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Preliminary communication

Selection of the Most Proper Underground Mining Method for Kodakan Gold Mine in Iran

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Abstract
The selection of mining methods is a challenging and complicated concept in mining engineering. It depends on various and different factors such as geotechnical, geological and economic properties and characteristics. Kodakan Gold Mine in Iran is currently mined using the open pit method. However, due to the special conditions of this mine and the increase in waste removal costs, it is inevitable to decide to select an underground mining method in the future. The purpose of this research is to select the most proper underground mining method for this mine. The shape, dip, and depth of the deposit, the thickness of the ore, grade distribution, recovery, skilled manpower, output per worker, and strength specifications of the ore, hanging-wall, and footwall are considered as the main decision attributes. Since there are different parameters in selecting the appropriate mining method using the multi-attribute decision making approach, therefore hybrid multi-attribute decision-making method was employed in this paper to enhance the strength of the decision model and eliminate the weaknesses of the classical methods. Regarding the results of this study, rock quality designation of the hanging-wall and deposit shape have the highest weight value in selecting the underground mining method. Moreover, the shrinkage mining method is proposed as the most appropriate method.

Keywords:
Mining method selection; AHP; TOPSIS; PROMETHEE; Kodakan Gold Mine

1. Introduction

Mines in countries are considered as one of the most important and vital economic sectors. Investment in this sector can be achieved to reach sustained economic growth and accordingly increase the mining income however, it also leads to the development of other economic and social infrastructures. Selection of the mining method is a crucial stage for extracting any mineral reserve. The best method is technically appropriate which has the least amount of difficulty and complexity, and has the lowest operating costs. Selection of the most proper extraction method for mineral deposits is usually based on the specification of the mineral deposit, characteristics of the host rocks, and environmental conditions. The decision-making process based on these characteristics does not lead to selecting a unique mining method. On the other hand, the most appropriate method must be selected among the various alternatives (**Yazdani-Chamzini et al., 2012**). Mineral extraction is a dynamic process because the size and depth of the mine have continuously increased, and accordingly, the mining operations must be adapted to new conditions (**Bajic et al., 2020**). Nowadays, different qualitative methods such as **Boshkov and Wright** (**1973**), **Morrison** (**1976**), **Laubscher** (**1981**), and **Hartman** (**1987**), and quantitative methods such as **Nicholas** (**1981**) and UBC (**Miller et al., 1995**) have been proposed to select the most proper mining method. As there are many criteria for selecting the suitable mining method that often conflict with each other, this is a multi-attribute decision-making (MADM) problem. The MADM methods have been applied in different studies for mining method selection. **Balusa and Gorai** (**2019**) ranked the underground mining methods for a uranium mine in India using the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS), VIseKriterijumska Optimizacija I Kompromisno Resenje (VIKOR), ÉLimination Et Choix Traduisant la REalité (ELECTRE), Preference Ranking Organization Method for Enrichment of Evaluations (PROMETHEE), and Weighted Product Model (WPM) methods. **Ali and Kim** (**2021**) applied TOPSIS to modify the University of British Columbia (UBC) method to select the best mining methods. In the reviewed study, all ore properties mentioned in the UBC method were considered and then the mining methods were prioritized using the TOPSIS method. **Shohda et al.** (**2022**) applied the artificial neural network to select the mining method. In the reviewing study, the criteria considered in the UBC method were used for the decision problem. Then, the TOPSIS method was developed based on experimental testing by

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using backpropagation neural networks for the mining method selection. **Li et al.** (**2023**) applied the TOPSIS method under a fuzzy environment to select the best underground mining method. In the mentioned study, Pythagorean fuzzy sets and the TOPSIS method were used to select the best mining method for Suichang underground gold mine in China.

The main scope of this paper is to prioritize mining methods for a gold mine in Iran, by using the MADM methods. To achieve this goal, at first, the weight of each decision attribute is determined by using the Analytic Hierarchy Process (AHP). Then, the most appropriate mining method is selected using the TOPSIS and PROMETHEE MADM methods. The AHP is easy to use, flexible, and handles qualitative and quantitative criteria. Regarding **Cheng and Li** (**2001**), AHP is more accurate in decision-making because the consistency of the expert's judgment can be verified. Nowadays, AHP has been used in different fields of mining problems, such as analysis of coal mine accidents (**Liu et al., 2018**), risk assessment of gas explosion (**Li et al., 2020**), equipment selection (**Yavuz, 2015**), selection of the proper plant species for mine reclamation (**Ebrahimabadi, 2016**), groundwater vulnerability assessment in coal mines (**Karan et al., 2018**), environmental conflicts assessment in mining industries (**Dao et al., 2019**), safety risk assessment of the underground mines (**Ameri Siahuei et al., 2021; Hazrathosseini, 2022**), risk assessment of water inrush (**Bai et al., 2022**), selection of the green mining strategy (**Wu et al., 2022**), safety risk assessment in coal mines (**Rahimdel et al., 2022**), and slope stability analysis (**Acuña and Mendoza, 2023**).

Among MADMs, TOPSIS is the most straightforward one and can find the best alternative faster than many MADM methods. TOPSIS's logic is reasonable and comprehensible (**Shih et al., 2007; Rahimdel and Noferesti, 2020**). Unlike the AHP, TOPSIS cannot check the inconsistency of the judgments. Moreover, TOPSIS cannot elicit weights and relies on other weighting methods, such as AHP. TOPSIS has been applied in various fields of mining engineering such as the assessment of the environmental conflicts in mining industries (**Dao et al., 2019**), risk assessment of water inrush (**Zhang et al., 2021**), determination of the stope boundary for underground mines (**Shami-Qalandari et al., 2022**), prediction of mining-induced subsidence (**Xu et al., 2023**), slope stability in open-pit mines (**Sun and Li, 2021**), site selection of stone crusher machine (**Mirzaei and Testik, 2021**), selection of the mining equipment (**Alpay and Iphar, 2018**), and selection of the best drilling and blasting pattern (**Rahimdel et al., 2020**). PROMETHEE is a new method for evaluating the decision alternatives concerning the decision criteria to identify the strength of preferring an alternative over other alternatives. PROMETHEE supports group-level decision-making to identify the positive and negative aspects of the alternatives. Regarding **Ulengin et al.** (**2001**), PROMETHEE is a user-friendly prioritization method based on the completeness of ranking. This has also been applied in many applications (**Hudej et al., 2013**; **Mladineo et al., 2016**; **Gul et al., 2019**; **Rahimdel et al., 2020**; **Rahimdel and Noferesti, 2020**).

The main purpose of this paper is to select the ideal underground mining method for Kodakan Gold Mine. It is worth noting that using the MADM methods in the same case did not result in the same ranking. This problem can be solved by using more than one MCDM method. A single MCDM method is not efficient in enabling a correct analysis of the problem. Therefore, to obtain a more reliable result, more than one MCDM method is usually used by utilizing the strengths of each method (**Wu et al., 2012; Beheshtinia and Omidi, 2017; Tang, 2018**). In this paper, the hybrid MADM methods were used to select the most appropriate and suitable mining method.

2. Methods

Kodakan Gold Mine is located in South Khorasan Province, 175 km from Birjand City in Iran. Exploration of the Kodakan Gold Mine was started by Zemin Kavan Zaman Company in 2015 by performing chemical, mineralogical, physical, and rock mechanics tests, and geophysical operations by 740 meters of core drilling. The proven reserve of the mine is estimated as 305,000 tons of gold with an average grade of 2.1 ppm and a limit grade of 0.2 ppm. Kodakan Gold Mine is now being extracted using the open-pit mining method. However, due to the special conditions of the mineral deposit and approaching the predetermined maximum value of mining depth, it is necessary to continue mining operations using an underground method. The technical characteristics of Kodakan Mine are obtained according to the exploration reports and the open pit mining operation, as given in **Table 1**.

Nowadays, different methodologies are proposed for solving decision-making problems with several conflicting criteria. The MADM is a branch of operations research applied to select the most appropriate alternative by considering different conflict decision criteria. This paper aims to apply hybrid MADM methods, named

Table 1: Specification of the studied ore deposit

Criterion	Ore property
Thickness (m)	0.3-1
Slope (deg.)	60-70
Depth below the surface (m)	> 60
Ore zone strength	High
Hanging-wall strength	High
Foot wall strength	High
General shape	Vein deposit
Grade distribution	Moderate

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AHP-TOPSIS and AHP-PROMETHEE, to select the best underground mining methods. This section presents steps of the AHP, TOPSIS, and PROMOTHEE MADM methods as a research methodology.

2.1. AHP method

The analytical Hierarchy Process (AHP) was presented by **Saaty** (**1983**). In the AHP, complex problems are broken down and analyzed as a hierarchy. This method is an effective MADM method, which is based on pairwise comparisons and provides the possibility of examining different scenarios in the problems. The steps of this method in determining the weight of decision criteria are given below (**Saaty, 2000**).

Step 1: Creating a hierarchical structure

In order to create a hierarchical structure in determining the importance degree of criteria, the goal of the problem is placed at the top level of the hierarchical structure and the criteria at the second level. The hierarchical structure depends on the type of decision problem. On the other hand, the number of levels can be increased as much as possible, and there is no limit in this respect.

Step 2: Calculating the relative weight of the criteria

In this step, first, a pairwise comparison matrix of criteria is constructed so that the elements of each level are compared to other elements related to themselves at a higher level. The pairwise comparison uses a scale from "equal importance" to "extreme importance." In a pairwise comparison matrix, the elements on the diagonal are equal to one and do not need to be evaluated. A $n \times n$ pairwise comparison matrix (A) is shown as **Equation 1**:

$$A = \begin{bmatrix} 1 & a_{12} & \dots a_{1n} \\ a_{21} & 1 & \dots a_{2n} \\ \vdots & \vdots & 1 \ \vdots \\ a_{n1} & a_{n2} \dots & 1 \end{bmatrix} \tag{1}$$

Where element a_{ij} is the relative importance of criterion a_i over criterion a_j. It is noted that $a_{ji} = 1/a_{ij}$. According to the uncertainties about the linguistic variables, including equal importance to extreme importance, the numerical values corresponding to linguistic variables are used, as mentioned in **Table 2**.

Table 2: Linguistic variables and their corresponding numerical values (**Saaty, 2000**)

Linguistic scale	Numerical value
Equal importance	1
Weak importance	3
Moderately importance	5
Strong importance	7
Extreme importance	9
Mid values	2,4,6,8

Step 3: Calculating the overall weight of each criterion

In AHP, the weight of criteria is usually derived from a pairwise comparison matrix by the maximal eigenvector method (EVM) or by the geometric mean method (GMM). However, past studies favor GMM over EVM (**Blanquero et al., 2006**; **Dijkstra, 2013**; **Krejčí and Stoklasa, 2018**). In this paper, the GMM is used. According to the GMM, the weight of criterion i is derived as the geometric means of the pairwise comparisons in the rows of the pairwise comparison matrix as **Equation 2** (**Krejčí and Stoklasa, 2018**):

$$W_i = \sqrt[n]{\prod_{j=1}^{n} a_{ij}} \tag{2}$$

Step 4: Calculating the consistency rate

The consistency of the AHP method is determined by using the inconsistency ratio of the pairwise comparison matrix. In order to measure the inconsistency of the decision, the inconsistency ratio (CR) is computed as follows (**Rahimdel, 2021**):

$$CR = \frac{CI}{RI} \tag{3}$$

Where CI is the consistency index and RI is the random index (RI).

The consistency index of the comparison matrix is calculated from **Equation 4**:

$$CI = \frac{(\lambda_{\max} - n)}{n - 1} \tag{4}$$

Where $\lambda_{\max}$ denotes the maximal eigenvalue of the judgment matrix, and n is the matrix size.

The random index is obtained from **Equation 5**:

$$RI = 1.98 \times \frac{(n-2)}{n} \tag{5}$$

Saaty (**1983**) decided the threshold of 0.10 to check the inconsistency of the decision. On the other hand, to avoid inconsistency in the AHP model, the consistency index must be smaller than 0.10; otherwise, the comparison matrix needs to be revised.

2.2. TOPSIS method

The TOPSIS method was presented by **Huang and Yoon** (**1981**). In the TOPSIS method, the alternatives are prioritized based on their similarity to the ideal solution. On the other hand, the more similar an option is to the ideal solution, the higher it will be ranked. The steps of the TOPSIS method are presented as follows (**Huang and Yoon, 1981**):

Step 1: Constructing the decision matrix

At this step of the TOPSIS method, the decision matrix, which represents the numerical value of each decision criterion for each alternative, is constructed as **Equation 6**:

$$X = \begin{bmatrix} x_{11} & \cdots & x_{1n} \\ \vdots & \ddots & \vdots \\ x_{m1} & \cdots & x_{mn} \end{bmatrix} \quad (6)$$

Where m is the number of the decision alternatives, n is the number of the decision attribute, and x_{11} ($i = 1,2,\ldots,m$; $j = 1,2,\ldots,n$) is the rating of alternatives.

Step 2: Constructing the weighted unscaled decision matrixes

After forming the decision matrix, criteria with different dimensions are converted into scale-free criteria. The unscaled performance ratings $r_{i,j}$ (i = 1, 2, ..., m; j = 1, 2, ..., n) can be computed by **Equation 7**:

$$r_{ij} = \frac{x_{ij}}{\sqrt{\sum_{i=1}^{m} x_{ij}^2}} \quad (7)$$

The $r_{i,j}$ values can be given as a matrix R, as shown in **Equation 8**:

$$R = \begin{bmatrix} r_{11} & \cdots & r_{1n} \\ \vdots & \ddots & \vdots \\ r_{m1} & \cdots & r_{mn} \end{bmatrix} \quad (8)$$

After constructing the unscaled decision matrix, the weighted unscaled decision matrix is obtained from the product of the unscaled decision matrix and the weight vector of the criteria according to **Equation 9**:

$$v_{ij} = w_j r_{ij} \quad (9)$$

Step 3: Calculating ideal and non-ideal solutions

The values of the ideal solution (A^*) and the non-ideal solution (A^-) for each criterion are calculated using **Equations 10** and **11**:

$$A^* = \left\{ v_1^*, v_2^*, \ldots, v_j^*, \ldots, v_n^* \right\} \quad (10)$$

$$A^- = \left\{ v_1^-, v_2^-, \ldots, v_j^-, \ldots, v_n^- \right\} \quad (11)$$

Where v_j^* is the best value for criterion j among all alternatives and v_j^- is the worst value for criterion j among all alternatives.

Step 4: Ranking the alternatives

After calculating the values of the ideal and non-ideal solutions, the distance from the ideal and non-ideal solutions for each alternative are obtained from **Equations 12** and **13**:

$$S_i^* = \sqrt{\sum_{j=1}^{n} \left(V_{ij} - V_i^* \right)^2} \quad (12)$$

$$S_i^- = \sqrt{\sum_{j=1}^{n} \left(V_{ij} - V_i^- \right)^2} \quad (13)$$

Where S_i^* is the distance from the ideal solutions, S_i^- is the distance from the non-ideal solutions, j (j=1,2,...,n) is the decision criterion, and i (i=1,2,...,m) represents the decision alternatives.

After determining the values of the distance from the ideal and non-ideal solutions for each alternative, the similarity index (C_i^*) is calculated to rank the alternatives from **Equation 14**:

$$C_i^* = \frac{S_i^-}{S_i^* + S_i^-} \quad (14)$$

It should be noted that the value of the similarity index changes between zero and one. In other words, the closer this value is to one, the closer the desired alternative is to the ideal solution. In this way, different alternatives can be prioritized.

2.3. PROMETHEE Method

The PROMETHEE method is one of the most recently proposed multi-attribute decision-making methods presented by **Brans** (**1982**). PROMETHEE is a ranking method that is considered a simple method in conception and computation in comparison to many other MCDM methods (**Ilangkumaran et al., 2013**). PROMETHEE I and II, developed by **Brans and Vincke** (**1994**), are two types of the PROMETHEE method, which allow partial and complete ranking of alternatives, respectively. The PROMETHEE method is based on pairwise comparisons of alternatives concerning each criterion qualitatively and quantitatively with flexible and accurate calculations. Moreover, in the PROMETHEE method, it is possible to use different preference functions regarding the characteristics of the criteria to eliminate the scaling effect of the decision attributes (**Taherdoost and Madanchian, 2023**). This method has been widely used in many applications of mining, such as the mining method selection (**Bogdanovic et al., 2012**), equipment selection (**Temiz and Calis, 2017**), safety risk assessment of the mining industry (**Gul et al., 2019**), selection of the drilling and blasting pattern (**Rahimdel et al., 2020**), selection of the emerging technology in mines (**Dayo-Olupona et al., 2020**), and investment preference of the mineral extraction sector (**Rahimdel and Noferesti, 2020**).

The PROMETHEE method needs three factors for the evaluation and ranking of alternatives: the decision matrix, the weight of criteria, and information about the preference function that is determined by experts. In PROMETHEE, to define deviations between alternatives for each attribute, the preference function is used. It should be noted that minor deviations indicate that the preference degrees are weak and vice versa. Regarding **Brans** (**1982**), the shape of the preference function is dependent on two thresholds, Q and P. The negligible threshold Q represents the most significant deviation, and the decisive threshold P represents the slightest deviation. The positive and negative flows are other parameters that need to be calculated for each alternative regarding the given weight of each attribute. A positive flow indicates how much each criterion is higher than all other criteria, while a negative flow indicates the superiority of the alternative over the other ones. It is worth noting that PROMETHEE identifies the positive and negative aspects of the alternatives and obtains a ranking among them; therefore, it can cover some limitations of TOPSIS. The steps of PROMETHEE are summarized as follows (**Anand and Kodali, 2008**):

Step 1. Defining the preference functions

In the first step, to find how much value *a* is preferred to value *b*, the preference function is computed from **Equation 15**:

$$P_j(a,b) = \begin{cases} 0 iff_j(a) - f_j(b) \le 0 \\ 1 iff_j(a) - f_j(b) > 0 \end{cases} \qquad (15)$$

Where $P_j(a,b)$ is the preference function in creation *j*, $f_j(a)$ and $f_j(b)$ are the preference functions for values *a* and *b* in the criterion *j*, respectively.

Step 2. Calculating the overall preference index

The overall preference index is calculated by considering the preference function as **Equation 16**:

$$\pi(a,b) = \sum_{j=1}^{k} W_j . P_j(a,b), \sum_{j=1}^{n} W_j = 1 \qquad (16)$$

Where $\pi(a,b)$ is the overall preference index and $f_j(a)$ and $f_j(b)$ is the weight of criteria *j*.

Step 3. Calculating the net flow and ranking the alternatives

The net flow (φ) for each alternative is calculated as **Equations 17** to **19**:

$$\varphi(a) = \varphi^+(a) - \varphi^-(a) \qquad (17)$$

$$\varphi^+(a) = \frac{1}{n-1} \sum_{x \epsilon A} \pi(a,x) \qquad (18)$$

$$\varphi^-(a) = \frac{1}{n-1} \sum_{x \epsilon A} \pi(x,a) \qquad (19)$$

Where $\varphi(a)$ is the net flow, $\varphi^+(a)$ is the positive flow, and $\varphi^-(a)$ is the negative flow for alternative $a \in A$.

To rank the alternatives, PROMETHEE *I* makes a partial ranking by using the positive and negative flows while, PROMETHEE *II* uses the net flow.

3. Results

In this research, the most appropriate and suitable underground mining method for Kodakan Gold Mine is chosen using the AHP-TOPSIS method. At the first stage, decision attributes are determined. The deposit shape, grade distribution, dip, thickness, and depth of the ore deposit, rock mechanics characteristics of the ore, hanging-wall, and footwall, ore recovery, skilled manpower; and output per man shift are considered decision criteria. The importance degree of the decision attributes was obtained and then the TOPSIS and PROMETHE were used to rank the decision alternatives.

3.1. Importance degree of the decision attribute

In the first step, the weight of the criteria was calculated using the AHP. To achieve this, the comparison matrix between the criteria is constructed based on expert judgment. The weight of each criterion is calculated from the geometric mean method, described in section 2.3, as shown in **Figure 1**.

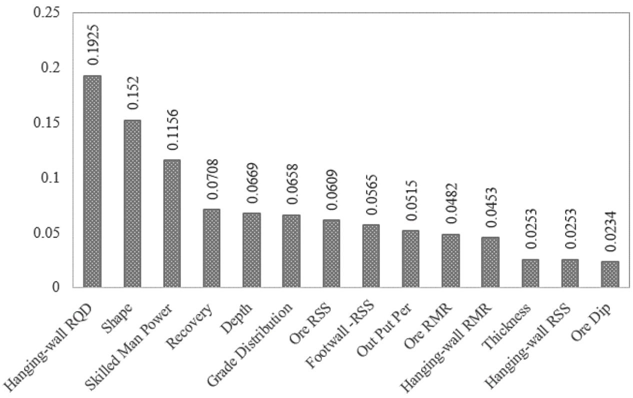

Figure 1: Importance degree of each decision criteria

Based on **Figure 1**, the hanging-wall RQD, deposit shape, and skilled manpower have the highest importance, respectively. It is worth noting that the consistency index of the pairwise comparison matrix of the criteria is calculated as 0.15, and the random rate of inconsistency is calculated as 1.67. In this case, the inconsistency ratio is 0.093 (less than 0.1), which indicates that the consistency of the judgments is acceptable.

3.2. Selection of the most proper mining method

This subsection is devoted to selecting the most proper underground mining method for Kodakan Gold Mine using the TOPSIS and PROMETHEE methods among the Block Caving, Cut and fill, Room and pillar, Shrinkage, Stope and pillar, Sublevel caving, Sublevel stoping, and Top slicing underground mining methods.

In applying the TOPSIS method to select the best alternative, first, the initial decision-making matrix is formed considering decision criteria and alternatives as given in **Table 3** (**Samimi Namin et al., 2008**). A matrix composed of alternatives and criteria was offered to the experts and specialists in mine design and mining method selection. Then, the quantitative decision matrix was constructed with the averaging of the results obtained from the various expert opinions.

It should be noted that the linguistic variables were converted to numbers considering the corresponding numerical values, as presented in **Table 2**. The normalized decision matrix was formed using **Equation 7**, and then

Table 3: Decision matrix based on expert opinions (**Samimi Namin et al., 2008**)

Criteria	**Deposit Shape**	**Grade Distribution**	**Ore Dip**	**Ore Thickness**	**Depth**	**Hanging-wall RMR**	**Ore RMR**
Block caving	Medium	Medium	Medium	Mol High	Mol High	Mol High	Low
Cut & pill	High	Mol High	Mol High	Mol Low	Mol High	High	Mol High
Room & pillar	High	Medium	Low	Very Low	Mol High	Mol High	Very High
Shrinkage	High	Medium	Low	Very Low	Mol High	Medium	Mol High
Stope & pillar	High	Mol High	Medium	Mol High	Mol High	Mol High	Very High
Sublevel caving	High	Mol Low	Mol Low	High	Medium	Mol High	Mol Low
Sublevel stoping	High	Mol Low	Mol Low	High	High	Mol High	High
Top slicing	Medium	Medium	Medium	Medium	Mol Low	Medium	Mol Low
Criteria	Hanging-wall RSS	Ore RSS	Footwall RSS	Recovery (%)	Skilled Man Power	Output Per Man shift	Hanging-wall RQD
Block caving	High	Medium	Medium	90	Very Low	90	Very High
Cut & pill	Mol High	Mol Low	Medium	100	Medium	30	High
Room & pillar	Low	Low	Medium	60	Mol High	35	Mol Low
Shrinkage	Low	Mol Low	Mol High	85	Mol High	12	Very High
Stope & pillar	Low	Low	Medium	60	Mol Low	40	Mol Low
Sublevel caving	High	Mol High	Medium	85	Mol Low	35	Very High
Sublevel stoping	Low	Medium	Mol High	85	Mol High	45	Low
Top slicing	High	Medium	Mol Low	95	Medium	10	High

Table 4: The weighted normalized decision matrix

	Deposit Shape	**Grade Distribution**	**Ore Dip**	**Ore Thickness**	**Depth**	**Hanging-wall RMR**	**Ore RMR**
Block caving	0.057	0.014	0.004	0.013	0.025	0.016	0.027
Cut & pill	0.058	0.054	0.010	0.009	0.025	0.016	0.003
Room & pillar	0.033	0.015	0.009	0.006	0.011	0.011	0.008
Shrinkage	0.060	0.014	0.004	0.001	0.025	0.012	0.020
Stope & pillar	0.058	0.022	0.014	0.003	0.025	0.021	0.020
Sublevel caving	0.061	0.009	0.005	0.012	0.032	0.016	0.025
Sublevel stoping	0.032	0.014	0.009	0.009	0.025	0.017	0.006
Top slicing	0.060	0.009	0.006	0.012	0.018	0.016	0.008
	Hanging-wall RSS	Ore RSS	Footwall RSS	Recovery	Skilled Man Power	Out Put Per Man shift	Hanging-wall RQD
Block caving	0.003	0.010	0.018	0.018	0.054	0.015	0.028
Cut & pill	0.003	0.010	0.018	0.018	0.023	0.017	0.025
Room & pillar	0.013	0.025	0.011	0.028	0.041	0.004	0.071
Shrinkage	0.003	0.014	0.028	0.025	0.054	0.005	0.090
Stope & pillar	0.010	0.015	0.018	0.030	0.039	0.012	0.074
Sublevel caving	0.003	0.025	0.026	0.025	0.054	0.019	0.018
Sublevel stoping	0.013	0.025	0.018	0.027	0.012	0.037	0.090
Top slicing	0.013	0.035	0.018	0.025	0.027	0.015	0.092

the weighted normalized decision matrix was formed using **Equation 9** and the quantitative decision matrix (see **Table 4**). The positive and negative ideal solutions were calculated using **Table 4** and **Equations 10** and **11** and given in **Table 5**.

The distance from the ideal and non-ideal solutions for each mining method was calculated using **Equations 12** and **13**. Then, the amount of similarity index is calculated, and the mining methods are prioritized based on this. The amount of similarity index for each mining method is given in **Table 6**. According to **Table 6**, the shrinkage mining method is suggested as the most appropriate underground mining method for Kodakan Gold Mine.

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Table 5: the values of ideal solution (A^*) and non-ideal solution (A^-) for each criterion

	Ore RMR	**Hanging-wall RMR**	**Depth**	**Ore Thickness**	**Ore Dip**	**Grade Distribution**	**Deposit Shape**
A^*	0.027	0.021	0.032	0.013	0.014	0.054	0.061
A^-	0.003	0.011	0.011	0.001	0.004	0.009	0.032
	Hanging-wall RQD	Out Put Per Man shift	Skilled Man Power	Recovery	Footwall RSS	Ore RSS	Hanging-wall RSS
A^*	0.092	0.037	0.054	0.030	0.028	0.035	0.013
A^-	0.018	0.004	0.012	0.018	0.011	0.010	0.003

Table 6: Similarity index and ranking of mining methods

Alternative	**Ideal solutions (S_i^*)**	**Non-ideal solution (S_i^-)**	**Similarity index (C_i^*)**
Block caving	0.0075	0.0036	0.327
Cut & pill	0.0075	0.0034	0.312
Room & pillar	0.0054	0.0042	0.440
Shrinkage	0.0036	0.0086	0.704
Stope & pillar	0.0029	0.0057	0.661
Sublevel caving	0.0082	0.0044	0.352
Sublevel stoping	0.0050	0.0071	0.588
Top slicing	0.0040	0.0076	0.653

Table 7: The overall preference function matrix for all mining methods

Alternative	**Block caving**	**Cut & fill**	**Room & pillar**	**Shrinkage**	**Stope & pillar**	**Sublevel caving**	**Sublevel stoping**	**Top slicing**
Block caving	0.000	0.438	0.561	0.170	0.241	0.332	0.341	0.322
Cut & pill	0.293	0.000	0.847	0.624	0.345	0.422	0.627	0.599
Room & pillar	0.439	0.513	0.000	0.115	0.182	0.291	0.530	0.324
Shrinkage	0.599	0.697	0.729	0.000	0.565	0.479	0.401	0.438
Stope & pillar	0.636	0.791	0.773	0.368	0.000	0.089	0.575	0.369
Sublevel caving	0.482	0.648	0.561	0.474	0.577	0.000	0.408	0.383
Sublevel stoping	0.536	0.551	0.438	0.495	0.356	0.475	0.000	0.324
Top slicing	0.525	0.747	0.676	0.424	0.508	0.302	0.620	0.000

Table 8: The positive, negative, and net flows for all alternatives

Alternative	**The positive flow (φ^+)**	**The negative flow (φ^-)**	**The net flows (φ)**
Block caving	0.344	0.501	-0.158
Cut & pill	0.537	0.626	-0.090
Room & pillar	0.342	0.655	-0.313
Shrinkage	0.558	0.381	0.177
Stope & pillar	0.514	0.396	0.118
Sublevel caving	0.505	0.341	0.163
Sublevel stoping	0.453	0.500	-0.047
Top slicing	0.543	0.394	0.149

In this subsection, the PROMETHEE is used to rank the mining method for Kodakan Gold Mine. In the first step, the comparison matrix is created. It is noted that because of the high volume of calculations, it was ignored to present details of the calculations. The overall preference index was calculated for all alternatives using **Equation 16** and given in **Table 7**. The net flow values were calculated using **Table 7** and **Equations 17** to **19**. The results are given in **Table 8**. According to **Table 8**, the order of alternatives is obtained as follows:

Shrinkage > Stope and pillar > Top slicing > Sublevel stoping > Room and pillar > Sublevel caving > Block caving > Cut and fill.

4. Discussion

When the application of different MADM methods provides different results, aggregation methods are used for making a reliable decision. In this paper, the alternatives are finally ranked based on the average of their orders obtained by the TOPSIS and PROMETHEE methods. The average of rank orders was calculated and shown in **Figure 2**. Regarding **Figure 2**, the shrinkage underground mining method is the best alternative for Kodakan Gold Mine.

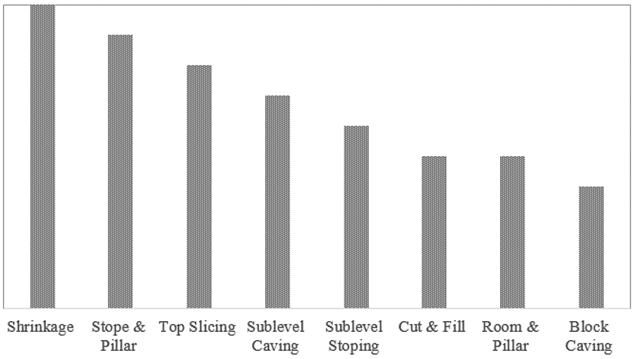

Figure 2: The final rank order for the underground mine selection

The shrinkage mining method is an underground method like sublevel caving but with a continuous backfilling operation from the top. Therefore, the broken material must have the ability to flow freely (**Brand and Haider, 2023**). Moreover, the grain size should not be too fine as much as it impacts the material flow and leads to high dilution. In the shrinkage mining method, ore is excavated in horizontal slices. The layout of the shrinkage stoping method is shown in **Figure 3** (**Didier et al., 2009**). The minerals are extracted using the drilling and blasting method, starting from the bottom of the stope and advancing upward. After each blasting operation, the volume of the broken rock increases by about 50%. Therefore, about 40% of the blasted ore must be drawn off continuously during mining. About 60% of the broken ore is left in the stope as a working platform for drill workers and supporting the stope walls (**Hustrulid et al., 2001**).

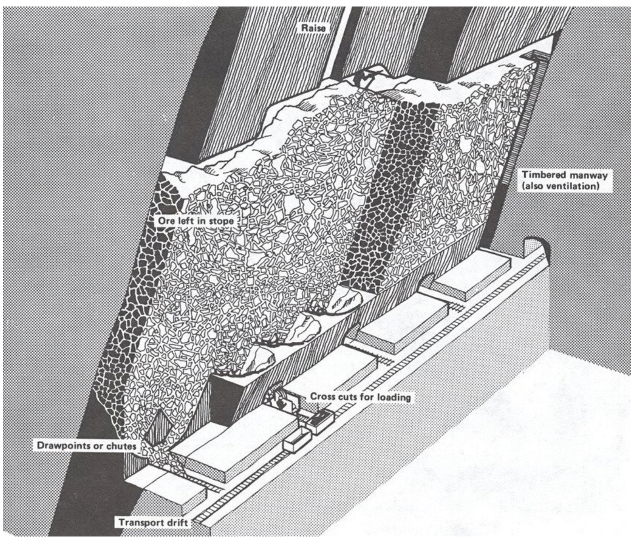

Figure 3: Shrinkage stoping in a large vertical body (**Didier et al., 2009**)

The shrinkage mining method is suitable for tabular deposits with steep dips and moderate thickness that meet the mineral properties of the vein deposit of Kodakan Mine with a thickness of 0.3 to 1 meter and deposit slope of 60 to 70 degrees. Regarding **Brand and Haider** (**2023**), the shrinkage method is a proper alternative when only small stope sizes would be possible due to geotechnical constraints.

It is worth noting that Kodakan Gold Mine is located only seven kilometers from Qaleh-Zari Copper Mine. This copper mine is the only underground mine in Iran extracted by the shrinkage-stoping method. The mining operation of Qaleh-Zari Mine was started in 1975 and is still ongoing. The width of the mineralization area in Qaleh-Zari Mine is between 0.5 and 7 m. The development process and access to the mineral deposit in Qaleh-Zari Mine include the drilling of the vertical wells, drift tunnels, and finally, man-way and ore pass raises. The extracted ores are moved to the surface through six vertical shafts, and one inclined shaft. The total mineral extraction is 450 tons per day, on average (**Rahimdel and Ghodrati, 2023**). In the development stages of the mining stopes of Qaleh-Zari Mine, the drift tunnels with the dimensions of 2.2×2.4 meters are drilled in different mine levels. The level intervals are approximately 30 meters, which dictates the height of the mining stopes at each level. To connect the upper and lower drifts, vertical raises with dimensions of 2.1×2.1 are drilled. The distance between these raises is considered according to the length of mining stopes, which varied from 40 to 60 meters.

This formation is helpful for the Kodakan Mine's contractors to develop the underground spaces and design the mining stopes. This is also a helpful guideline for managers to provide adequate production scheduling.

5. Conclusions

The selection of mining methods and the concept of how the orebody would be extracted are among the most crucial tasks in mining projects. In this paper, the most suitable underground mining method was proposed for the Kodakan Gold Mine in Iran using hybrid multi-attribute decision-making (MADM) methods. Regarding the results, the slope of the deposit and mining cost have the highest importance degree while the depth below the surface and ore thickness, have the lowest importance. Among different mining methods, shrinkage-stopping mining is proposed as the most appropriate underground mining method. The results of this study are helpful for mine managers and contractors to select the most suitable mining method. The results of this paper indicated that by application of the hybrid MADM approaches for the underground mining method selection, it is possible to overcome the scarcities of some problems related to a single MADM. The proposed approach applied in this work can be used in conditions with numerous decision criteria. However, as some decision criteria have been self-claimed, determination of the adequate values for the deposit specifications, especially the geotechnical properties of the ore and county rock, and application of the decision-making approach under the fuzzy environment for consideration of the uncertainties in the form of ambiguity and vagueness are proposed for future studies. Economic and feasibility studies of the mining operation, considering safety and health issues during the mining operation, and applying other multi-attribute decision-making methods to find the most suitable alternative are also recommended for future studies.

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SAŽETAK

Odabir najprikladnije metode eksploatacije u iranskome rudniku zlata Kodakan

Odabir eksploatacijske metode izazovan je i složen proces u rudarskome inženjerstvu. Ovisi o raznim čimbenicima kao što su geotehnička, geološka i ekonomska svojstva i karakteristike. U iranskome rudniku zlata Kodakan trenutačno se eksploatira površinskim kopom. Međutim, zbog posebnih uvjeta i povećanja troškova uklanjanja otkrivke neizbježno je u budućnosti odabrati određenu metodu podzemne eksploatacije. Cilj je istraživanja odabir najprikladnije metode podzemne eksploatacije za ovaj rudnik. Oblik, nagib i dubina ležišta, debljina rude, distribucija kvalitete rude, iskorištenje, kvalificirana radna snaga, učinak po radniku, čvrstoća rude, krovine i podine smatraju se glavnim parametrima za odluku. Zbog različitih čimbenika u odabiru odgovarajuće metode eksploatacije pri pristupu odlučivanja s više parametara korištena je hibridna metoda odlučivanja kako bi se povećala uspješnost modela odlučivanja i otklonili nedostatci klasičnih metoda. Rezultati istraživanja pokazali su da najveću težinsku vrijednost pri odabiru metode podzemne eksploatacije imaju indeks kvalitete jezgre krovine i oblik ležišta. Pored toga, natkopna metoda predložena je kao najprikladnija metoda podzemne eksploatacije.

Ključne riječi:
odabir metode eksploatacije, AHP, TOPSIS, PROMETHEE, rudnik zlata Kodakan

Author’s contribution

The author prepared the whole work.