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USE OF INTEGRATED AHP-TOPSIS METHOD IN SELECTION OF OPTIMUM MINE PLANNING FOR OPEN-PIT MINES

Successful mine planning is necessary for the sustainability of mining activities. Since this process depends on many criteria, it can be considered a multi-criteria decision making (MCDM) problem. In this study, an integrated MCDM method based on the combination of the analytic hierarchy process (AHP) and the technique for order of preference by similarity to the ideal solution (TOPSIS) is proposed to select the optimum mine planning in open-pit mines. To prove the applicability of the proposed method, a case study was carried out. Firstly, a decision-making group was created, which consists of mining, geology, planning engineers, investors, and operators. As a result of studies performed by this group, four main criteria, thirteen sub-criteria, and nine mine planning alternatives were determined. Then, AHP was applied to determine the relative weights of evaluation criteria, and TOPSIS was performed to rank the mine planning alternatives. Among the alternatives evaluated, the alternative with the highest net present value was selected as the optimum mine planning alternative. It has been determined that the proposed integrated AHP-TOPSIS method can significantly assist decision-makers in the process of deciding which of the few mine planning alternatives should be implemented in open-pit mines.

Keywords: open-pit mine; mine planning; multi-criteria decision making (MCDM); analytic hierarchy process (AHP); technique for order of preference by similarity to ideal solution (TOPSIS)

1. Introduction

Mine planning is one of the most critical procedures during the operation of a mine that is difficult to reverse. An incorrect decision taken at this stage in the mining sector, where production costs per unit have increased, and profitability has decreased, can result in significant losses during operation. As almost all of the high-quality ores have been produced, it is a known fact that

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low-quality and limited resources remain worldwide [1,2]. Also, reliable mine planning should be made to prevent technical, operational, and environmental problems that may arise during the mining operation, to avoid additional costs to the mine owner/owners and to use limited resources more efficiently. For this reason, it has become essential today to carry out mine planning studies in a more precise, detailed, and reliable manner [3-5].

Deutsch [6] emphasised that open pit mines involve complex operations that require a considerable investment, and hundreds or thousands of people are employed here. Based on this, he stated that the planning of such large-scale operations is laborious and cannot be done manually. Therefore, in the mine planning process, detailed studies should be conducted in which every useful data obtained from the mine area is evaluated, and many alternatives are produced by testing variable input values using mining software [7]. Studies were carried out on the development and application of mathematical models, optimising the production schedule and applying operations research methods in mining [8-10]. The mathematical programming models being employed at this point can suggest various optimum mine planning options for various parameters, but they cannot decide which option should be put into practice. These models also provide information on how altering any parameter affects the best alternative. In this case, the problem arises as to which of the alternatives should be selected. After mine planning alternatives are obtained by experts, these are presented to decision-makers to identify which one to apply. The decision-makers need to analyse many parameters at the same time and apply a method to evaluate how each parameter affects their choices. In this case, the selection of the optimum mine planning among a set of alternatives can be considered a multi-criteria decision making (MCDM) problem as it depends on many parameters or criteria having relative importance [11]. Thus, it is understood that the decision-maker will need the method suggested in this article when choosing which one, among many alternatives, should be applied. The greatest advantage of the application of the MCDM method is that it enables decision-makers to make decisions based on scientific criteria.

MCDM is part of the Operations Research (OR) technique that can help decision-makers with selecting problems under the presence of a finite number of decision criteria and alternatives [12-15]. MCDM is a combination of mathematical and computational tools that may be utilised under either certainty or uncertainty and can evaluate the quantitative and qualitative criteria together [16]. Recently, MCDM methods have been employed to solve problems in many studies, such as energy, environment and sustainability, management, engineering, manufacturing systems, operation research and soft computing, and other fields [17]. Commonly used MCDM methods are as follows: Analytic Hierarchy Process (AHP), Analytic Network Process (ANP), Elimination Et Choix Traduisant la Realit (ELECTRE), Preference Ranking Organisation Method for Enrichment Evaluation (PROMETHEE), Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS), Vlse Kriterijumsk Optimizacija Kompromisno Resenje (VIKOR) and Weighted Aggregated Sum Product Assessment (WASPAS).

It has been found that applying a single MCDM method is insufficient to overcome any decision-making problem [16]. To improve the strengths and to make up for shortcomings in a single MCDM method, some hybrid models have been developed by using two MCDM methods together [18-20]. In this way, the uncertainties in the decision problem will be reduced, and decision making will be able to make more robust decisions [16]. The hybrid MCDM methods are based on improving the weaknesses of one method by integrating the strength of another method [21]. While achieving this integration, one method is used for weighting the criteria and another for ranking the alternatives [22-23]. While creating hybrid MCDM methods, the most frequently used ones are AHP, ANP, DEMATEL, TOPSIS, and VIKOR methods because they feature strong mathematical backgrounds and valuable characteristics [24]. Also, other combinations of MCDM methods are present [25].

Over the last years, various integrated MCDM methods to solve decision problems have increasingly been carried out in a wide range of areas every year [17,24,26]. Mahase et al. [27] have done extensive work on the application of multi-criteria decision analysis (MCDA) techniques in the mining industry. It is common to use the AHP method in combination with other MCDA techniques, and it's an important result of this study. In addition, Namin et al. [28] uncovered existing research using MCDM methods in mining method selection and created a reference bank based on the classification scheme. The distribution of the studies that have been performed using the hybrid MCDM method, especially in the mining field, is presented in Table 1.

TABLE 1

Scientific journal articles on the application of hybrid MCDM methods in the mining field
(modified from Sitorus et al. [16])

Author(s)	**Method**	**Problem addressed**
Bazzazi et al. [29]	AHP-FTOPSIS	Selecting of loading-haulage equipment in open pit
Namin et al. [30]	FTOPSIS	Selecting of mineral deposit for mining method
Karadogan et al. [31]	Yager	Selecting of underground mining method
Bazzazi et al. [32]	AHP-entropy-FTOPSIS	Selecting the most suitable ore transportation system
Golestanifar and Bazzazi [33]	FAHP-FTOPSIS	Selecting of tailing impoundment site
Azadeh et al. [34]	FAHP	Selecting mining method based on modifying Nicholas technique
Bazzazi et al. [35]	AHP-entropy-VIKOR	Selecting of the loading-haulage equipment in open pit mines
Bogdanovic et al. [36]	AHP-PROMETHEE	Selecting of mining method
Shariati et al. [37]	FAHP-TOPSIS	Selecting the best mining method
Yari et al. [38]	AHP-TOPSIS	Selecting the most suitable blasting pattern
Ataei et al. [39]	Monte Carlo simulation-AHP	Selecting the optimum mining method
Adebimpe et al. [40]	AHP-FTOPSIS	Selecting of mine equipment
Wang and Tu [41]	AHP and FPROMETHEE	Selecting of an appropriate mechanised mining technical process for thin coal seam mining
Wang et al. [42]	entropy and FPROMETHEE	Selecting of an auxiliary transportation model in a fully-mechanised face in a nearly horizontal thin coal seam
Stojanovic et al. [43]	AHP-ELECTRE	Selecting an optimal technology for surface mining in the open pit coal mine
Pazand and Hezarkhani [44]	AHP-TOPSIS	Selecting Porphyry Cu potential area
Ghasvareh et al. [45]	AHP-TOPSIS/AHP-VIKOR	Selecting of haulage system

When Table 1 is examined, it is understood that studies on MCDM methods in the mining sector are used in many areas. Researchers specifically focused on mine planning and equipment selection. In studies related to mine planning, open pit/underground mining method alternatives or production method alternatives of these mining methods were evaluated. However, there is a research gap in the literature on the evaluation of mine planning alternatives, consisting of different production parameters using MCDM methods. The desire to fill this gap constitutes the motivation of the current study. The novelty of this study is the investigation of mine planning alternatives consisting of different production parameters instead of mining methods or production methods, unlike existing studies.

The main objectives of this article can be written as:

(i) Developing an integrated AHP-TOPSIS method for optimum mine planning selection in open pit mines,

(ii) Carrying out a case study on the open pit chrome field to prove the feasibility of this method,

(iii) Determining the order of importance of the main criteria and sub-criteria in the selection of the mine planning alternative

(iv) To create a resource that can help decision makers in similar problems of the proposed method.

2. Methodology

2.1. AHP method

The AHP, which was first developed by Saaty [46,47], uses a pairwise comparison method to determine relative weights of criteria based on a hierarchical structure, and it is one of the most popular MCDM methods. AHP is a powerful tool, which entails that complicated problems are converted to a hierarchical structure with the help of a series of pairwise comparisons by arranging the decision attributes and alternatives, and so it helps the decision-makers [48,49]. The basic structure of AHP is known as a hierarchical tree consisting of the final goal, criteria, sub-criteria, and alternatives. In a hierarchical problem, each element is compared with the other elements for its relative significance [19]. In AHP, the process of measuring the relative weights of certain criteria is based on expert judgement [50]. The AHP process can be expressed as follows:

Step 1. The final goal, criteria, sub-criteria, and alternatives are determined and a hierarchical structure of the decision problem by using these is constructed.

Step 2. The relative importance of different criteria for the objective of the problem is determined using the AHP. Thus, a pairwise comparison matrix of criteria is established by using a scale of relative importance, and it enables the decision-maker to evaluate the impact of each factor on the objective [51]. The judgments are entered using the fundamental scale of the AHP, which is shown in Table 2.

TABLE 2

The relational scale proposed by Saaty [46] for pairwise comparisons

Intensity of Importance	Definition
1	Equal importance
3	Weak importance of one over another
5	Essential or strong importance
7	Very strong or demonstrated importance
9	Absolute importance
2, 4, 6, 8	Intermediate values between adjacent scale value

For N criteria, a pairwise comparison matrix is a square matrix of $N \times N$ and the entry c_{ij} denotes the comparative importance of criteria i for criteria j. In the matrix $c_{ij} = 1$ when $i = j$ and $c_{ji} = 1/c_{ij}$. The pairwise comparison matrix (C) can be represented as follows:

$$C = \begin{bmatrix} 1 & c_{12} & \cdots & c_{1N} \\ c_{21} & 1 & \cdots & c_{2N} \\ \cdots & \cdots & 1 & \cdots \\ c_{N1} & c_{N2} & \cdots & 1 \end{bmatrix} \quad c_{ii} = 1,\ c_{ji} = 1/c_{ij},\ c_{ij} \neq 0 \tag{1}$$

Step 3. After the pairwise comparison matrix was obtained, the relative weights of the decision elements are calculated. The widely utilised eigenvalue approach is one of many approaches that can be used for this. In this approach, the relative weights of criteria (w) can be estimated as follows:

$$C \times w = \lambda_{\max} \times w \tag{2}$$

where $\lambda_{\max}$ is the largest eigenvalue of the pairwise comparison matrix C. During the AHP process, due to the inconsistency of human judgments when assessing weights, the aggregation weight vector might be invalid. Thus, the consistency property of the importance of degrees should be made in the evaluation process, which needs to be examined [52-54]. To measure the consistency between pairwise comparison judgments, the consistency index (CI) and consistency ratio (CR) is used. The CI and CR values are defined as follows:

$$CI = \frac{\lambda_{\max} - N}{N - 1} \tag{3}$$

$$CR = \frac{CI}{RI} \tag{4}$$

where RI is a random index, and its value can be obtained from Table 3 by different orders of pairwise comparison matrices [55]. If the value of CR is 0.1 or less than the judgement is detected

TABLE 3

Values of Random Index (*RI*) (taken from Saaty [55])

Matrix order	3	4	5	6	7	8	9	10	11
RI	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49	1.51

to be acceptable. Otherwise, the judgement may not be reliable, and the decision-makers have to revise their judgements.

2.2. TOPSIS method

The TOPSIS method is a useful MCDM technique that was developed by Hwang and Yoon [56] and then modified by Yoon [57] and Hwang et al. [58]. The basic principle of the TOPSIS method is based on the concept that the selected alternative should have the shortest distance from the positive ideal solution and the farthest distance from the negative ideal solution [59]. To compare the alternatives, firstly, the Euclidean distances between each alternative and both the ideal and the negative-ideal solutions are calculated, and then the relative closeness is calculated to measure the two distances respectively [60]. Finally, the order of preference of the alternatives is determined by ranking according to their relative closeness values. The procedure of the TOPSIS can be expressed as follows [49,56,61-63].

Step 1. The weights of criteria obtained through the AHP method are used to establish the decision matrix. If M and N represent the number of alternatives and criteria (sub-criteria), respectively, then the structure of the decision matrix having an order $M \times N$ can be concisely expressed as follows:

$$D_{M\times N} = \begin{bmatrix} a_{11} & a_{12} & \cdots & a_{1N} \\ a_{21} & a_{22} & \cdots & a_{2N} \\ \cdots & \cdots & \cdots & \cdots \\ a_{M1} & a_{M2} & \cdots & a_{MN} \end{bmatrix} \tag{5}$$

where a_{ij} represents the actual value of the i^{th} alternative in terms of j^{th} decision criteria.

Step 2. It is known that the decision matrix consists of attributes with different units, therefore, to make all attributes comparable, the decision matrix is converted to a normalised decision matrix. An element r_{ij} of the normalised decision matrix R is calculated as follows:

$$r_{ij} = \frac{a_{ij}}{\sqrt{\sum_{i=1}^{M} a_{ij}^2}} \qquad i = 1, 2, \ldots, M; \quad j = 1, 2, \ldots, N \tag{6}$$

Step 3. The weighted normalised decision matrix is constructed. An element v_{ij} of weighted normalisd matrix V is calculated as follows:

$$v_{ij} = w_j * r_{ij} \qquad i = 1, 2, \ldots, M; \quad j = 1, 2, \ldots, N \tag{7}$$

where w_j is the weight of the j^{th} attribute or criterion.

Step 4. The positive ideal solution (A^+), composed of all the best criteria values, and the negative ideal solution (A^-), composed of all the worst criteria values, are determined as follows:

$$A^+ = \begin{array}{l} \left\{\left(\max v_{ij} \mid j \in J\right), \left(\min v_{ij} \mid j \in J'\right)\right. \\ \left.\text{for } i = 1, 2, \ldots, M\right\} = \left\{v_1^+, v_2^+, \ldots, v_N^+\right\} \end{array} \tag{8}$$

$$A^- = \begin{matrix} \left\{ \left(\min v_{ij} \mid j \in J \right), \left(\max v_{ij} \mid j \in J' \right) \right. \\ \left. \text{for } i = 1,2,\ldots,M \right\} = \left\{ v_1^-, v_2^-, \ldots, v_N^- \right\} \end{matrix} \tag{9}$$

where J is the set of benefit or positive criteria and J' is the set of cost or negative criteria.

Step 5. The separation measures are calculated using the N-dimensional Euclidean distance method. The separation of each alternative from the positive ideal solution (S_i^+) and negative ideal solution (S_i^-) is given as follows:

$$S_i^+ = \left\{ \sum_{j=1}^{N} \left(V_{ij} - V_j^+ \right)^2 \right\}^{0.5}, \quad i = 1,2,\ldots,M \tag{10}$$

$$S_i^- = \left\{ \sum_{j=1}^{N} \left(V_{ij} - V_j^- \right)^2 \right\}^{0.5}, \quad i = 1,2,\ldots,M \tag{11}$$

Step 6. The relative closeness (C_i^+) value of each alternative concerning the ideal solution is defined as follows:

$$C_i^+ = \frac{S_i^-}{\left(S_i^+ + S_i^- \right)}, \qquad 0 < C_i^+ < 1, i = 1,2,\ldots,M \tag{12}$$

Step 7. Finally, all the alternatives are ranked according to the descending order of C_i^+. The best alternative is the one that has the highest C_i^+.

3. Case Study

3.1. Case study area

Considering that metallic mines are popular today, an open-pit chrome mine, which is in the planning stage, is selected for the case study. It is planned that the excavation works will be carried out with the drilling-blasting method, and the loading and transportation operations will be performed with the excavator + truck system. The chrome ore produced from the field will be fed to the mineral processing plant, and a concentrated product will be obtained, resulting from a series of processes. This chrome mine is approximately 105 km from Bursa city centre, located south of the Büyükorhan district. The grade value of the study area has a wide range of 0.3-51.9%. Most of the chrome concentrate produced is exported abroad.

3.2. Data set

To be used in mine planning studies, data such as geology and hydrology of the study area, technical features of mining machines, safe working conditions, current economic data (such as sales income, and costs), and drilling data were collected. By evaluating the above, the mine planning alternatives for different parameters were produced by experts using 3D mining software and Simsched. Netpro/mine and Surpac software were used comparatively to obtain reliable results during the modelling phase [64,65]. SimSched software is based on the direct block scheduling algorithm. The basis of this software is mixed integer programming and heuristic techniques [66]. For each alternative, the bench width and discount rate values were fixed by experts as 5 and 0.1, respectively. Also, the blasting-hauling value of each alternative was on a scale of 1-3 (1: low, 2: medium, 3: high), according to the impact of mining activities.

3.3. Proposed method

The flow chart of the integrated AHP-TOPSIS method developed in this study is shown in Fig. 1. The decision-making group was composed of people from different engineering disciplines and positions. These individuals were selected from mining, geological and planning engineers, investors, and operators. Assessment of possible main criteria and sub-criteria, determination of the weights of defined criteria and selection of optimum mine planning were carried out by this group. The obtained mine planning alternatives were presented to the decision-makers group to select which alternative to apply. Studies such as literature review, expert opinions, surveys, and interviews were conducted, and the data that was predicted to affect the mine planning selection process were evaluated closely. As a result of the meetings held and face-to-face interviews by the decision-makers group, the hierarchical structure of the proposed method consisting of four main criteria, thirteen sub-criteria, and nine mine planning alternatives was constructed. Fig. 2 shows the hierarchical structure of the method developed from top to bottom. Above is the final goal. Below that, the main criteria and sub-criteria for each main criterion are marked. Finally, there are alternatives associated with these criteria.

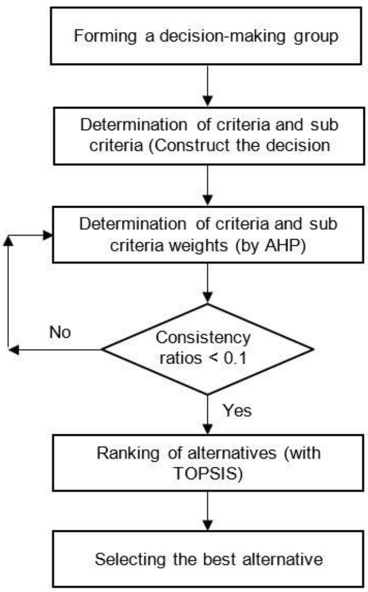

Fig. 1. The flow chart of the proposed method

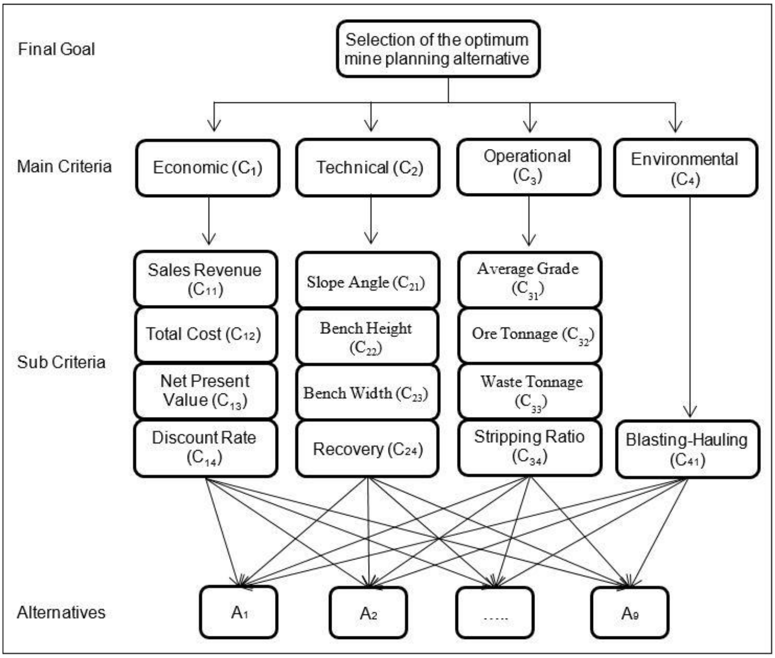

Fig. 2. The hierarchical structure of the proposed method

The four main criteria thought out in this research were economic (C_1), technical (C_2), operational (C_3), and environmental (C_4). The main criteria were further broken down into sub-criteria. The economics were broken down into sales revenue (C_{11}), total costs (C_{12}), net present value (C_{13}), and discount rate (C_{14}). The technical was separated into slope angle (C_{21}), bench height (C_{22}), bench width (C_{23}), and recovery (C_{24}). The operational was associated with average grade (C_{31}), ore tonnage (C_{32}), waste tonnage (C_{33}), and stripping ratio (C_{34}). Environmental was characterised by blasting-hauling (C_{41}). Identification of the main criteria and sub-criteria are given in Table 4.

4. Results and Discussion

In this study, an integrated AHP-TOPSIS method was developed to evaluate mine planning alternatives consisting of different production parameters. The developed method was applied to the open pit chrome mine. To estimate the relative weights of four main criteria, the pairwise comparison matrix was formed. The obtained matrix and calculated priority weights of the main criteria were shown in Table 5.

The priority weight values of the main criteria were depicted in Fig. 3. As seen, the order of importance of the main criteria in the selection of the optimum mine planning alternative for the decision-makers group is economic (0.558), technical (0.263), operational (0.122), and environmental (0.057), respectively. In other words, economics is the most important main criterion in determining the optimum mine planning alternative.

TABLE 4

Defining of main criteria and sub-criteria

Main Criteria	Symbol	Sub-criteria	Symbol
Economic	C_1	Sales revenue	C_{11}
		Total costs	C_{12}
		Net present value	C_{13}
		Discount rate	C_{14}
Technical	C_2	Slope angle	C_{21}
		Bench height	C_{22}
		Bench width	C_{23}
		Recovery	C_{24}
Operational	C_3	Average grade	C_{31}
		Ore tonnage	C_{32}
		Waste tonnage	C_{33}
		Stripping ratio	C_{34}
Environmental	C_4	Blasting-hauling	C_{41}

TABLE 5

Pairwise comparison matrix and priority weights for the main criteria

Criteria	Economic	Technical	Operational	Environmental	Weight
Economic	1	3	5	7	0.558
Technical	1/3	1	3	5	0.263
Operational	1/5	1/3	1	3	0.122
Environmental	1/7	1/5	1/3	1	0.057

* *CR* (consistency ratio) = 0.044

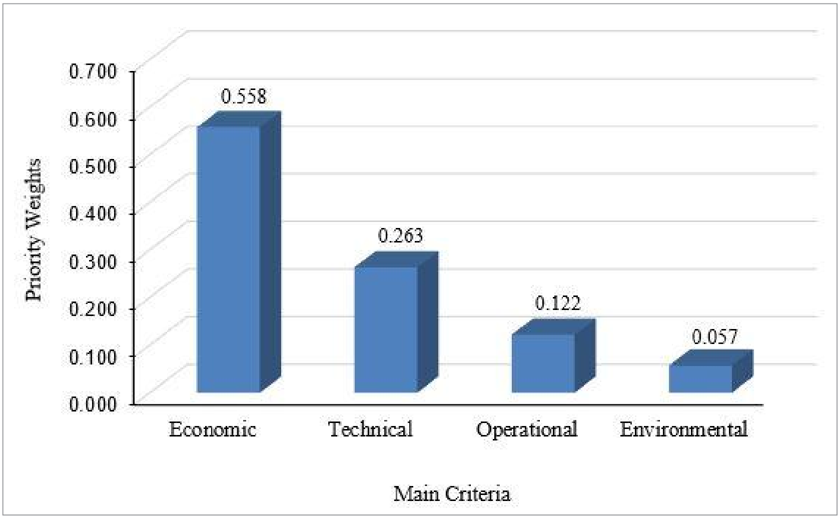

Fig. 3. Priority weight values of main criteria calculated using the AHP method

Then, the priority weights for the economic, technical, and operational sub-criteria pairwise comparison matrices were determined. The acquired results are shown in Tables 6 through 8, respectively.

TABLE 6

Pairwise comparison matrix and priority weights for the economic sub-criteria

Economic Criteria	Sales Revenue	Total Cost	Net Present Value	Discount Rate	Weight
Sales Revenue	1	3	1	7	0.358
Total Cost	1/3	1	1/7	5	0.129
Net Present Value	1	7	1	9	0.470
Discount Rate	1/7	1/5	1/9	1	0.043

* *CR* (consistency ratio) = 0.079

TABLE 7

Pairwise comparison matrix and priority weights for the technical sub-criteria

Technical Criteria	Slope Angle	Bench Height	Bench Width	Recovery	Weight
Slope Angle	1	3	5	5	0.543
Bench Height	1/3	1	3	3	0.245
Bench Width	1/5	1/3	1	1/3	0.076
Recovery	1/5	1/3	3	1	0.136

* *CR* (consistency ratio) = 0.076

TABLE 8

Pairwise comparison matrix and priority weights for the operational sub-criteria

Operational Criteria	Average Grade	Ore Tonnage	Waste Tonnage	Stripping Ratio	Weight
Average Grade	1	2	7	1	0.397
Ore Tonnage	1/2	1	5	2	0.308
Waste Tonnage	1/7	1/5	1	1/3	0.062
Stripping Ratio	1	1/2	3	1	0.233

* *CR* (consistency ratio) = 0.067

Net present value (0.262), sales revenue (0.200), and slope angle (0.143) were found to be the most crucial sub-criteria in selecting the optimum mine planning alternative for the decision-makers group, respectively. The priority weight values of these sub-criteria are higher than the others. This finding indicates that net present value, sales revenue and slope angle criteria are more important than other criteria for decision-makers. In Fig. 4, the spider diagram shows the priority weight values of sub-criteria.

Afterwards, studies were carried out to create the decision matrix, and the obtained matrix is presented in Table 9.

The decision matrix was normalised and the current matrix is given in Table 10. Then, by multiplying this matrix with the weights of the criteria defined through the AHP method, the weighted normalised decision matrix was created (Table 11).

The following positive and negative ideal solutions were determined, as shown in Table 12.

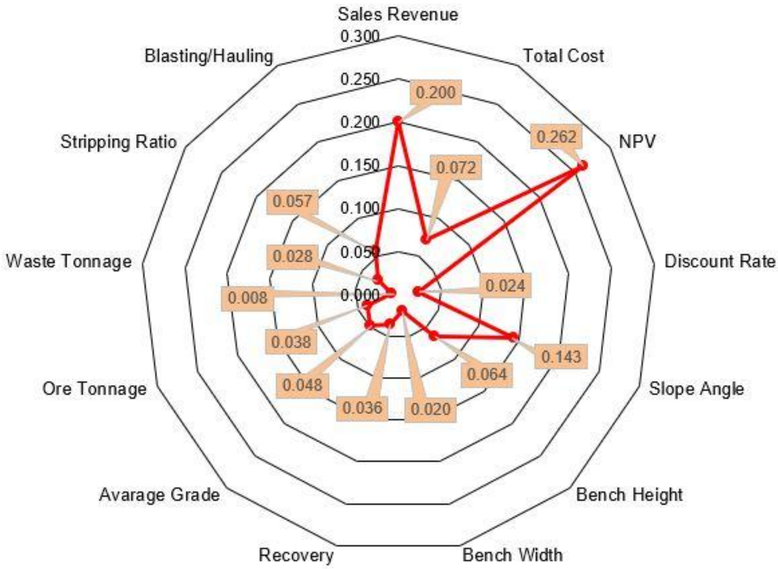

Fig. 4. Priority weight values of sub-criteria calculated using the AHP method

Then, the distance from the positive and negative ideal solutions was calculated, respectively, and the results were given in Table 13. Finally, the relative closeness of each alternative to the ideal solution was calculated, and then the alternatives were arranged in descending order according to their relative closeness. The relative closeness and rank of alternatives were shown in Table 14.

Descending order of the relative closeness was given in Fig. 5. As can be seen, the *A*9 with a relative closeness of 0.857 was selected to be the optimum mine planning alternative for the

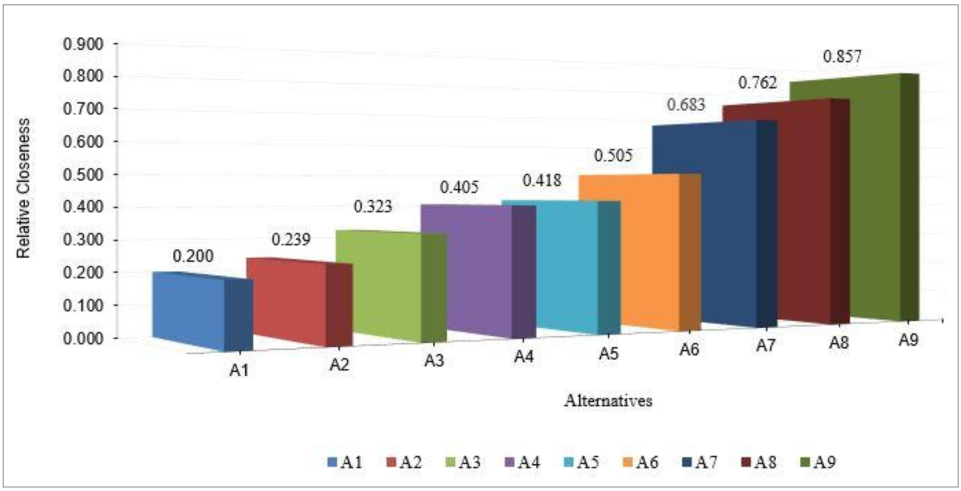

Fig. 5. The relative closeness of each alternative

TABLE 9

Decision matrix

Alternatives	**C_{11} (M$)**	**C_{12} (M$)**	**C_{13} (M$)**	**C_{14} (%)**	**C_{21} (°)**	**C_{22} (m)**	**C_{23} (m)**	**C_{24} (%)**	**C_{31} (%)**	**C_{32} (Mton)**	**C_{33} (Mm^3)**	**C_{34}**	**C_{41}**
Weights	0.200	0.072	0.262	0.024	0.143	0.064	0.020	0.036	0.048	0.038	0.008	0.028	0.057
A1	17.140	8.306	6.489	10	48	10	5	76	14.3	0.437	6.141	14.0	3
A2	17.131	8.306	6.482	10	48	12	5	76	14.3	0.437	6.141	14.1	3
A3	16.974	8.307	6.363	10	48	15	5	76	14.2	0.437	6.144	14.0	3
A4	16.763	7.732	6.377	10	50	10	5	75	14.1	0.437	5.705	13.1	2
A5	16.579	7.748	6.219	10	50	12	5	75	14.0	0.436	5.720	13.1	2
A6	16.596	7.731	6.257	10	50	15	5	75	14.0	0.437	5.707	13.1	2
A7	16.210	7.186	6.853	10	52	10	5	75	13.8	0.436	5.293	12.1	1
A8	16.206	7.189	6.845	10	52	12	5	75	13.8	0.436	5.295	12.2	1
A9	16.233	7.192	6.861	10	52	15	5	75	13.8	0.436	5.297	12.1	1

TABLE 10

Normalised decision matrix

	C_{11} (M$)	**C_{12} (M$)**	**C_{13} (M$)**	**C_{14} (%)**	**C_{21} (°)**	**C_{22} (m)**	**C_{23} (m)**	**C_{24} (%)**	**C_{31} (%)**	**C_{32} (Mton)**	**C_{33} (Mm^3)**	**C_{34}**	**C_{41}**
A1	0.3431	0.3569	0.3311	0.3333	0.3198	0.2666	0.3333	0.3363	0.3396	0.3338	0.3575	0.3570	0.4629
A2	0.3429	0.3569	0.3308	0.3333	0.3198	0.3199	0.3333	0.3363	0.3396	0.3337	0.3575	0.3572	0.4629
A3	0.3398	0.3570	0.3247	0.3333	0.3198	0.3999	0.3333	0.3352	0.3373	0.3340	0.3577	0.3570	0.4629
A4	0.3356	0.3322	0.3254	0.3333	0.3332	0.2666	0.3333	0.3341	0.3349	0.3333	0.3321	0.3321	0.3086
A5	0.3319	0.3329	0.3174	0.3333	0.3332	0.3199	0.3333	0.3330	0.3325	0.3331	0.3329	0.3332	0.3086
A6	0.3322	0.3322	0.3193	0.3333	0.3332	0.3999	0.3333	0.3330	0.3325	0.3335	0.3322	0.3321	0.3086
A7	0.3245	0.3088	0.3497	0.3333	0.3465	0.2666	0.3333	0.3307	0.3278	0.3327	0.3081	0.3087	0.1543
A8	0.3244	0.3089	0.3493	0.3333	0.3465	0.3199	0.3333	0.3307	0.3278	0.3326	0.3082	0.3089	0.1543
A9	0.3249	0.3090	0.3501	0.3333	0.3465	0.3999	0.3333	0.3307	0.3278	0.3332	0.3083	0.3085	0.1543

TABLE 11

Weighted normalised decision matrix

	C_{11} (M\$)	C_{12} (M\$)	C_{13} (M\$)	C_{14} (%)	C_{21} (°)	C_{22} (m)	C_{23} (m)	C_{24} (%)	C_{31} (%)	C_{32} (Mton)	C_{33} (Mm^3)	C_{34}	C_{41}
A1	0.0686	0.0256	0.0869	0.0079	0.0457	0.0172	0.0067	0.0120	0.0164	0.0125	0.0027	0.0101	0.0263
A2	0.0686	0.0256	0.0868	0.0079	0.0457	0.0206	0.0067	0.0120	0.0164	0.0125	0.0027	0.0101	0.0263
A3	0.0679	0.0256	0.0852	0.0079	0.0457	0.0257	0.0067	0.0120	0.0163	0.0126	0.0027	0.0101	0.0263
A4	0.0671	0.0238	0.0854	0.0079	0.0476	0.0172	0.0067	0.0120	0.0162	0.0125	0.0025	0.0094	0.0176
A5	0.0664	0.0239	0.0833	0.0079	0.0476	0.0206	0.0067	0.0119	0.0161	0.0125	0.0025	0.0095	0.0176
A6	0.0664	0.0238	0.0838	0.0079	0.0476	0.0257	0.0067	0.0119	0.0161	0.0125	0.0025	0.0094	0.0176
A7	0.0649	0.0222	0.0918	0.0079	0.0495	0.0172	0.0067	0.0118	0.0159	0.0125	0.0023	0.0088	0.0088
A8	0.0649	0.0222	0.0917	0.0079	0.0495	0.0206	0.0067	0.0118	0.0159	0.0125	0.0023	0.0088	0.0088
A9	0.0650	0.0222	0.0919	0.0079	0.0495	0.0257	0.0067	0.0118	0.0159	0.0125	0.0023	0.0088	0.0088

TABLE 12

Determine positive and negative ideal solutions

	C_{11} (M\$)	C_{12} (M\$)	C_{13} (M\$)	C_{14} (%)	C_{21} (°)	C_{22} (m)	C_{23} (m)	C_{24} (%)	C_{31} (%)	C_{32} (Mton)	C_{33} (Mm^3)	C_{34}	C_{41}
A^+	0.0686	0.0222	0.0919	0.0079	0.0495	0.0257	0.0067	0.0120	0.0164	0.0126	0.0023	0.0088	0.0088
A^-	0.0649	0.0256	0.0833	0.0079	0.0457	0.0172	0.0067	0.0118	0.0159	0.0125	0.0027	0.0101	0.0263

TABLE 13

The distance of each alternative to the positive and negative ideal solutions

	A1	***A2***	***A3***	***A4***	***A5***	***A6***	***A7***	**A8**	***A9***
S^+	0.0209	0.0197	0.0195	0.0142	0.0138	0.0124	0.0094	0.0064	0.0037
S^-	0.0052	0.0062	0.0093	0.0097	0.0099	0.0127	0.0202	0.0205	0.0220

TABLE 14

The relative closeness and rank of alternatives

	A9	***A8***	***A7***	***A6***	***A5***	***A4***	***A3***	***A2***	***A1***
C	0.857	0.762	0.683	0.505	0.418	0.405	0.323	0.239	0.200
Rank	1	2	3	4	5	6	7	8	9

open-pit mine used as the case study area. This alternative was followed by $A8$ with a relative closeness of 0.762, and $A1$ was determined as the worst alternative with 0.200.

In this study, unlike previous ones, production parameters were taken as the basis for creating mine planning alternatives. Production parameters including economic, technical, operational and environmental, were analysed by the decision-making group. Then, among these parameters, those applicable to the case study area were selected, and their maximum and minimum values were determined. Then, mining planning alternatives were created using these parameters. Finally, the optimum mine planning alternative was determined as a result of the application of the integrated AHP-TOPSIS method.

According to the implications obtained in the proposed method, many parameters can be easily controlled. The results can be interpreted quickly, similar to previous studies using integrated MCDM methods. Moreover, since the proposed method has been developed based on scientific criteria, practitioners will have less hesitation in the implementation of the decisions taken as a result of using this method.

Another important finding is that the alternative with the highest NPV was determined as the optimum mine planning alternative. In the previous studies carried out to determine the optimum mine plan, alternatives with the maximum NPV value were investigated [67-69]. This finding shows that the proposed method is supported by previous studies and is reliable in choosing the optimum mine planning.

5. Conclusions

Choosing the optimum mine planning is a vital decision-making problem to ensure mining operations are conducted with high profitability and efficiency. This process is quite complicated due to many parameters and criteria, such as geological, economic, technical, and environmental must be evaluated together by decision-makers. An incorrect decision at this stage can result in major financial difficulties, including the stop of mining operations.

In this paper, an integrated AHP-TOPSIS method for selecting optimum mine planning in open-pit mines is proposed, and a case study is presented to evidence the applicability of this method. During the case study, a decision-making group was formed, and detailed data that could be effective in the selection of the mine planning alternative were collected. Four main criteria, thirteen sub-criteria, and nine mine planning alternatives were determined by evaluating the obtained data. In the integrated AHP-TOPSIS method, the weights of criteria and sub-criteria were calculated by using the AHP method. the consistency ratio was calculated to test the consistency of the determined weights. Then, the mine planning alternatives were evaluated and ranked according to the descending order of relative closeness by using the TOPSIS method. The alternative that had the highest relative closeness, was selected as the best mine planning alternative.

The main conclusions of the current study are as follows:

(1) The Integrated AHP-TOPSIS method, consisting of four main criteria, thirteen sub-criteria, and nine mine planning alternatives, was developed to determine the optimum mine planning alternative, and was successfully applied to an open pit chrome field.
(2) It was found that the economic (priority = 0.558) was the most important main criteria, followed by technical (priority = 0.263), operational (priority = 0.122), and environmental (priority = 0.057).

(3) The highest weight values for sub-criteria were obtained as the net present value (priority = 0.262), sales revenue (priority = 0.200), and slope angle (priority = 0.143), respectively.

(4) Among nine alternatives that were examined, $A9$ was determined as the optimum mine planning alternative with a relative closeness of 0.857. Also, $A1$ with a relative closeness value of 0.200 was detected as the worst alternative.

Based on the above findings, it is understood that the research gap in the literature has been filled. Also, the proposed method can be modified and used by decision-makers to solve similar problems that may be encountered in real life, and it will be a scientific resource for other researchers in this field.

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