m\times n}$$

and

(15)

$$\tilde{r}_{ij} = \left(\frac{a_{ij}}{c_j^*}, \frac{b_{ij}}{c_j^*}, \frac{c_{ij}}{c_j^*}\right),\ c_j^* = \max_i c_{ij}$$

Step 5. Calculate the weighted normalized fuzzy decision matrix.

We can compute the weighted normalized fuzzy decision matrix by considering the relative importance of evaluation criteria as

(16)

$$\tilde{V} = [\tilde{v}_{ij}]_{m\times n}$$

and

(17)

$$\tilde{v}_{ij} = \tilde{r}_{ij} \times w_j$$

Where $W = \left\{ w_j : j = 1, 2, ..., n \right\}$ normalized criteria weights.

Step 6. Identify positive ideal (A^*) and negative ideal (A^-) solutions. The fuzzy positive –ideal solution and the fuzzy negative-ideal solution are shown in Eqs. (18), (19).

(18)

$$A^* = (\tilde{v}_1^+, \tilde{v}_2^+, \tilde{v}_3^+, ..., \tilde{v}_n^+) = \left\{ \max_i \ v_{ij} \middle| (i = 1, 2, ..., n) \right\}$$

(19)

$$A^- = (\tilde{v}_1^-, \tilde{v}_2^-, \tilde{v}_3^-, ..., \tilde{v}_n^-) = \left\{ \min_i \ v_{ij} \middle| (i = 1, 2, ..., n) \right\}$$

Step 7. Calculate separation measures. The distance of each alternative from A^* and A^- can be currently calculated using Eqs. (20), (21).

(20)

$$d_i^+ = \sum_{j=1}^{n} d(\tilde{v}_{ij}, \tilde{v}_j^+) \ , \ i = 1, 2, ..., m$$

(21)

$$d_i^- = \sum_{j=1}^{n} d(\tilde{v}_{ij}, \tilde{v}_j^-) \ , \ i = 1, 2, ..., m$$

Step 8. Calculate the similarities to ideal solution. This step solves the similarities to an ideal solution by Eq. (22).

(22)

$$CC_i^* = \frac{d_i^-}{d_i^- + d_i^*}$$

Step 9. Rank preference order. Choose an alternative with maximum CC_i^* or rank alternatives according to CC_i^* in descending order.

V. THE PROPOSED MODEL

The proposed model for evaluating the underground mining methods in Angouran mine, contained of FAHP and FTOPSIS methods, comprises of three main steps: (1) determine the main and sub evaluation criteria; (2) calculate the relative weights of criteria by FAHP and (3) evaluate the possible alternatives by FTOPSIS and finally select the optimum alternative among a pool of alternatives. Schematic diagram of the proposed model for mining method selection is depicted in Fig. 4.

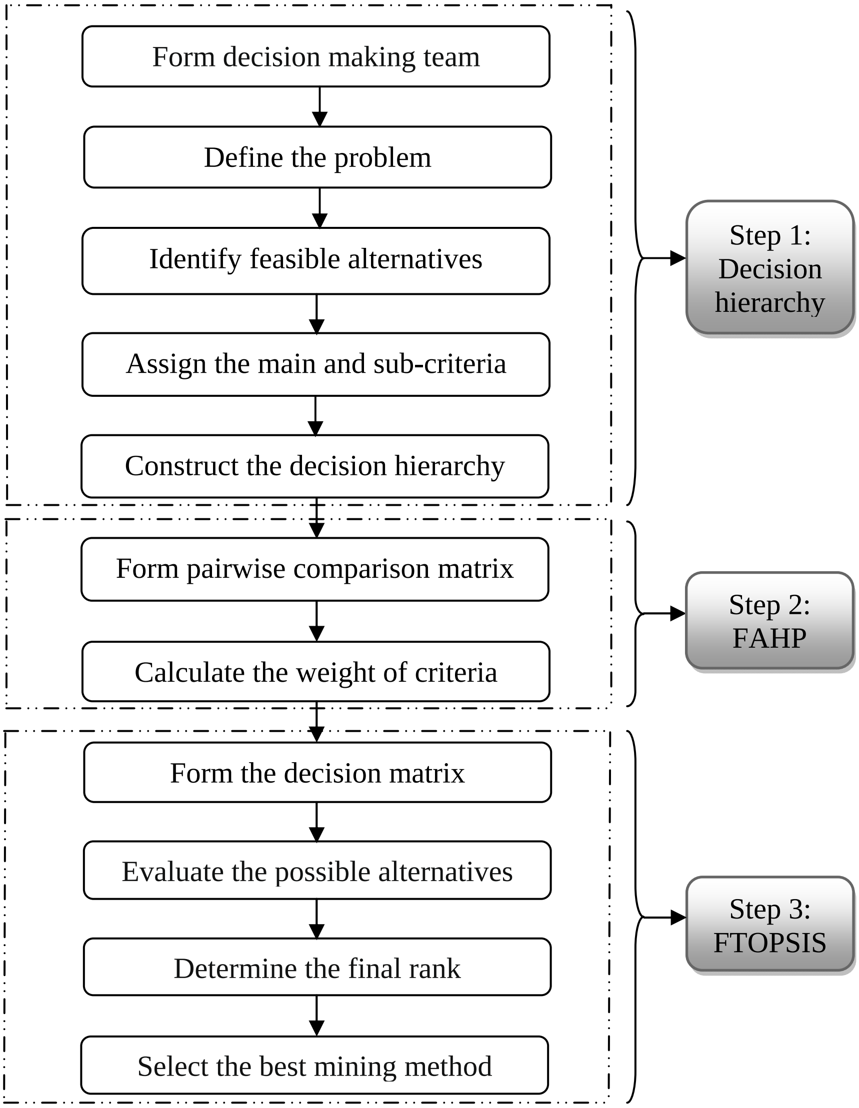

Fig. 4. Schematic diagram of the proposed model

Source: Author's calculation

In the step 1, after defining the problem, the feasible mining methods for the extraction process of the ore are identified. Next, the effective criteria of possible alternatives are determined. In the final phase of the step 1, the decision hierarchy is structured such that the goal is in the first level, evaluation criteria are in the second level, sub-criteria are in the third level, and possible alternatives are on the last level.In the step 2, after constructingthe decision hierarchy, the relative weights of the evaluation criteria are obtained by using the FAHP technique. Based on these evaluation criteria, the required data in order to form the pairwise comparison matrix are collected from expert's knowledge.In the step 3, the performance ratings of the feasible alternatives corresponding to the evaluation criteriaare assigned by applying linguistic variables. Finally, FTOPSIS is appliedto evaluate the alternativesand select the best underground mining method among a pool of alternatives.

VI. AN EMPIRICAL APPLICATION

The purpose of the empirical application is to illustrate the use of the suggested method. Angouran Zn–Pb deposit is located in the western Zanjan province about 450 km northwest of Tehran (Fig. 5a). This deposit is one of the major zinc producers in Iran, a country with approximately 11 million tons of zinc metal constituent. Angouran has 16 million tons of ore with a zinc concentration of 26% and a lead concentration of 6% [4]. This deposit is close to the Urumieh-Dokhtar Magmatic Arc, which is situated within one of a number of metamorphic inlier complexes in the central Sanandaj-Sirjan Zone of the Zagros orogenic belt (Gilg et *al.* 2005). A metamorphic core complex surrounds the Angouran deposit, which comprises amphibolites, serpentinites, gneisses, micaschists, and various, mainly calcitic and rarely dolomitic marbles. Some of the geological specifications of the area are represented in Fig.5b.

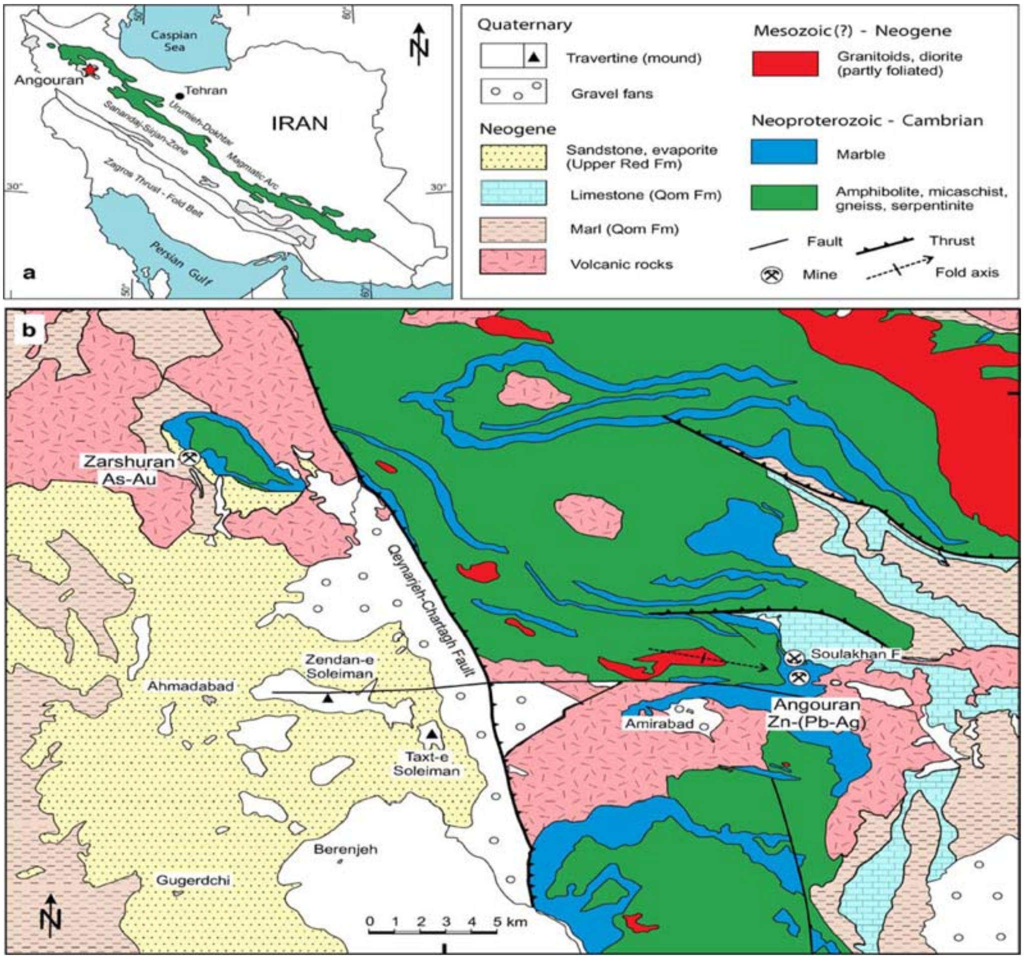

Fig. 5. Geography of Angouran mine (a) and schematic regional geological map of the area (b) (Boni *et al*, 2007)

Source: Author's calculation

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[4] www.turquoisepartners.com

The Angouran orebody is located in the crest of an open anticlinal structure within the metamorphic basement that plunges eastward at 10–20° (Gilg et *al.* 2005). This orebody is some 600 m long in Northern-Southern line and 200–400 m across. The orebody is delimited by two major NNW-SSE and NW-SE trending faults and a third NE-SW fault (Boni et *al.* 2007).

In Angouran mine, extraction of deposit has been started from near surface by open pit mining and it has continued to the level of 2880 meters. According to increasing the extraction depth and environmental requirements, mine is designed to transfer from open pit to underground mining. For this reason, underground mining method should be selected; so that, the evaluation criteria under consideration be satisfied.

A. Determine the main and sub-criteria

Criteria should be determined that cover the requirements connected with the mining method selection problem. For instance, various criteria should be considered for health, safety, and the environment (HSE). As the focus of this study is on mining method selection, the proposed set of criteria, taken from literature review and a number of face to face interviews with experts as well as after preliminary screening, consists of ten technical parameters, nineoperational parameters, and three economical parameters that every mining method should satisfy.

The main characteristics of the technical parameters are Ore body thickness (C11), Ore body shape (C12), Ore body depth (C13), Ore body dip (C14), Footwall RMR[5](C15), Hanging wall RMR (C16), Ore body RMR (C17), Footwall RSS[6] (C18), Hanging wall RSS (C19), and Ore body RSS (C110). The operational parameters to be taken into account are Safety (C21), health (C22), Environmental aspects (C23), Subsidence (C24), Dilution (C25), Flexibility (C26), Production rate (C27), Needed newtechnology (C28), and Having need of skilled labor force (C29). The economical parameters are related to Operating costs (C31), Capital costs (C32), and Reclamation costs (C33).

As a result, these twenty two criteria were employed in the process of the evaluation and decision hierarchy is established accordingly as depicted in Fig. 6.The hierarchy of mining method selection can be divided into three levels: level 1 includes the main goal of the hierarchy, which is selection the most optimum mining method. The main criteria are on the second level. The sub-criteria are located in the third level. Level 4 comprises the feasible alternatives determined by the decision maker team, including Block Caving (A1), Sublevel Stoping (A2), Sublevel Caving (A3), Cut & Fill (A4),Top Slicing (A5), and Square Set Stoping (A6).

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[5] Rock mass rating

[6]Rock Substance strength

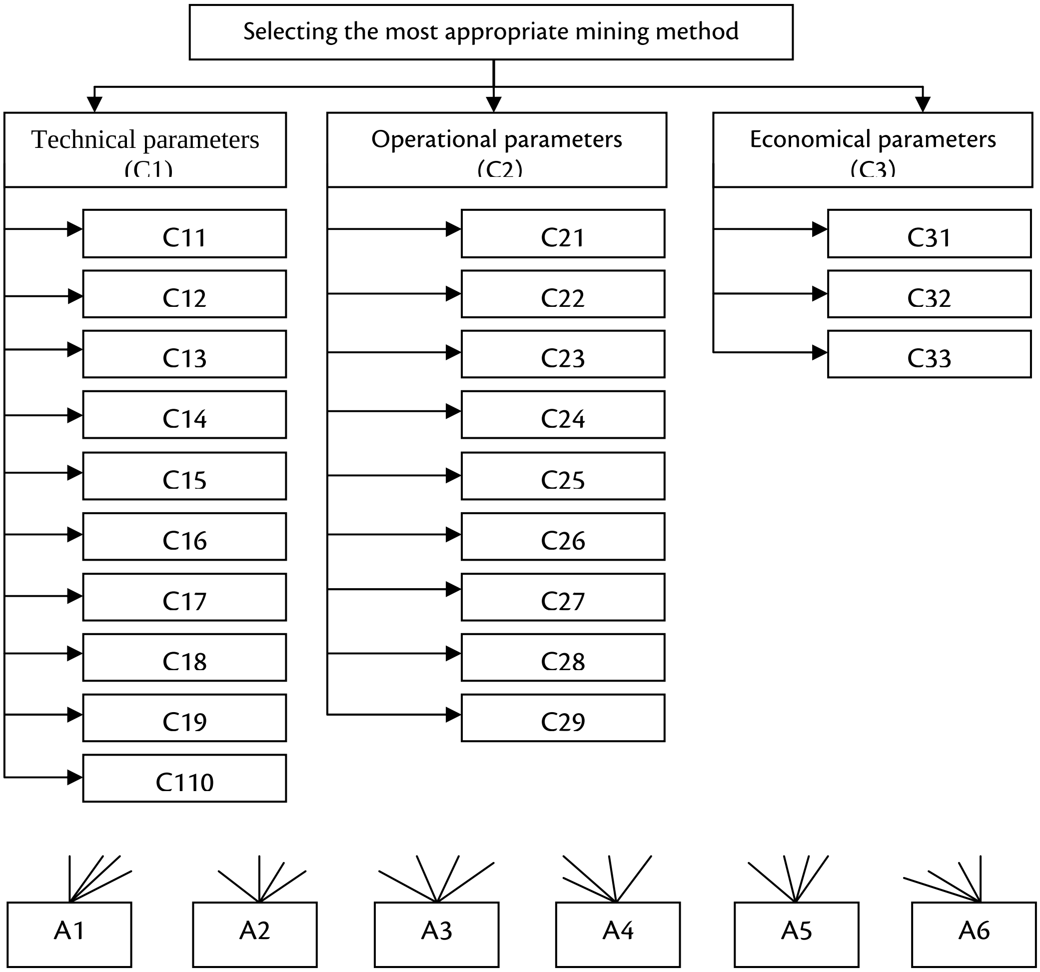

Fig. 6. Decision hierarchy

Source: Author's calculation

B. Calculate the relative weights of criteria by FAHP

After constructing the decision hierarchy for the problem, the relative weights of the main and sub-criteria to be utilized in evaluation process are calculated by using the FAHP method. Group decision is used in assigning the relative importance of the evaluation criteria, as well as in the next steps of this study. An aggregation method is employed to combine expert's judgments. In this step, the fifteendecision makers with a high level of experience in the field of mining design are given the task of constructing individual pairwise comparison matrix by using the scale presented in Fig. 2 and Table 1. Arithmetic means of these values are calculated by using Eq. (13) to obtain the overall pairwise comparison matrixon which there is a consensus. For instance, when comparing the safety (C21) and health (C22) criteria, the responses of fifteen experts are EM, MP, MP, EM, MP, MS, MP, EM, MS, MS, EM, EM, SP, EM and EM, respectively.The results derived from the computations according to the final fuzzy matrices provided in Tables (4), (5), (6), and (7), are presented in Tables(8), (9), (10), and (11), respectively.The weight calculation details by using FAHP are given below.

TABLE 4. FINAL PAIRWISE COMPARISON MATRIX OF TECHNICAL PARAMETERS

	C11	C12	C13	C14	C15	C16	C17	C18	C19	C110
C11	1.00	0.56	1.32	0.51	1.79	1.03	0.64	1.47	1.35	0.56
	1.00	0.90	2.70	0.83	3.70	1.85	0.89	3.45	2.94	0.93
	1.00	1.35	4.17	1.92	5.26	2.78	1.33	5.88	4.76	1.61
C12	0.74	1.00	2.44	0.54	2.63	1.72	1.12	2.70	1.79	1.20
	1.11	1.00	4.35	0.85	3.45	2.56	1.92	3.57	2.78	2.04
	1.78	1.00	7.14	1.28	4.76	3.85	2.78	6.25	4.55	2.94
C13	0.24	0.14	1.00	0.27	0.51	0.37	0.31	0.68	0.34	0.27
	0.37	0.23	1.00	0.36	0.81	0.58	0.45	1.04	0.51	0.37
	0.76	0.41	1.00	0.53	1.15	1.09	0.83	1.59	0.92	0.59
C14	0.52	0.78	1.89	1.00	1.79	0.89	1.15	1.59	1.72	1.10
	1.21	1.17	2.76	1.00	2.78	1.47	1.89	3.23	2.56	1.54
	1.97	1.86	3.76	1.00	4.17	2.38	2.56	5.26	3.70	2.94
C15	0.19	0.21	0.87	0.24	1.00	0.32	0.23	1.05	0.66	0.36
	0.27	0.29	1.24	0.36	1.00	0.47	0.30	1.85	1.09	0.57
	0.56	0.38	1.98	0.56	1.00	0.76	0.43	2.70	1.69	1.02
C16	0.36	0.26	0.92	0.42	1.31	1.00	0.32	1.27	1.19	0.58
	0.54	0.39	1.73	0.68	2.12	1.00	0.47	2.17	1.61	0.90
	0.97	0.58	2.73	1.12	3.12	1.00	0.81	3.70	2.44	1.23
C17	0.75	0.36	1.21	0.39	2.32	1.24	1.00	1.64	1.15	1.59
	1.12	0.52	2.21	0.53	3.32	2.12	1.00	2.56	1.54	2.08
	1.57	0.89	3.21	0.87	4.32	3.12	1.00	4.17	2.44	2.70
C18	0.17	0.16	0.63	0.19	0.37	0.27	0.24	1.00	0.32	0.26
	0.29	0.28	0.96	0.31	0.54	0.46	0.39	1.00	0.46	0.35
	0.68	0.37	1.47	0.63	0.95	0.79	0.61	1.00	0.76	0.53
C19	0.21	0.22	1.09	0.27	0.59	0.41	0.41	1.32	1.00	0.34
	0.34	0.36	1.98	0.39	0.92	0.62	0.65	2.17	1.00	0.52
	0.74	0.56	2.98	0.58	1.51	0.84	0.87	3.17	1.00	0.92
C110	0.62	0.34	1.69	0.34	0.98	0.81	0.37	1.89	1.09	1.00
	1.08	0.49	2.69	0.65	1.76	1.11	0.48	2.89	1.91	1.00
	1.78	0.83	3.69	0.91	2.76	1.72	0.63	3.89	2.91	1.00

Source: Author’s calculation

TABLE 5. FINAL PAIRWISE COMPARISON MATRIX OF OPERATIONAL PARAMETERS

	C21	C22	C23	C24	C25	C26	C27	C28	C29
C21	1.00	0.26	0.32	0.24	0.20	0.25	0.64	0.32	0.30
	1.00	0.35	0.47	0.32	0.26	0.34	0.93	0.47	0.42
	1.00	0.53	0.81	0.48	0.34	0.52	1.28	0.83	0.73
C22	1.87	1.00	1.22	0.39	0.33	0.36	1.47	0.45	0.32
	2.87	1.00	2.08	0.65	0.49	0.56	2.86	0.81	0.46
	3.87	1.00	2.94	1.03	0.89	1.12	4.17	1.47	0.70
C23	1.23	0.34	1.00	0.38	0.26	0.22	1.05	0.36	0.37
	2.11	0.48	1.00	0.62	0.35	0.27	1.64	0.56	0.60
	3.11	0.82	1.00	1.28	0.54	0.38	2.63	1.03	1.09
C24	2.09	0.97	0.78	1.00	0.32	0.32	2.08	0.52	0.35
	3.09	1.55	1.62	1.00	0.47	0.48	3.45	0.89	0.53
	4.09	2.55	2.62	1.00	0.88	0.81	4.76	1.15	0.92
C25	2.92	1.12	1.85	1.14	1.00	0.32	1.92	1.06	0.45
	3.92	2.04	2.85	2.14	1.00	0.48	2.56	2.13	0.81
	4.92	3.04	3.85	3.14	1.00	0.79	3.85	2.94	1.15
C26	1.94	0.89	2.64	1.23	1.27	1.00	3.23	1.19	0.42
	2.94	1.78	3.64	2.08	2.08	1.00	4.17	1.85	0.74
	3.94	2.78	4.64	3.08	3.08	1.00	7.14	2.44	0.94
C27	0.78	0.24	0.38	0.21	0.26	0.14	1.00	0.24	0.22
	1.07	0.35	0.61	0.29	0.39	0.24	1.00	0.31	0.29
	1.57	0.68	0.95	0.48	0.52	0.31	1.00	0.45	0.41
C28	1.21	0.68	0.97	0.87	0.34	0.41	2.23	1.00	0.38
	2.12	1.24	1.78	1.12	0.47	0.54	3.23	1.00	0.61
	3.12	2.24	2.78	1.92	0.94	0.84	4.23	1.00	1.02
C29	1.37	1.43	0.92	1.09	0.87	1.06	2.45	0.98	1.00
	2.37	2.17	1.68	1.87	1.23	1.36	3.45	1.64	1.00
	3.37	3.17	2.68	2.87	2.23	2.36	4.45	2.64	1.00

Source: Author's calculation

TABLE 6. FINAL PAIRWISE COMPARISON MATRIX OF ECONOMICAL PARAMETERS

		C31			C32			C33	
C31	1.00	1.00	1.00	0.89	1.67	2.67	2.21	3.21	4.21
C32	0.37	0.60	1.12	1.00	1.00	1.00	0.98	1.45	2.45
C33	0.24	0.31	0.45	0.41	0.69	1.02	1.00	1.00	1.00

Source: Author's calculation

TABLE 7. FINAL PAIRWISE COMPARISON MATRIX OF MAIN CRITERIA

		C1			C2			C3	
C1	1.00	1.00	1.00	0.78	1.19	1.86	0.94	1.23	1.67
C2	0.54	0.84	1.28	1.00	1.00	1.00	0.58	0.89	1.35
C3	0.60	0.81	1.06	0.74	1.12	1.72	1.00	1.00	1.00

Source: Author's calculation

TABLE 8. VALUES RESULT FOR TECHNICAL PARAMETERS

	S_{11}	S_{12}	S_{13}	S_{14}	S_{15}	S_{16}	S_{17}	S_{18}	S_{19}	S_{110}
$V(S_{11} \geq \cdots)$		1	0.4	1	0.42	0.72	0.93	0.34	0.55	0.82
$V(S_{12} \geq \cdots)$	0.85		0.2	0.97	0.21	0.53	0.76	0.14	0.34	0.63
$V(S_{13} \geq \cdots)$	1	1		1	1	1	1	0.95	1	1
$V(S_{14} \geq \cdots)$	0.89	1	0.27		0.28	0.59	0.81	0.21	0.42	0.69
$V(S_{15} \geq \cdots)$	1	1	0.97	1		1	1	0.91	1	1
$V(S_{16} \geq \cdots)$	1	1	0.68	1	0.7		1	0.61	0.84	1
$V(S_{17} \geq \cdots)$	1	1	0.42	1	0.44	0.77		0.36	0.59	0.88
$V(S_{18} \geq \cdots)$	1	1	1	1	1	1	1		1	1
$V(S_{19} \geq \cdots)$	1	1	0.85	1	0.88	1	1	0.79		1
$V(S_{110} \geq \cdots)$	1	1	0.57	1	0.6	0.91	1	0.51	0.73	

Source: Author's calculation

TABLE 9. *V* VALUES RESULT FOR OPERATIONAL PARAMETERS

	S_{21}	S_{22}	S_{23}	S_{24}	S_{25}	S_{26}	S_{27}	S_{28}	S_{29}
$V(S_{21} \geq \cdots)$		1	1	1	1	1	0.95	1	1
$V(S_{22} \geq \cdots)$	0.59		0.79	1	1	1	0.53	1	1
$V(S_{23} \geq \cdots)$	0.8	1		1	1	1	0.75	1	1
$V(S_{24} \geq \cdots)$	0.53	0.95	0.74		1	1	0.47	1	1
$V(S_{25} \geq \cdots)$	0.27	0.72	0.49	0.77		1	0.21	0.79	1
$V(S_{26} \geq \cdots)$	0.12	0.56	0.33	0.61	0.86		0.05	0.64	0.98
$V(S_{27} \geq \cdots)$	1	1	1	1	1	1		1	1
$V(S_{28} \geq \cdots)$	0.48	0.93	0.69	0.97	1	1	0.42		1
$V(S_{29} \geq \cdots)$	0.11	0.56	0.32	0.61	0.87	1	0.04	0.64	1

Source: Author's calculation

TABLE 10. *V* VALUES RESULT FOR ECONOMICAL PARAMETERS

	S_{31}	S_{32}	S_{33}
$V(S_{31} \geq \cdots)$		1	1
$V(S_{32} \geq \cdots)$	0.53		1
$V(S_{33} \geq \cdots)$	0.08	0.61	

Source: Author's calculation

TABLE 11. *V* VALUES RESULT FOR MAIN CRITERIA

	S_1	S_2	S_3
$V(S_1 \geq \cdots)$		1	1
$V(S_2 \geq \cdots)$	0.79		0.93
$V(S_3 \geq \cdots)$	0.85	1	

Source: Author's calculation

The value of fuzzy synthetic extent with respect to the *i*th object is calculated as

$$S_{11} = (4.8, 7.33, 11.81) \otimes (0.005, 0.008, 0.012) = (0.024, 0.055, 0.138)$$

$$S_{12} = (4.03, 5.63, 8.23) \otimes (0.005, 0.008, 0.012) = (0.02, 0.043, 0.096)$$

$$S_{13} = (13.05, 21.62, 32.13) \otimes (0.005, 0.008, 0.012) = (0.066, 0.163, 0.375)$$

$$S_{14} = (4.16, 5.96, 9.4) \otimes (0.005, 0.008, 0.012) = (0.021, 0.045, 0.11)$$

$$S_{15} = (13.28, 20.4, 29.0) \otimes (0.005, 0.008, 0.012) = (0.067, 0.154, 0.339)$$

$$S_{16} = (8.06, 12.25, 18.33) \otimes (0.005, 0.008, 0.012) = (0.041, 0.093, 0.214)$$

$$S_{17} = (5.79, 8.45, 11.85) \otimes (0.005, 0.008, 0.012) = (0.029, 0.064, 0.138)$$

$$S_{18} = (14.61, 23.94, 37.62) \otimes (0.005, 0.008, 0.012) = (0.073, 0.181, 0.439)$$

$$S_{19} = (10.6, 16.4, 25.17) \otimes (0.005, 0.008, 0.012) = (0.053, 0.124, 0.294)$$

$$S_{110} = (7.27, 10.3, 15.49) \otimes (0.005, 0.008, 0.012) = (0.037, 0.078, 0.181)$$

$$S_{21} = (14.41, 21.49, 28.99) \otimes (0.006, 0.009, 0.014) = (0.09, 0.2, 0.4)$$

$$S_{22} = (6.93, 10.96, 16.81) \otimes (0.006, 0.009, 0.014) = (0.04, 0.1, 0.23)$$

$$S_{23} = (10.08, 15.74, 22.27) \otimes (0.006, 0.009, 0.014) = (0.06, 0.14, 0.31)$$

$$S_{24} = (6.56, 10.09, 15.28) \otimes (0.006, 0.009, 0.014) = (0.04, 0.09, 0.21)$$

$$S_{25} = (4.85, 6.73, 10.42) \otimes (0.006, 0.009, 0.014) = (0.03, 0.06, 0.14)$$

$$S_{26} = (4.09, 5.28, 8.13) \otimes (0.006, 0.009, 0.014) = (0.03, 0.05, 0.11)$$

$$S_{27} = (16.07, 23.29, 33.51) \otimes (0.006, 0.009, 0.014) = (0.1, 0.21, 0.46)$$

$$S_{28} = (6.12, 9.66, 13.95) \otimes (0.006, 0.009, 0.014) = (0.04, 0.09, 0.19)$$

$$S_{29} = (3.81, 5.46, 7.96) \otimes (0.006, 0.009, 0.014) = (0.02, 0.05, 0.11)$$

$$S_{31} = (4.1, 5.88, 7.88) \otimes (0.067, 0.091, 0.123) = (0.27, 0.54, 0.97)$$

$$S_{32} = (2.35, 3.05, 4.57) \otimes (0.067, 0.091, 0.123) = (0.16, 0.28, 0.56)$$

$$S_{33} = (1.65, 2.0, 2.47) \otimes (0.067, 0.091, 0.123) = (0.11, 0.18, 0.31)$$

$$S_1 = (2.72, 3.42, 4.53) \otimes (0.084, 0.11, 0.139) = (0.23, 0.38, 0.63)$$

$$S_2 = (2.12, 2.73, 3.63) \otimes (0.084, 0.11, 0.139) = (0.18, 0.3, 0.51)$$

$$S_3 = (2.34, 2.94, 3.79) \otimes (0.084, 0.11, 0.139) = (0.2, 0.32, 0.53)$$

Then priority weights are computed by using Eq. (9):

$$d'(C11) = \min(1, 0.4, 1, 0.42, 0.72, 0.93, 0.34, 0.55, 0.82) = 0.4$$

$$d'(C12) = \min(0.85, 0.2, 0.97, 0.21, 0.53, 0.76, 0.14, 0.34, 0.63) = 0.14$$

$$d'(C13) = \min(1,1,1,1,1,1, 0.95,1,1) = 0.95$$

$$d'(C14) = \min(0.89, 1, 0.27, 0.28, 0.59, 0.81, 0.21, 0.42, 0.69) = 0.21$$

$$d'(C15) = \min(1,1, 0.97,1,1,1, 0.91,1,1) = 0.91$$

$$d'(C16) = \min(1,1, 0.68,1, 0.7,1, 0.61, 0.84,1) = 0.61$$

$$d'(C17) = \min(1,1, 0.42,1, 0.44, 0.77, 0.36, 0.59, 0.88) = 0.36$$

$$d'(C18) = \min(1,1,1,1,1,1,1,1,1) = 1$$

$$d'(C19) = \min(1,1, 0.85,1, 0.88,1,1, 0.79,1) = 0.79$$

$$d'(C110) = \min(1,1, 0.57,1, 0.6, 0.91,1, 0.51, 0.73) = 0.51$$

$$d'(C21) = \min(1,1,1,1,1, 0.95,1,1) = 0.95$$

$$d'(C22) = \min(0.59, 0.79,1,1,1, 0.53,1,1) = 0.53$$

$$d'(C23) = \min(0.8,1,1,1,1, 0.75,1,1) = 0.75$$

$$d'(C24) = \min(0.53, 0.95, 0.74,1,1, 0.47,1,1) = 0.47$$

$$d'(C25) = \min(0.27, 0.72, 0.49, 0.77,1, 0.21, 0.79,1) = 0.21$$

$$d'(C26) = \min(0.12, 0.56, 0.33, 0.61, 0.86, 0.05, 0.64, 0.98) = 0.05$$

$$d'(C27) = \min(1,1,1,1,1,1,1,1) = 1$$

$$d'(C28) = \min(0.48, 0.93, 0.69, 0.97, 1, 1, 0.42, 1) = 0.42$$

$$d'(C29) = \min(0.11, 0.56, 0.32, 0.61, 0.87, 1, 0.04, 0.64) = 0.04$$

$$d'(C31) = \min(1,1) = 1$$

$$d'(C32) = \min(0.53, 1) = 0.53$$

$$d'(C33) = \min(0.08, 0.61) = 0.08$$

$$d'(C1) = \min(1,1) = 1$$

$$d'(C2) = \min(0.79, 0.93) = 0.79$$

$$d'(C33) = \min(0.85, 1) = 0.85$$

The global weights of evaluation criteria are calculated by multiplying local weight of the evaluation indicators with the weights of the main criteria to which it belongs. After the computation of these values priority weights respect to main objective are obtained as (0.024, 0.01, 0.067, 0.015, 0.064, 0.043, 0.025, 0.071, 0.056, 0.036, 0.061, 0.034, 0.048, 0.03, 0.014, 0.003, 0.064, 0.027, 0.003, 0.216, 0.078, 0.012). Mentioned priority weights have presented for each criterion in Table 12. The results of the FAHP analysis for relative weights of the evaluation criteria are summarized in Fig. 7.

TABLE 12. PRIORITY WEIGHTS FOR CRITERIA

Criteria	Local weights	Global weights
C1	0.411	
C11	0.058	0.024
C12	0.024	0.01
C13	0.162	0.067
C14	0.036	0.015
C15	0.156	0.064
C16	0.105	0.043
C17	0.061	0.025
C18	0.172	0.071
C19	0.137	0.056
C110	0.088	0.036
C2	0.283	
C21	0.215	0.061
C22	0.120	0.034
C23	0.169	0.048
C24	0.106	0.03
C25	0.048	0.014
C26	0.012	0.003
C27	0.227	0.064
C28	0.094	0.027
C29	0.009	0.003
C3	0.306	
C31	0.707	0.216
C32	0.255	0.078
C33	0.038	0.012

Source: Author’s calculation

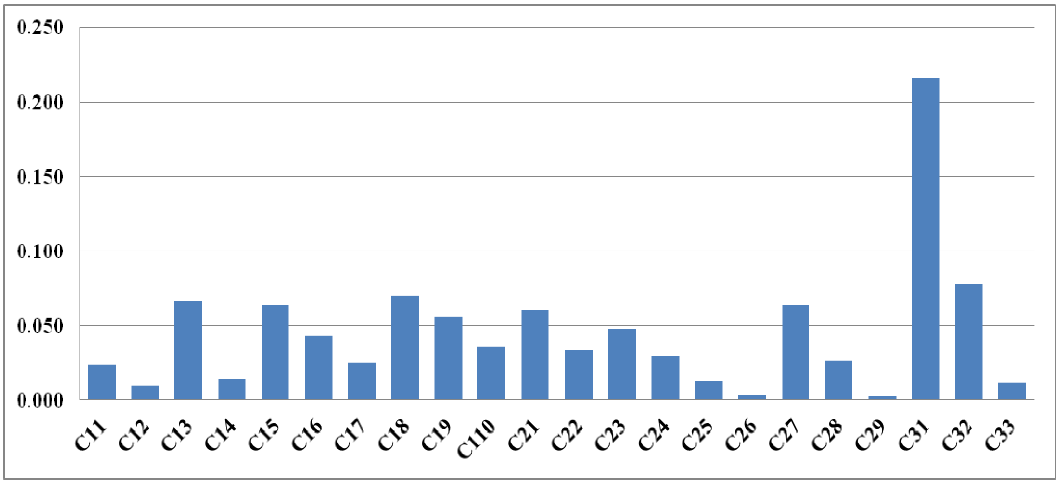

FIGURE. 7. RELATIVE WEIGHTS OF CRITERIA

Source: Author's calculation

C. Determine the final rank and select the best alternative through FTOPSIS

In this step, fuzzy evaluation matrices are established by fifteendecision makers for evaluating theunderground mining methods under different criteria based on linguistic variables listed in Table 2 and shown in Fig. 3. For the benefit criteria (C11, C12, C13, C14, C15, C16, C17, C18, C19, C110, C21, C22, C23, C26, and C27), the higher the score, the better the performance of the mining method is; whereas, for the cost criteria (C24, C25, C28, C29, C31, C32, and C33), the higher the score, the worse the performance of the mining method is.For example, the fuzzy decision matrix filled by one of the decision makers is presented in Table 13.

TABLE 13. SAMPLE OF FILLED QUESTIONNAIRE

	A1	A2	A3	A4	A5	A6
C11	P	VG	G	G	G	F
C12	F	G	G	VG	G	G
C13	P	G	F	G	G	VG
C14	G	G	G	G	F	G
C15	G	VG	F	VG	G	G
C16	F	G	F	G	G	G
C17	F	G	G	G	G	G
C18	F	G	F	VG	F	G
C19	F	G	F	G	G	G
C110	F	G	G	G	G	G
C21	G	P	F	G	F	G
C22	P	P	F	G	F	F
C23	VP	F	VP	VG	F	G
C24	VG	F	G	P	F	P
C25	VG	F	G	VP	G	P
C26	VP	G	P	VG	F	G
C27	VG	G	G	G	F	VP
C28	VG	F	P	VP	F	F
C29	P	F	P	P	F	VG
C31	VP	F	P	F	F	VG
C32	G	G	G	P	G	VG
C33	VG	F	VG	VP	F	P

Source: Author's calculation

Then, the aggregated fuzzy performance ratings of mining methods with respect to each criterion are computed by Eq. (12) and the results are presented in Table 14.

TABLE 14. AGGREGATED FUZZY PERFORMANCE RATINGS

	A 1			A 2			A 3			A 4			A 5			A 6		
C11	0.15	0.30	0.45	0.65	0.80	0.95	0.55	0.69	0.83	0.53	0.68	0.83	0.55	0.69	0.83	0.27	0.38	0.50
C12	0.25	0.37	0.49	0.53	0.66	0.80	0.57	0.70	0.84	0.67	0.82	0.97	0.56	0.69	0.82	0.56	0.70	0.84
C13	0.13	0.28	0.43	0.53	0.67	0.81	0.37	0.49	0.61	0.55	0.70	0.84	0.54	0.68	0.82	0.65	0.80	0.94
C14	0.55	0.70	0.84	0.55	0.69	0.83	0.56	0.71	0.86	0.57	0.72	0.86	0.37	0.48	0.60	0.57	0.71	0.85
C15	0.57	0.70	0.83	0.63	0.78	0.93	0.39	0.54	0.69	0.65	0.79	0.94	0.56	0.69	0.82	0.57	0.70	0.84
C16	0.27	0.38	0.49	0.52	0.66	0.79	0.34	0.46	0.59	0.55	0.68	0.81	0.55	0.69	0.83	0.59	0.74	0.88
C17	0.29	0.41	0.53	0.55	0.69	0.83	0.57	0.72	0.87	0.53	0.66	0.79	0.52	0.65	0.78	0.54	0.68	0.81
C18	0.41	0.53	0.65	0.57	0.71	0.84	0.42	0.56	0.70	0.56	0.71	0.83	0.33	0.46	0.59	0.56	0.71	0.86
C19	0.31	0.43	0.55	0.56	0.71	0.86	0.41	0.54	0.66	0.52	0.66	0.81	0.53	0.68	0.83	0.53	0.67	0.81
C110	0.28	0.39	0.50	0.52	0.66	0.80	0.54	0.68	0.81	0.53	0.67	0.81	0.50	0.64	0.78	0.53	0.67	0.81
C21	0.56	0.69	0.83	0.17	0.30	0.43	0.37	0.52	0.67	0.51	0.64	0.78	0.42	0.53	0.65	0.55	0.69	0.83
C22	0.15	0.28	0.42	0.16	0.31	0.46	0.31	0.45	0.59	0.56	0.68	0.81	0.41	0.56	0.71	0.41	0.53	0.65
C23	0.07	0.22	0.37	0.42	0.54	0.66	0.08	0.23	0.38	0.64	0.79	0.94	0.38	0.49	0.61	0.57	0.72	0.86
C24	0.63	0.78	0.93	0.29	0.41	0.53	0.15	0.29	0.43	0.39	0.51	0.63	0.51	0.65	0.79	0.14	0.28	0.43
C25	0.63	0.78	0.93	0.31	0.43	0.55	0.57	0.70	0.84	0.05	0.20	0.35	0.53	0.66	0.80	0.16	0.31	0.46
C26	0.09	0.24	0.39	0.55	0.63	0.71	0.13	0.26	0.39	0.63	0.78	0.93	0.30	0.41	0.53	0.59	0.74	0.89
C27	0.63	0.78	0.93	0.58	0.72	0.85	0.53	0.68	0.83	0.57	0.71	0.85	0.37	0.49	0.61	0.05	0.20	0.35
C28	0.66	0.81	0.96	0.37	0.50	0.62	0.17	0.32	0.46	0.08	0.23	0.38	0.39	0.51	0.62	0.43	0.55	0.67
C29	0.17	0.31	0.45	0.32	0.44	0.55	0.15	0.28	0.41	0.17	0.30	0.44	0.41	0.52	0.64	0.65	0.79	0.93
C31	0.05	0.20	0.35	0.40	0.51	0.62	0.17	0.29	0.42	0.44	0.57	0.70	0.40	0.55	0.70	0.66	0.80	0.93
C32	0.54	0.68	0.81	0.48	0.62	0.76	0.58	0.71	0.83	0.17	0.30	0.44	0.55	0.68	0.81	0.68	0.83	0.98
C33	0.65	0.79	0.93	0.31	0.44	0.57	0.65	0.80	0.95	0.08	0.23	0.38	0.33	0.44	0.56	0.15	0.29	0.43

Source: Author's calculation

After forming the fuzzy evaluation matrix, the second phase is to calculatethe normalized fuzzydecision matrix using Eq. (15). Next, using the criteria weights obtained by FAHP, the weighted decision matrix is derived as presented in Table 15.

TABLE 15. WEIGHTED DECISION MATRIX

	A1			A2			A3			A4			A5			A6		
C11	0.004	0.007	0.011	0.016	0.020	0.024	0.014	0.018	0.021	0.013	0.017	0.021	0.014	0.017	0.021	0.007	0.010	0.013
C12	0.003	0.004	0.005	0.005	0.007	0.008	0.006	0.007	0.009	0.007	0.008	0.010	0.006	0.007	0.008	0.006	0.007	0.009
C13	0.009	0.020	0.031	0.037	0.047	0.057	0.026	0.035	0.044	0.039	0.049	0.060	0.038	0.048	0.058	0.046	0.057	0.067
C14	0.010	0.012	0.015	0.009	0.012	0.014	0.010	0.012	0.015	0.010	0.012	0.015	0.006	0.008	0.010	0.010	0.012	0.015
C15	0.039	0.048	0.057	0.043	0.053	0.063	0.026	0.037	0.047	0.044	0.054	0.064	0.038	0.047	0.056	0.039	0.048	0.057
C16	0.013	0.019	0.024	0.026	0.032	0.039	0.017	0.023	0.029	0.027	0.033	0.040	0.027	0.034	0.041	0.029	0.036	0.043
C17	0.008	0.012	0.015	0.016	0.020	0.024	0.017	0.021	0.025	0.015	0.019	0.023	0.015	0.019	0.022	0.016	0.019	0.023
C18	0.033	0.043	0.053	0.047	0.058	0.069	0.034	0.046	0.057	0.046	0.058	0.068	0.027	0.038	0.049	0.046	0.058	0.071
C19	0.020	0.028	0.036	0.037	0.046	0.056	0.027	0.035	0.043	0.034	0.043	0.053	0.035	0.045	0.054	0.034	0.044	0.053
C110	0.012	0.017	0.022	0.023	0.029	0.035	0.024	0.030	0.036	0.024	0.030	0.036	0.022	0.028	0.035	0.024	0.030	0.036
C21	0.041	0.051	0.061	0.013	0.022	0.032	0.027	0.038	0.050	0.037	0.047	0.057	0.031	0.039	0.048	0.041	0.051	0.061
C22	0.006	0.012	0.018	0.007	0.013	0.019	0.013	0.019	0.025	0.024	0.029	0.034	0.017	0.024	0.030	0.017	0.022	0.027
C23	0.003	0.011	0.019	0.021	0.027	0.034	0.004	0.012	0.019	0.033	0.040	0.048	0.019	0.025	0.031	0.029	0.036	0.044
C24	0.020	0.025	0.030	0.010	0.013	0.017	0.005	0.010	0.014	0.013	0.017	0.020	0.017	0.021	0.026	0.005	0.009	0.014
C25	0.009	0.011	0.014	0.005	0.006	0.008	0.008	0.010	0.012	0.001	0.003	0.005	0.008	0.010	0.012	0.002	0.005	0.007
C26	0.000	0.001	0.001	0.002	0.002	0.003	0.000	0.001	0.001	0.002	0.003	0.003	0.001	0.002	0.002	0.002	0.003	0.003
C27	0.044	0.054	0.064	0.040	0.049	0.059	0.037	0.047	0.057	0.039	0.049	0.058	0.026	0.034	0.042	0.004	0.014	0.024
C28	0.018	0.022	0.027	0.010	0.014	0.017	0.005	0.009	0.013	0.002	0.006	0.011	0.011	0.014	0.017	0.012	0.015	0.019
C29	0.000	0.001	0.001	0.001	0.001	0.002	0.000	0.001	0.001	0.000	0.001	0.001	0.001	0.001	0.002	0.002	0.002	0.003
C31	0.012	0.047	0.082	0.093	0.118	0.144	0.039	0.068	0.097	0.102	0.132	0.162	0.093	0.128	0.162	0.153	0.185	0.216
C32	0.043	0.054	0.065	0.038	0.049	0.060	0.046	0.056	0.066	0.013	0.024	0.035	0.044	0.054	0.065	0.054	0.066	0.078
C33	0.008	0.010	0.011	0.004	0.005	0.007	0.008	0.010	0.012	0.001	0.003	0.005	0.004	0.005	0.007	0.002	0.004	0.005

Source: Author's calculation

After forming the weighted decision matrix, the fuzzy positive-ideal solution (FPIS, A*) and the fuzzynegative-ideal solution (FPIS, A^-) are derived as $A^* = (1,1,1)$ and $A^- = (0,0,0)$ for benefit criteria, and $A^* = (0,0,0)$ and $A^- = (1,1,1)$ for cost criteria.

Finally, alternatives are ranked in descending order as presented in Table 16. According to CC_i values, the ranking of the alternatives in descending order are A4, A2, A3, A5, A1 and A6. The proposed model indicates that Cut & Fill (A4) is the best method with CC value of 0.3322. Rankings of the alternatives according to CC_i values are depicted in Fig. 8.

TABLE 16. FUZZY TOPSIS RESULTS

	d_i^+	d_i^-	CC_i	Rank
A1	14.841	7.179	0.326	5
A2	14.772	7.24	0.3289	2
A3	14.79	7.226	0.3282	3
A4	14.67	7.313	0.3322	1
A5	14.824	7.188	0.3265	4
A6	14.843	7.17	0.3257	6

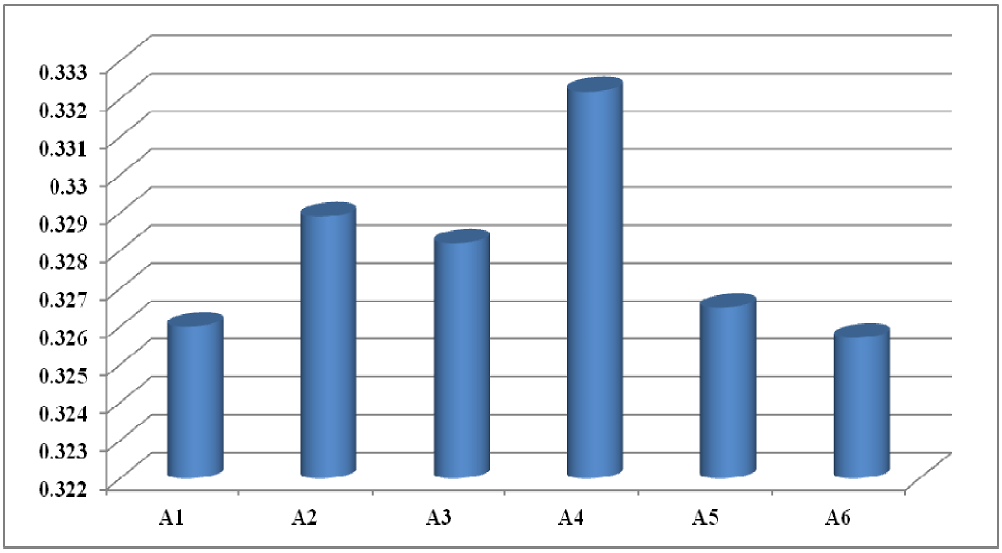

FIGURE. 8. FINAL RANK OF ALTERNATIVES

Source: Author's calculation

VII. SENSITIVITY ANALYSIS

In order to identify thecause of the difference in the outcome of the proposed model, a sensitivity analysis is conducted. This technique generates different scenarios that may change the priority of alternatives and be needed to reach a consensus. If the ranking order be changed by increasing or decreasing the importance of the criteria, the results are expressed to be sensitive otherwise it is robust. In this study, sensitivity analysis is implemented to see how sensitive the alternatives change with the importance of the criteria. This tool graphical exposes the importance of criteria weights in selecting the optimal alternative among the feasible alternatives. The main goal of sensitivity analysis is to see which criteria is most significant in influencing the decision making process. For this reason, twenty two experiments were conducted that each experiment is generatedbyan increase of 100% in the amount of the weight of the criterion under consideration.

It can be shown from Fig. 9 that alternative A4 has the highest score in twenty two experiments. Therefore, it can be resulted that the decision making process is not sensitive to the criteria weight with alternative A4 emerging as the winner.

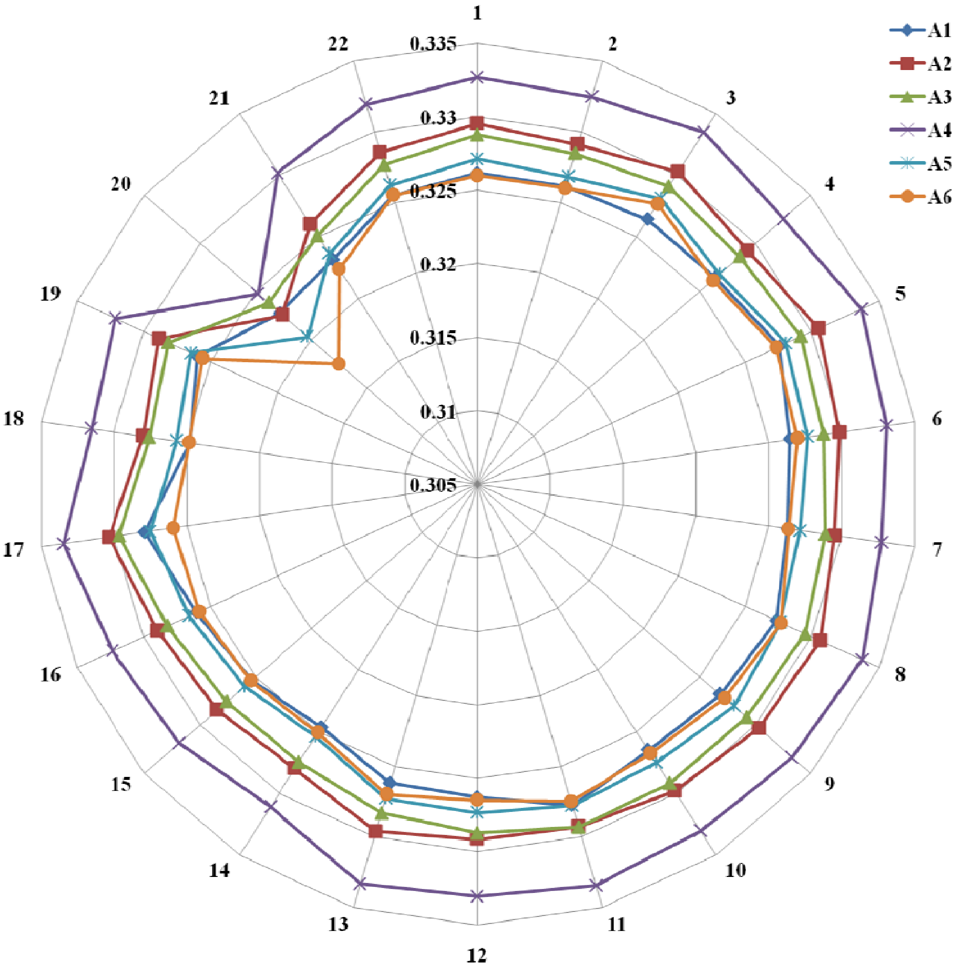

FIGURE. 9. SENSITIVITY ANALYSIS

Source: Author's calculation

VIII. CONCLUSION

The process of mining method selection is a methodology for evaluating the proper alternatives and selecting the best alternative with respect to criteria under consideration. The main goal of this study is to evaluate the feasible alternatives and select the most appropriate candidate among a pool of alternatives by using theMCDM methods. According to the complex structure of the problem,inaccurate and imprecise data,less of information, and inherent uncertainty, the usage of the fuzzy sets can be useful. In other words, in such situations using linguistic preferences can be very valuable.

In this paper, an integrated model based on FAHP and FTOPSIS is developed. FAHP based on the extent analysis techniqueis applied to obtain weights of the evaluation criteria, while FTOPSIS is utilized to prioritize the feasible alternatives. The weights derived from FAHP are involved in the problem of the mining method selection by using them in FTOPSIS calculations and ranking order is determined based on these weights. Finally, the alternative with the highest score is selected. Also, sensitivity analysis was conducted to determine the influence of criteria weights on the problem of the mining method selection. The strength of the proposed model is the ability to evaluate and rank alternatives under partial or lack of quantitative information. In order to demonstrate the potential application of the proposed model, a real world case study was implemented.

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KORIŠTENJE INTEGRIRANOG MCDM MODELA ZA ODABIR TEHNIKE RUDARENJA U SLUČAJU NESIGURNOSTI

Sažetak: Cilj ovog rada je izvođenje efikasnog i primjenjivog modela odabira najbolje proizvodne tehnike na primjeru Angouran rudnika koji je jedan od glavnih proizvođača cinka u Iranu. Proizvodne tehnike ekstrakcije ruda su izravno ili neizravno ovisne o izboru tehnika izvlačenja ruda, jednog od najkritičnijih pitanja u odlučivanju u fazi projektiranja rudnika koji bi trebao biti izrađen. Broj evaluacijskih kriterija često su u sukobu jedni s drugima pri odabiru i ocjeni prihvatljive proizvodne (rudarske) metode i tehnike. Dakle, problem odabira prihvatljive proizvodne rudarske metode u praksi je problem odabira multi-kriterijskog odlučivanja (MCDM). S druge strane, s obzirom na složenost i strukturu problema, nepreciznih podataka, manjkavost informacija, a time i inherentnu nesigurnost, korištenje fuzzy tehnika može biti od iznimne koristi. U ovom radu integrirani model koji se temelji fuzzy analitičkoj hijerarhiji procesa (FAHP) i fuzzy tehnikama za redom preferencija po sličnosti idealnog rješenja (FTOPSIS) je razvijen i prezentiran. FAHP se primjenjuje za određivanje relativne težine kriterija za ocjenu najbolje proizvodne tehnike pri ekstrakciji ruda u odnosu na ostale dostupne alternativne proizvodne tehnike. Rezultati istraživanja rada testirani su analizom osjetljivosti rezultata. Rezultati ovog istraživanja pokazuju učinkovitost, sposobnost i robusnost predloženog modela izbora proizvodnih tehnika, koji se mogu primijeniti na različite vrste složenih problema u stvarnom životu.

Ključne riječi: Odabir metode rudarstva, MCDM, FTOPSIS, FAHP, grupno odlučivanje