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A new model for mining method selection based on grey and TODIM methods

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Abstract
One of the most important steps involved in mining operations is to select an appropriate extraction method for mine resources. After choosing the extraction method, it is usually impossible to replace it with another one because it may be so expensive that implementation of the entire project could be economically impossible. Choosing a mining method depends on the geological and geometrical characteristics of the mine. Due to the complexity of the process of choosing an appropriate mining method and the effect of the parameters involved on the results of this process, it is necessary to utilize the new decision-making methods that have the ability to consider the relationship between the existing parameters and the mining methods. Grey and TODIM (an acronym in Portuguese, i.e. Tomada de Decisão Interativa Multicritério) decision-making methods are among the existing ones, which in addition to the convenience, show high accuracy. The proposed models are presented to determine the best mining method in the Gol-e-gohar iron ore mine in Iran. The results obtained are compared with the methods used in the previous research works. Among the decision-making methods introduced, the open pit mining method is the most appropriate option and the square-set mining is the worst one.

Keywords: *Mining Method Selection, Multi-Criteria Decision-Making Methods, Grey, TODIM.*

1. Introduction

Selecting a mining method is always considered as one of the most important and challenging stages in the mining operations because the accuracy of choosing the process greatly affects its economic potential and any mistake in decision-making imposes some irreparable finance to the owners. Due to the complexities and uncertainties inherent in the geological and geotechnical parameters involved, it is impossible to always utilize an extraction method for the extraction of all types of mineral resources. In addition, all the presented models do not provide a single comprehensive extraction model to choose due to the advantages and disadvantages inherent in their basis. The first quantitative extraction method was presented in 1981 by Nicholas. It was suitable for the projects in which the mineral deposits were marked by exploratory drilling. With all its weaknesses, this method is still the base of most research works.

With time and the increasing need to the key selection, the multi-criteria decision-making methods have been used to achieve the desired purpose. Development of multi-criteria decision-making techniques by adopting a variety of quantitative and qualitative characteristics and their weighting is an appropriate tool in a decision-making analysis. In order to overcome the crisis and achieve a more favorable result in this field, several studies have been carried out, the most important of which are as follow: Guray et al. used the fuzzy and neuro-fuzzy hybrid system to determine an appropriate mining method [1]; Bitarafan and Ataei selected an appropriate mining method in anomaly No. 3 of the Gol-e-gohar mine using fuzzification of the decision-making methods [2]; Alpay and Yavuz provided a decision support system to select an underground mining method [3]; Karadogan et al. studied application of the fuzzy set theory to the underground mining method selection [4]; Yavuz et al. selected the most appropriate method for an underground mine by means of the analytic hierarchy process (AHP) [5]; Zare Naghadehi et al. applied the analytic hierarchy process method to choose the optimal underground mining method in the Jajarm bauxite mine [6]; Ataee et al. used the analytic hierarchy process to choose the best mining method [7]; Samimi Namin et al. proposed a new model to select the mining method based on the fuzzy TOPSIS [8]; Jamshidi et al. applied the analytic hierarchy process to choose the optimal underground mining method in the Jajarm bauxite mine [9]; Samimi Namin et al. investigated the application of several decision-making techniques such as AHP, TOPSIS, and PROMETHEE to select an appropriate mining method in Iran [10]; Bogdanovic et al. applied the PROMETHEE and analytic hierarchy process methods to determine an appropriate mining method in the Coka Marin mine in Serbia [11]; Azadeh et al. presented a new method to select a mining method based on the improved Nicholas technique [12]; Ataei et al. applied the Monte Carlo analytic hierarchy process method to select the best mining method in the Jajarm bauxite mine [13]; Gelvez et al. used the analytic hierarchy process and the VIKOR methods to choose the most optimal mining method in the coal mine in Colombia [14]; Karimnia and Bagloo applied the analytical hierarchy process to choose the most optimal extraction method in a salt mine in Iran [15]. Yavuz used the AHP method to choose a suitable underground mining method for a lignite mine located in Istanbul [16]. Lv and Zhang predicted a suitable mining method for thin coal seam using the artificial neural networks [17]. Chen and Tu used the AHP and PROMATEHEE methods to propose the most suitable technique for mechanized mining in a thin coal mine in china [18]. Jianhong et al. compared the results of the TOPSIS method with those for the AHP-VICOR method in the mining method selection problems. The results of this work showed that the proposed model could predict a mining method with more precision [19]. Other research works are summarized in Table 1.

In the present study, in order to choose the most optimal mining method in the Gol-e-gohar mine, the Grey and TODIM decision-making techniques were used. The main advantages of these methods in relation to the other prevalent methods are to apply the distance numbers, to consider the intensity of criteria changes, and high accuracy in decision-making. The outcome of such decision-making systems is to obtain the best results in the light of considering all the technical, economic, and safety criteria.

Table 1. Research works on mining method selection [20-49].

Researcher	Year	Researcher	year
Peel and Church	1941	Hamrin	1998
Boshkov and Wright	1973	Tatiya	1998
Morrison	1976	Basu	1999
Nicholas and Mark	1981	Kahriman	2000
Loubscher	1981	Kesimal and Bascetin	2002
Karabeyogˇlu	1986	Clayton et al.	2002
Hartman	1987	Yiming et al.	2003
Bandopadhyay and Venkatasubramanian	1987	Samimi namin et al.	2003
Marano and Everitt	1987	Yiming et al.	2004
Agoshkov et al.	1988	Samimi namin et al.	2004
Camm and Smith	1992	Mihaylov	2005
Nicholas	1993	Bascetin	2005
Mutagwaba and Terezopoulos	1994	Miranda and Almeida	2005
Miller et al.	1995	Shahriar et al.	2007
Gershon et al.	1995	Karadogan et al.	2008

2. Grey method

Grey theory [50, 51], proposed by Deng in 1982, is one of the mathematical theories born out of the concept of the grey set. It is an effective method used to solve the uncertainty problems with discrete data and incomplete information. The theory includes five major parts: grey prediction,

grey relational analysis (GRA) [52, 53], grey decision, grey programming, and grey control.
During the decision-making processes, the decision-makers always try to use every kind of method such as investigation, questionnaire, examination, and sampling so as to collect as much practical information as possible in the hope that the best decision of aspired/desired levels can be reached. Even if such efforts have been made, the hope to have obtained all the necessary information for the decision-making remains an impossibility, and therefore, decision-makers are often compelled to reach their decisions in grey processes (Table 2) [54].
Suppose that in a system, there are n series of data (number of run tests), and in each series, m responses (number of dependent variables). The test results are then determined by $y_{i,j}\,(i=1,2,...,n\ \&\ j=1,2,...,m)$. In the Grey Relational analysis of such a system, the following steps are performed [55-56]:
In a multiple-criteria decision-making with m alternatives and n attributes, for each alternative, the following equation can be established [57]:

$$Y_i=\left(y_{i1},y_{i2},...,y_{ij},...y_{nm}\right) \quad (1)$$

where Y_i is the importance of alternative i based on the attribute j. The normalized matrix, Xi, can be determined using Eq. (2).

$$X_i=\left(X_{i1},X_{i2},...,X_{ij},...,X_{in}\right) \quad (2)$$

In order to normalize the alternatives, the following equations can be used.
-If the target value of the original sequence is infinite, then it has a characteristic of "the larger-the better". The original sequence can be normalized as follows:

$$x_{ij}=\frac{y_{ij}-\min\left(y_{ij}\right)}{\max\left(y_{ij}\right)-\min\left(y_{ij}\right)} \quad (3)$$

-If the expectancy is "the smaller-the better", then the original sequence should be normalized as follows:

$$x_{ij}=\frac{\max\left(y_{ij}\right)-y_{ij}}{\max\left(y_{ij}\right)-\min\left(y_{ij}\right)} \quad (4)$$

-However, if there is a definite target value to be achieved, the original sequence is normalized in the following form:

$$x_{ij}=\frac{\left|y_{ij}-y^*\right|}{\max\left\{\max\left(y_{ij}\right)-y^*,\,y^*-\min\left(y_{ij}\right)\right\}} \quad (5)$$

Following data normalizing, a grey relational coefficient is calculated to express the relationship between the ideal and actual normalized experimental results. The grey relational coefficient can be expressed as follows:

$$\gamma\left(x_{oj},x_{ij}\right)=\frac{\Delta\min-r\Delta\max}{\Delta_{ij}-r\Delta\max} \quad (6)$$

where Δ_{ij} is the deviation sequence of the reference sequence, and can be calculated as follows:

$$\Delta_{ij}=x_{oj}-x_{ij} \quad (7)$$

where, $\Delta_{\min}$ is the minimum value of Δ_{ij}, $\Delta_{\max}$ is the maximum value of Δ_{ij}, and r is the distinguishing or identification coefficient. r is between [0,1]. $r=0.5$ is generally used. The grey relational grade is defined as follows:

$$\Gamma\left(x_o,x_j\right)=\sum_{j}^{n}w_j\gamma\left(x_{oj},x_{ij}\right) \quad (8)$$

where w_j represents the normalized weighting value of factor j. Tables 2 and 3 show the weights for the alternatives and attributes [57].

Table 2. Linguistic rank and grey numbers for attribute weights.

Value	Linguistic rank
[0.0-0.1]	Very low
[0.1-0.3]	Low
[0.3-0.4]	MOL low
[0.4-0.5]	Medium
[0.5-0.6]	MOL high
[0.6-0.9]	High
[0.9-1.0]	Very high

Table 3. Linguistic rank and grey numbers for alternative weights.

Value	Linguistic rank
[0-1]	Very weak
[1-3]	Weak
[3-4]	MOL weak
[4-5]	Medium
[5-6]	MOL strong
[6-9]	strong
[9-10]	Very strong

3. TODIM method

TODIM is a discrete multi-criteria method founded on the prospect theory. The TODIM method has been successfully used and empirically validated in different applications. It is an experimental method based on how people make effective decisions in risky conditions. The shape of the value function of TODIM is identical to the prospect theory gain and loss function (Figure 1).

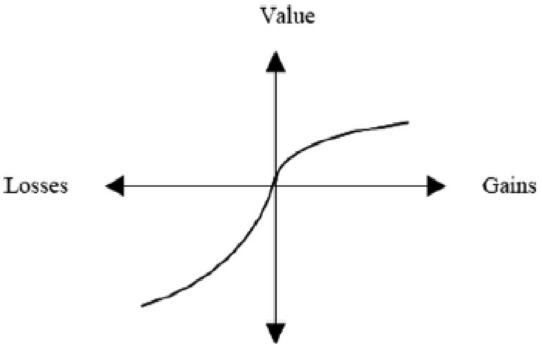

Figure 1. Value function of the TODIM method [61].

The global multi-criteria value function of TODIM aggregates all measures of gains and losses considering all criteria. Gomes and Rangel [58] have applied TODIM to investigate and recommend options for upstream projects for the natural gas reserves recently discovered in the Mexilho field in the Santos Basin, Brazil. In addition, Gomes and Rangel have presented an evaluation of the residential properties with real estate agents in Brazil, and have defined a reference value for the rents of these property characteristics using the TODIM method for multi-criteria decisions. This approach can assist the professionals in a real estate market to evaluate the alternatives clearly using the criteria defined by the specialists. In general, TODIM can be used for the qualitative and quantitative criteria. The verbal scales of the qualitative criteria are converted into the cardinal scales, and both types of scales are normalized. The relative measure of the dominance of an alternative over another one is determined for each pair of alternatives. This measure is computed as the sum of all criteria for the relative gain and loss values for these alternatives. This sum is a gain, a loss or zero depending on the performance of each alternative with respect to each criterion [59, 60].
The TODIM method uses pairwise comparisons between the criteria using technically simple resources to eliminate occasional inconsistencies resulting from these comparisons. TODIM allows the value judgments to be performed on a verbal scale using hierarchy of criteria, fuzzy value judgments, and interdependence relationships among the alternatives. The decision matrix consists of alternatives and criteria. The alternatives $A_1, A_2, ..., A_m$ are viable alternatives, $C_1, C_2, ..., C_n$ are criteria, and X_{ij} indicates the rating of alternative A_i according to the criteria C_j. The weight vector $w = (w_1, w_2, ..., w_n)$ comprises the individual weights $w_j = (j = 1, 2, ..., n)$ for each criterion C_j satisfying $\sum w_j = 1$. The data of decision matrix A originates from different sources. The matrix must be normalized to be dimensionless, and allows various criteria to be compared with each other [62, 63]. This study uses the normalized decision matrix $R = [r_{ij}] \times n$ with $i = 1, 2, ..., m$ and $j = 1, 2, ..., n$:

$$A = \begin{pmatrix} X_{11} & \cdots & X_{1n} \\ \vdots & \ddots & \vdots \\ X_{m1} & \cdots & X_{mn} \end{pmatrix} \qquad (9)$$

TODIM then calculates the partial dominance matrices and the final dominance matrix. The first calculation that the decision-makers must define is a reference criterion (typically, the criterion with the greatest importance weight). Therefore, w_{rc} indicates the weight of criterion c by the reference criterion r. TODIM is expressed by the following equations [64, 65].
The dominance of an alternative over the other is as follows:

$$\delta(A_i, A_j) = \sum \varphi_c(A_i, A_j), \forall (i, j) \qquad (10)$$

where:

$$\varphi_c(A_i, A_j) = \begin{cases} \sqrt{\dfrac{w_{rc}(X_{ic} - X_{jc})}{\sum w_{rc}}} & if\ (X_{ic} - X_{jc}) > 0 \quad a \\ 0 & if\ (X_{ic} - X_{jc}) = 0 \quad b \\ -\dfrac{1}{\theta}\left(\sqrt{\dfrac{\sum w_{rc}(X_{ic} - X_{jc})}{w_{rc}}}\right) & if\ (X_{ic} - X_{jc}) < 0 \quad c \end{cases} \qquad (11)$$

Thus $\delta(A_i, A_j)$ represents the measurement of dominance of alternative A_i over alternative A_j; m is the number of criteria; c is any criterion for $c = 1, 2, ..., m$; w_{rc} is equal to w_c divided by w_r, where r is the reference criterion; X_{ic} and X_{jc}

are the performances of the alternatives A_i and A_j in relation to c, respectively; θ is the attenuation factor of the losses; different choices of h lead to different shapes of the prospect theoretical value function in the negative quadrant [66].

The expression $\varphi_c(A_i, A_j)$ represents the parcel of the contribution of criterion c to function $\delta(A_i, A_j)$ when comparing alternative i with alternative j. If the value for $X_{ic} - X_{jc}$ is positive, it represents a gain for the function $\delta(A_i, A_j)$, and therefore, the expression $\varphi_c(A_i, A_j)$ is used, corresponding to Eq. (11a). If $X_{ic} - X_{jc}$ is nil, the value zero is assigned to $\varphi_c(A_i, A_j)$ by applying Eq. (11b). If $X_{ic} - X_{jc}$ is negative, $\varphi_c(A_i, A_j)$ is represented by Eq. (11c). The construction of function $\varphi_c(A_i, A_j)$, in fact, permits an adjustment of the data of the problem to the value function of the Prospect Theory, thus explaining the aversion and the propensity to risk. This function has the shape of an ‘‘S’’, represented in Figure 1. Above the horizontal axis, considered as a reference for this analysis, there is a concave curve representing the gains, and below the horizontal axis, there is a convex curve representing the losses. The concave part reflects the aversion to risk in the face of gains, and the convex part, in turn, symbolizes the propensity to risk when dealing with losses.

After the diverse partial matrices of dominance have been calculated, one for each criterion, the final dominance matrix of the general element $\delta(A_i, A_j)$ is obtained through the sum of the elements of the diverse matrices.

Eq. (12) is used to determine the overall value for alternative i through normalization of the corresponding dominance measurements. The rank of every alternative originates from the ordering of its respective values [67, 68].

$$\xi_i = \frac{\frac{\sum \delta(i,j)}{min \sum \delta(i,j)}}{max \sum \delta(i,j) - min \sum \delta(i,j)} \qquad (12)$$

Therefore, the global measures obtained, computed by Eq. (12), permit the complete rank ordering of all alternatives. A sensitivity analysis should then be applied to verify the stability of the results based on the decision-makers' preferences. The sensitivity analysis should, therefore, be carried out on h as well as on the criteria weights, choice of the reference criterion, and performance evaluations [69].

4. Numerical analysis

In this study, in order to make a decision concerning the choice of the mining method in the Gol-e-gohar mine, the grey and TODIM multi-criteria decision-making techniques were used. In this regard, in order to form the initial decision-making matrix, the mining methods including Block caving, Cut and fill, Long-wall mining, Open-pit mining, Room and pillar, shrinkage mining, Stope and pillar, Sub-level stoping, Sub-level caving, and Top slicing extraction were selected as the extraction options. Likewise, the parameters geometry, grade distribution, slope of ore deposit, thickness of ore deposit, depth, hanging wall RMR, ore body RMR, hanging wall RSS, ore body RSS, footwall RSS, recovery, individual skills, shift production per person, hanging wall RQD, and mining costs were selected as the effective factors involved in choosing the mining method. Then the decision matrix composed of these factors and options were scored by the elites (Table 4), and the grey and TODIM decision-making techniques were applied to the selected matrix.

Table 4. Decision matrix based on expert opinions [8].

Attribute Name	Deposit Shape	Grade Distribution	Ore Dip	Ore Thickness	Depth	Hanging-wall RMR	Ore RMR	Hanging-wall RSS
Attribute Data Type	Linguistic	Linguistic	Linguistic	Linguistic	Linguistic	Linguistic	Linguistic	Linguistic
Attribute Weight	Medium	Mol Low	Mol High	Mol High	Mol High	Mol High	Medium	Mol High
Block Caving	Medium	Medium	Medium	Mol High	Mol High	Mol High	Low	High
Cut & Fill	High	Mol High	Mol High	Mol Low	Mol High	High	Mol High	Mol High
Long Wall	High	Mol Low	Low	Very Low	Medium	High	Medium	Very High
Open Pit	Medium	Mol High	Mol High	High	Low	High	Mol High	Mol High
Room & Pillar	High	Medium	Low	Very Low	Mol High	Mol High	Very High	Low
Shrinkage	High	Medium	Low	Very Low	Mol High	Medium	Mol High	Low
Square-Set	Mol Low	Mol Low	Mol High	Low	Mol Low	Mol Low	Low	High
Stope & Pillar	High	Mol High	Medium	Mol High	Mol High	Mol High	Very High	Low
Sublevel Caving	High	Mol Low	Mol Low	High	Medium	Mol High	Mol Low	High
Sublevel Stopping	High	Mol Low	Mol Low	High	High	Mol High	High	Low
Top Slicing	Medium	Medium	Medium	Medium	Mol Low	Medium	Mol Low	High

Table 4. (Continued).

Attribute Name	Ore RSS	Footwall RSS	Recovery	Skilled Man Power	Out Put Per Man shift	Hanging-wall RQD	Mining Cost
Attribute Data Type	Linguistic	Linguistic	Deterministic	Linguistic	Deterministic	Linguistic	Triangular Fuzzy
Attribute Weight	Medium	Medium	High	High	Mol High	Medium	Mol High
Block Caving	Medium	Medium	90	Very Low	90	Very High	M: 12.5, a: 4, b: 20
Cut & Fill	Mol Low	Medium	100	Medium	30	High	M: 32.5, a: 15, b: 50
Long Wall	Very High	Mol High	95	Medium	40	Very High	M: 15, a: 5, b: 25
Open Pit	Mol High	High	100	Very High	90	High	M: 11.5, a: 3, b: 20
Room & Pillar	Low	Medium	60	Mol High	35	Mol Low	M: 20, a: 10, b: 30
Shrinkage	Mol Low	Mol High	85	Mol High	12	Very High	M: 27.5, a: 15, b: 40
Square-Set	Mol High	Low	100	Very Low	8	High	M: 77.5, a: 30, b: 125
Stope & Pillar	Low	Medium	60	Mol Low	40	Mol Low	M: 19, a: 8, b: 30
Sublevel Caving	Mol High	Medium	85	Mol Low	35	Very High	M: 26, a: 12, b: 40
Sublevel Stopping	Medium	Mol High	85	Mol High	45	Low	M: 23.5, a: 12, b: 35
Top Slicing	Medium	Mol Low	95	Medium	10	High	M: 42.5, a:20, b: 65

4.1. Application of grey matrix

A matrix composed of alternatives and attributes were offered to the experts of this field; and with the averaging of the results obtained from the various expert opinions, the target matrix was constructed. Then using the tables prepared for converting the quality features into the quantity ones (Tables 2 and 3), the opinions were converted to numbers (Table 5); and with the help of the equations presented in section 2, the desired analysis was performed. The results obtained showed that the open-pit mining method was the optimal option, and that the Square-set mining was the worst one in our study (Figure 2).

Table 5. Decision matrix of expert opinions considering grey relational coefficients.

Attribute Name	Deposit Shape		Grade Distribution		Ore Dip		Ore Thickness		Depth		Hanging-wall RMR		Ore RMR		Hanging-wall RSS	
Attribute Data Type	Linguistic		Linguistic		Linguistic		Linguistic		Linguistic		Linguistic		Linguistic		Linguistic	
Bound	L	U	L	U	L	U	L	U	L	U	L	U	L	U	L	U
Attribute Weight	0.4	0.5	0.3	0.4	0.5	0.6	0.5	0.6	0.5	0.6	0.5	0.6	0.4	0.5	0.5	0.6
Block Caving	4	5	4	5	6	9	1	3	5	6	5	6	3	4	4	5
Cut & Fill	6	9	6	9	6	9	6	9	6	9	6	9	5	6	6	9
Long Wall	6	9	1	3	0	1	1	3	6	9	6	9	4	5	4	5
Open Pit	4	5	4	5	3	4	5	6	6	9	6	9	5	6	6	9
Room & Pillar	6	9	1	3	3	4	3	4	5	6	5	6	9	10	4	5
Shrinkage	6	9	4	5	6	9	1	3	4	5	4	5	5	6	5	6
Square-Set	3	4	5	6	4	5	4	5	3	4	3	4	1	3	3	4
Stope & Pillar	6	9	5	6	4	5	5	6	5	6	5	6	9	10	1	3
Sublevel Caving	6	9	4	5	6	9	1	3	5	6	5	6	3	4	4	5
Sublevel Stopping	6	9	5	6	6	9	5	6	5	6	5	6	6	9	6	9
Top Slicing	4	5	3	4	1	3	1	3	4	5	4	5	3	4	4	5

Table 5. (Continued).

Attribute Name	Ore RSS		Footwall RSS		Recovery		Skilled Man Power		Out Put Per Man shift		Hanging-wall RQD		Mining Cost	
Attribute Data Type	Linguistic		Linguistic		Deterministic		Linguistic		Deterministic		Linguistic		Triangular Fuzzy	
Bound	L	U	L	U	L	U	L	U	L	U	L	U	L	U
Attribute Weight	0.4	0.5	0.4	0.5	0.4	0.5	0.6	0.9	0.4	0.5	0.4	0.5	0.5	0.6
Block Caving	4	5	4	5	90		0	1	90		9	10	5	20
Cut & Fill	3	4	4	5	100		4	5	30		6	9	15	20
Long Wall	9	10	5	6	95		4	5	40		9	10	5	25
Open Pit	5	6	6	9	100		9	10	90		6	9	3	20
Room & Pillar	1	3	4	5	60		5	6	35		3	4	10	30
Shrinkage	3	4	5	6	85		5	6	12		9	10	15	40
Square-Set	5	6	1	3	100		0	1	8		6	9	30	125
Stope & Pillar	1	3	4	5	60		3	4	40		3	4	8	30
Sublevel Caving	5	6	4	5	85		3	4	35		9	10	12	40
Sublevel Stopping	4	5	5	6	85		5	6	45		1	3	12	35
Top Slicing	4	5	3	4	95		4	5	10		6	9	20	65

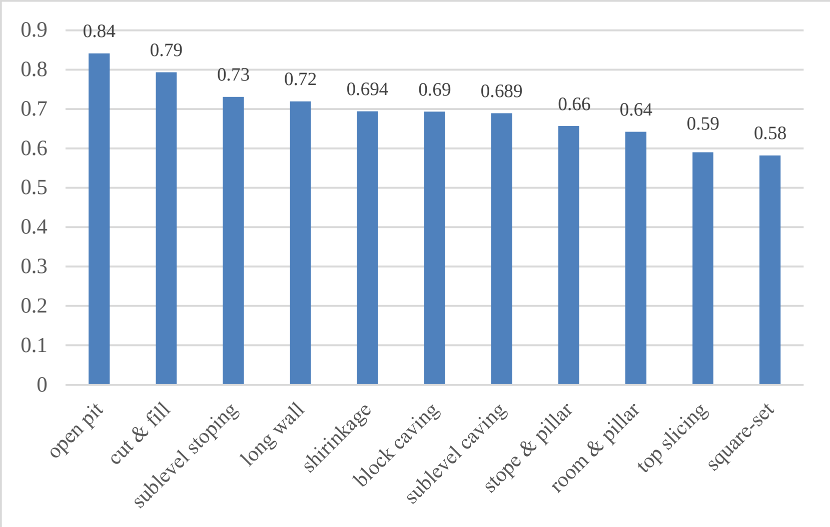

Figure 2. Result of grey method.

The advantage of this decision-making method is the use of grey (distance) numbers in order to resolve the problem of lack of knowledge about the exact amount of impressionability of the options and use in issues with vague and incomplete information.

4.2. Application of TODIM matrix

According to the parameters affecting the extraction methods, which are defined on the basis of the expert opinions and practical experiences on this issue, the initial decision matrix was formed qualitatively and quantitatively using the expert opinions. Then the qualitative amounts of the initial decision matrix were converted to the quantitative amounts using the polar scale method (with 11 points). In the next step, using the norm method (Eq. 13), the decision matrix became without scale (presented in Table 6).

$$n_{ij} = \frac{r_{ij}}{\sqrt{\sum r^2_{ij}}} \tag{13}$$

After making the without-scale matrix and the weight amount of each criterion, which were weighted according to their importance by experts, using the equations provided for the TODIM method, application of the method to this matrix was performed. For this purpose, all options were compared with each other, and then the value for each option was obtained by forming a 11×11 dominate matrix, presented in Table 7 (Figure 3). Finally, the open-pit mining method with the highest value and Square-set method with the lowest value were chosen as the best and worse mining methods for the Gol-e-Gohar mine, respectively.

Table 6. Normalized decision matrix in TODIM method.

Attribute Name	Deposit Shape	Grade Distribution	Ore Dip	Ore Thickness	Depth	Hanging-wall RMR	Ore RMR	Hanging-wall RSS
Attribute Data Type	Linguistic	Linguistic	Linguistic	Linguistic	Linguistic	Linguistic	Linguistic	Linguistic
Attribute Weight	0.0571	0.042	0.071	0.0714	0.071	0.0711	0.0571	0.071
Block Caving	0.195	0.265	0.320	0.359	0.352	0.299	0.049	0.399
Cut & Fill	0.352	0.371	0.449	0.1540	0.352	0.384	0.249	0.310
Long Wall	0.352	0.159	0.064	0.051	0.251	0.384	0.348	0.399
Open Pit	0.195	0.371	0.449	0.462	0.050	0.384	0.448	0.310
Room & Pillar	0.352	0.265	0.064	0.051	0.352	0.299	0.348	0.044
Shrinkage	0.352	0.265	0.064	0.051	0.352	0.213	0.348	0.044
Square-Set	0.117	0.159	0.449	0.051	0.150	0.128	0.049	0.399
Stop & Pillar	0.352	0.371	0.320	0.359	0.352	0.299	0.348	0.044
Sublevel Caving	0.352	0.265	0.192	0.462	0.251	0.299	0.149	0.399
Sublevel Stopping	0.352	0.477	0.192	0.462	0.452	0.299	0.448	0.044
Top Slicing	0.195	0.159	0.320	0.256	0.150	0.213	0.149	0.399

Table 6. (Continued).

Attribute Name	**Ore RSS**	**Footwall RSS**	**Recovery**	**Skilled Man Power**	**Out Put Per Man shift**	**Hanging-wall RQD**	**Mining Cost**
Attribute Data Type	Linguistic	Linguistic	Deterministic	Linguistic	Deterministic	Linguistic	Triangular Fuzzy
Attribute Weight	0.057	0.0571	0.085	0.085	0.071	0.057	0.071
Block Caving	0.278	0.262	0.312	0.055	0.619	0.348	0.359
Cut & Fill	0.166	0.262	0.312	0.278	0.068	0.348	0.279
Long Wall	0.500	0.367	0.312	0.278	0.206	0.348	0.359
Open Pit	0.389	0.472	0.312	0.500	0.619	0.348	0.359
Room & Pillar	0.055	0.262	0.243	0.389	0.206	0.116	0.359
Shrinkage	0.166	0.367	0.312	0.389	0.068	0.348	0.279
Square-Set	0.389	0.052	0.312	0.055	0.068	0.348	0.039
Stop & Pillar	0.055	0.262	0.243	0.166	0.2067	0.116	0.359
Sublevel Caving	0.389	0.262	0.312	0.166	0.206	0.348	0.279
Sublevel Stopping	0.278	0.367	0.312	0.389	0.206	0.038	0.279
Top Slicing	0.278	0.157	0.312	0.278	0.068	0.348	0.199

Table 7. Dominate matrix for TODIM.

	Block Caving	Cut & Fill	Long Wall	Open Pit	Room & Pillar	Shrinkage	Square-Set	Stop & Pillar	Sublevel Caving	Sublevel Stopping	Top Slicing
Block Caving	0	-8.58	-9.37	-13.21	-4.99	-6.59	-1.76	-6.02	-6.28	-11.69	-2.19
Cut & Fill	-7.46	0	-8.22	-13.03	-4.17	-3.24	-2.05	-12.33	-6.01	-12.67	-0.81
Long Wall	-8.50	-6.38	0	-13.26	-3.23	-3.31	0.06	-20.76	-4.79	-10.04	-2.76
Open Pit	-2.30	-2.82	-4.95	0	-2.30	-2.42	-0.98	-10.49	-0.56	-4.617	-1.09
Room & Pillar	-13.10	-10.06	-10.13	-21.19	0	-5.41	-8.81	-17.27	-10.89	-12.55	-9.86
Shrinkage	-12.05	-8.32	-8.39	-19.15	-3.19	0	-5.57	-25.86	-10.01	-12.21	-6.54
Square-Set	-14.68	-16.06	-16.08	-20.04	-15.85	-14.37	0	-59.13	-16.19	-20.43	-9.56
Stop & Pillar	-9.13	-9.44	-11.06	-18.27	-1.26	-6.67	-26.08	0	-8.33	-10.88	-7.39
Sublevel Caving	-5.55	-7.77	-7.57	-13.90	-4.96	-5.30	-3.30	-6.52	0	-8.78	-1.70
Sublevel Stopping	-8.60	-6.48	-6.96	-14.27	-1.58	-1.54	-24.47	-2.84	-5.39	0	-4.82
Top Slicing	-10.95	-11.93	-12.77	-18.55	-12.52	-10.39	-3.97	-13.39	-12.2	-16.62	0

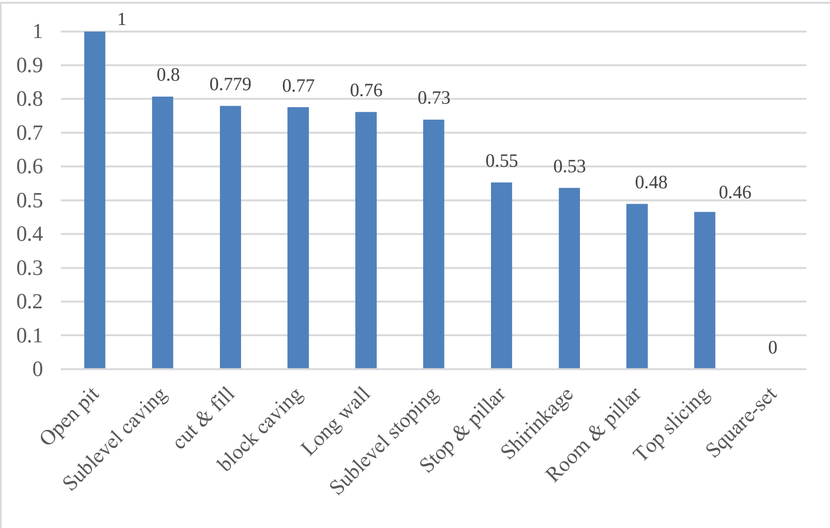

Figure 3. Results of TODIM method.

5. Discussion

In the present study, to choose an appropriate extraction method for the Gol-e-gohar iron ore mine, the multi-criteria decision methods were used. For this purpose, the two decision-making methods Grey and TODIM were used. In the beginning, the selected decision matrix of the elites presented by Samimi Namin et al. was used [8]. According to the type of method used, transfers were carried out to normalize the selected decision matrix of the elites, and calculations corresponding to each method were implemented for choosing an appropriate extraction method. The results of the Grey decision-making method showed that the open-pit mining method, by allocating the value of 0.84, obtained the highest value, and thus it was chosen as the best option, which followed by cut & fill and sub-level stopping mining methods as the subsequent best options with the 0.79 and 0.73 values, respectively. Likewise, the Square-Set mining method, by obtaining the value of 0.58, was chosen as the last option for extraction in the Gol-e-gohar iron ore mine. The results of the TODIM decision-making method showed that the open-pit mining method, by allocating the value of 1, obtained the highest value, and thus it was chosen as the best option, which followed the sub-level stopping and cut & fill mining methods as the subsequent best options with the 0.80 and 0.77 values, respectively. Likewise, the square-set mining method, by obtaining the value of zero, was chosen as the last option for extraction in the Gol-e-gohar iron ore mine. Based on the results of the Grey and TODIM decision-making methods, in both methods, the open-pit mining method was chosen as the best option for extraction in the Gol-e-gohar mine, showing the high correlation of both methods. Table 8 shows the case-history of the extraction method selection for the Gol-e-gohar iron ore mine. Based on Table 8, the results of this research work confirm the results of the previous studies in this field, indicating the high accuracy of both methods used.

Table 8. Summary of mining method selection for Gol-e-Gohar.

Researcher Name	Year	Method	Result
Osanloo et al.	2003	AHP	Open Pit
Samimi Namin et al.	2003	MMS System	Sublevel Caving
Bitarafan & Ataei	2004	Yager	Open Pit
Samimi Namin et al.	2008	FTOPSIS	Open Pit
Samimi Namin et al.	2008	AHP, TOPSIS, PROMITEE	Open Pit
Azadeh et al.	2010	FAHP	Open Pit
Asadi et al.	2011	FTOPSIS	Open Pit
Current study	2015	Grey, TODIM	Open Pit

6. Conclusions

Choosing an appropriate method for extracting a mine is of great importance because if an appropriate method is not chosen, many problems will be created during the mining operations, and additional costs will be imposed to the mine owner(s). Using the multi-criteria decision-making methods is required to choose an appropriate method for extracting a mine due to the involvement of multiple factors and their interaction with each other. In the present study, in order to choose the extraction method for the Gol-e-gohar mine, the two decision-making methods Grey and TODIM were used. The results obtained were as follow:

TODIM method: Using the TODIM decision-making method to choose the optimal extraction method, the open-pit mining and Square with values of 1 and 0 were selected as the best and worst options for mining in the studied mine, respectively. Among the advantages of this method, simple calculations and high precision to choose the preferential option can be mentioned. The disadvantage of this method stemmed from the allocation of the absolute scores 0 and 1 to the best and worst options, making it is impossible to compare the values of this option with the other ones since the difference between these two options and the other options would be unrealistic. However, it may provide very precise results.

Grey method: In the present study, the Grey analysis method was used in order to choose the most optimal mining method for the studied mine. The open-pit mining with a correlation degree of 0.84 and the Square Set mining with a correlation degree of 0.58 were selected as the best and worst mining methods (in relation to the ideal option) in the Gol-e-gohar mine, respectively. This method is among the multi-criteria decision-making techniques that can easily be combined with the fuzzy theory. Among other benefits of this method, its ability to use the absolute and grey (distance) numbers in calculations, its applicability in the case of incomplete and limited information, simpler calculations compared to its counterpart method, and containing the correlation values based on the distance from the option would be referred.

In both methods used in this research work, with almost an appropriate correlation to the ranking of the mining options, the open-pit and the Square Set mining methods were chosen as the best and worst options. By comparing these results with the other research works carried out in the Gol-e-gohar mine, it can be concluded that the open-pit mining is the best extraction method for this mine.

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ارائه یک مدل نوین برای انتخاب روش استخراج بر مبنای روش‌های Grey و TODIM

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چکیده:

یکی از مهم‌ترین مراحل عملیات معدنکاری، انتخاب روش استخراج مناسب برای ذخیره معدنی است. بعد از انتخاب روش استخراج، معمولاً جایگزینی آن با سایر روش‌ها امکان‌پذیر نیست، زیرا این کار ممکن است آن‌قدر هزینه‌بر باشد که کل پروژه را از لحاظ اقتصادی غیرممکن سازد. انتخاب روش معدنکاری وابسته به خصوصیات زمین‌شناسی و هندسی منبع است. با توجه به پیچیدگی فرآیند انتخاب روش معدنکاری مناسب و مؤثر بودن پارامترها بر نتیجه این فرآیند، لازم است تا از روش‌های نوین تصمیم‌گیری که توانایی در نظر گرفتن ارتباط میان پارامترهای موجود و روش‌های گوناگون معدنکاری را داشته باشند، بهره جست. روش‌های تصمیم‌گیری خاکستری و TODIM از جمله روش‌های کارآمد تصمیم‌گیری هستند که علاوه بر سهولت کار از دقت بالایی نیز برخوردارند. در تحقیق حاضر، مدل‌های پیشنهادی جهت تعیین بهترین روش استخراج در معدن سنگ آهن گل‌گهر ارائه شد و نتایج به دست آمده با روش‌های به کار رفته در کارهای تحقیقاتی پیشین مورد مقایسه قرار گرفت. هر دو تکنیک تصمیم‌گیری، روش استخراج روباز را به عنوان مناسب‌ترین گزینه و روش کرسی چینی را به عنوان بدترین گزینه معرفی کردند.

کلمات کلیدی: انتخاب روش معدنکاری، روش‌های تصمیم‌گیری چند معیاره، روش Grey، روش TODIM.