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Quantifying Roof Falling Potential based on CMRR Method by Incorporating DEMATEL-MABAC Method; A Case Study

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Abstract

This work incorporates the DEMATEL-MABAC method for quantifying the potential of roof fall in coal mines by means of the coal mine roof rating (CMRR) parameters. For this purpose, considering the roof weighting interval as a quantitative criterion for the stability of the roof, the immediate roof falling potential was quantified and ranked in 15 stopes of Eastern Alborz Coal Mines Company. In this regard, on the basis of the experts' judgments, the fuzzy DEMATEL method was used for designation weights of the parameters, and the MABAC method was incorporated to quantify and rank the stopes (alternatives). "UCS of roof" and "joint spacing" in the immediate roof were found to be the most important parameters that controlled roof falling in stopes; and "joint persistence" was also found to be a quite significant parameter. Finding confirms that overall strength of rood rock mass plays a main role in the falling potential. Comparison of the coefficients of determination (R2) between the weighting interval and proposed model with that and original CMRR indicated more than 15% increase, which represented that the new proposed model was more accurate to quantify roof quality. The findings of this work show that using this combined method and specializing the CMRR method for a given mine geo-condition to assess the quality of the roof and its potential of collapse possesses a higher performance when compared with the original CMRR method.

1. Introduction

The quality of coal mine roof plays a key role in assessing the stability of the stopes and adjacent spaces as well as the roof cavability during advancement of working face. Up to the present time, different methods have been developed for characterization and classifying coal mine roofs for different purposes. The coal mine roof rating (CMRR) method, introduced in 1994 by Mark and Molinda, is the most common roof quality classification system in coal mines that has found numerous applications in the ground control design [1, 2]. CMRR has integrated underground coal mine geological investigations and experiences over the years with concepts of rock mass classification systems in order to describe the roof quality as an international tool for more than two decades. The CMRR weights influence the parameters for roof competence, and sums them as a rate scale from 0 to 100. It focuses on the characteristics of any form of discontinuities in the roof that weakens the fabric rock mass. The value of CMRR is comprised of four parameters including the uniaxial compressive strength (UCS) of the intact rock, the intensity of discontinuities such as bedding planes and slickensides (spacing and persistence), the shear strength of discontinuities (cohesion and roughness), and groundwater presence with respect to the moisture sensitivity of the rock.

Since its introduction, CMRR has been used in a range of ground control issues. CMRR has been used for description of the rock mass characteristics of roof as the input for numerical modeling [3], feasibility studies [4], pillar design

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[5, 6], multiple seam mine design [7], roof support analysis and design [8-13], roof stability [14-18], roof fall rate [19-21], prediction of safe coal mining advance distance of extended-cuts [22], and geo-hazards risk assessment [23, 24]. It should be noted that in some previous research works, CMRR has been used in combination with other parameters as an indication of roof quality [13, 19-21, 24]. In addition to the application of CMRR, some modifications have been conducted on CMRR such as using the fuzzy sets theory in the calculation of CMRR [25], adding additional parameters to design the support requirements [26], and using the fuzzy type-2 theory [27].

Nowadays, CMRR is truly an international procedure to quantify the roof quality with involvement in mine designs in the USA, South Africa, Canada, and Australia. In Australia, it has been claimed that it is an “established coal industry standard” through an investigation in the Queensland coal mines [28]. It has been stated that CMRR is a suitable tool for preliminary examination of roof state from the stability viewpoint on the basis of a recent investigation of its application in the Chinese coal mines [24]. Despite these successful applications, there were some issues of CMRR applicability when it was faced with moisture sensitivity in weak roof in Illinois Basin of the USA [12]. Due to that, CMRR requires less expertise and experience in calculation and usage; the risks associated with human error, inexperience, and incompetence are more likely in it [29]. In addition, this method is empirical and is based on a database comprising the experiences in the United States and its application in Iran's coal mines, which have different structural conditions than the basic conditions of the method development.

In order to meet the above-mentioned objectives, this work aims to use the main parameters of the original CMRR method in addition to the tensile strength to quantify the potential of roof falling incorporating a hybrid MCDM technique in the fifteen stopes of the Eastern Alborz Coal Mines Company (EACMCO). In this regard, roof weighting interval was taken into account as a quantitative criterion for roof strength quality. A lower weighting interval occurred for mining in the incompetent strata that represent instability of roof. In such a situation, a higher roof falling rate is more likely on the stopes and adjacent spaces. In order to investigate the capability of the proposed method, its correlation with weighting interval was compared with the correlation between the conventional CMRR and the weighting interval, and the results obtained were discussed.

2. Methods and Materials

2.1 Methods

A hybrid method by combining fuzzy decision-making trial and evaluation laboratory (DEMATEL) and multi-attributive approximation area comparison (MABAC) was used to evaluate and rank the potential of roof fall. In this regard, fuzzy DEMATEL was applied to weight the parameters based on the expert judgments, and the MABAC method was incorporated to rank the roof falling potential, as shown in Figure 1.

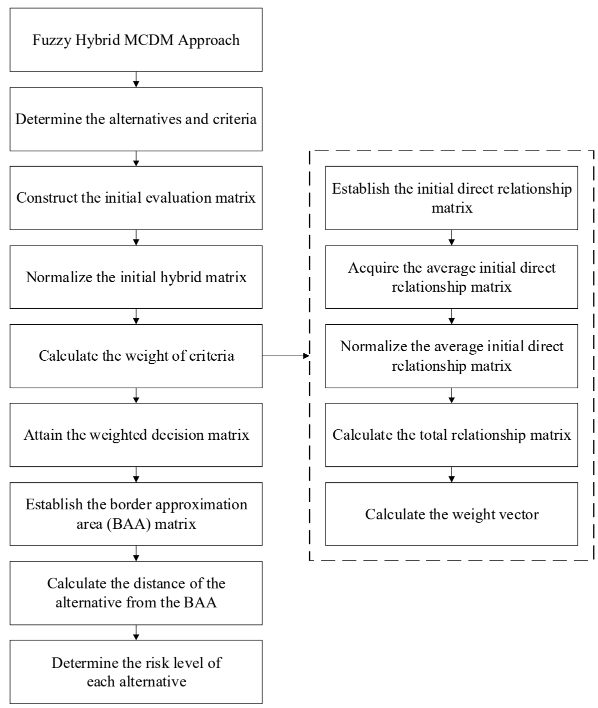


Figure 1. Steps of the proposed hybrid MCDM method.

2.1.1. Decision-making trial and evaluation laboratory (DEMATEL)

From 1972 till 1976, Fontela and Gabus developed the DEMATEL method based on the graph theory [30-32]. It visualizes complex relationships among the components of a system in the form of matrices or directed graphs. The value of the exerted/received influence on/from a component is determined by the experts’ judgments. In this regard, exact values lead to an unclear and uncertain opinion. Accordingly, in order to reduce the uncertainties of human assessment, fuzzy numbers were incorporated into the DEMATEL procedure. The fuzzy DEMATEL steps can be described as follow [33]:

Step 1: Initial and average direct relationship matrices. Direct influence that factor *i* exerts on factor *j* is indicated by experts using a fuzzy triangular number (TFN) (Table 1 and Figure 2).

Table 1. Correspondences of linguistic terms and linguistic values [33].

Linguistic terms	Linguistic value
Very high influence (VH)	(0.75, 1.0, 1.0)
High influence (H)	(0.5, 0.75, 1.0)
Low influence (L)	(0.25, 0.5, 0.75)
Very low influence (VL)	(0, 0.25, 0.5)
No influence (NO)	(0, 0, 0.25)

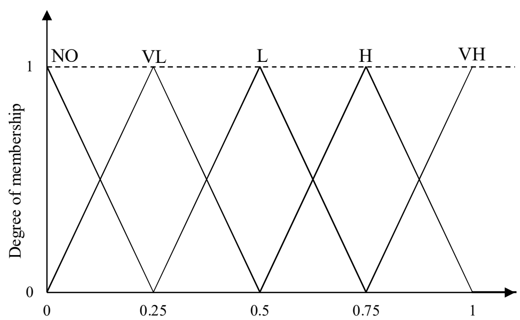


Figure 2. Linguistic variables [33].

Elements of the initial direct relationship matrix, $\tilde{z}_{ij}$, are in the form of *(l_{ij}, m_{ij}, u_{ij})*, corresponding to TFN. The average direct relationship matrix $\tilde{A}$ is calculated by taking the average of *h* expert's value matrices as follows [33]:

$$\tilde{A} = \frac{(\tilde{Z}^1 \oplus \tilde{Z}^2 \oplus \cdots \oplus \tilde{Z}^h)}{h} \tag{1}$$

Step 2: Normalized direct relationship matrix. The normalized direct relationship matrix $\tilde{X}$ is derived by normalizing the matrix $\tilde{A}$ as follow [33]:

$$\tilde{X} = \frac{\tilde{A}}{r} \tag{2}$$

$$r = \max\left[\max_{1\le i\le n} \sum_{j=1}^{n} u_{ij}, \max_{1\le j\le n} \sum_{i=1}^{n} u_{ij}\right], \tag{3}$$

$$i, j = 1, 2, \ldots, n.$$

$\tilde{x}_{ij} = (l'_{ij}, m'_{ij}, u'_{ij})$ are elements of $\tilde{X}$, and define three crisp matrices, whose elements are extracted from $\tilde{X}$ as follow [33]:

$$X_l = \begin{bmatrix} 0 & l'_{12} & \cdots & l'_{1n} \\ l'_{21} & 0 & \cdots & l'_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ l'_{n1} & l'_{n2} & \cdots & 0 \end{bmatrix}$$

$$X_m = \begin{bmatrix} 0 & m'_{12} & \cdots & m'_{1n} \\ m'_{21} & 0 & \cdots & m'_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ m'_{n1} & m'_{n2} & \cdots & 0 \end{bmatrix}$$

$$X_u = \begin{bmatrix} 0 & u'_{12} & \cdots & u'_{1n} \\ u'_{21} & 0 & \cdots & u'_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ u'_{n1} & u'_{n2} & \cdots & 0 \end{bmatrix}$$

Step 3: Total relationship matrix. The total relationship matrix $\tilde{T}$ is computed using Equation (4) [33]:

$$\tilde{T} = \tilde{X}(I - \tilde{X})^{-1} \tag{4}$$

where *I* is the identity matrix.

Elements of $\tilde{T}$ are $\tilde{t}_{ij} = (l''_{ij}, m''_{ij}, u''_{ij})$. On the basis of crisp cases, crisp elements of total relationship matrices are calculated as follow [33]:

$$T_l = [l''_{ij}] = X_l(I - X_l)^{-1}$$

$$T_m = [m''_{ij}] = X_m(I - X_m)^{-1}$$

$$T_m = [m''_{ij}] = X_m(I - X_m)^{-1}$$

Step 4: Weight of factors. $\tilde{w}_i$ is weight of factor *i*th, and is calculated using Equation (5) [33].

$$\tilde{w}_i = \left(\frac{l_{\tilde{D}_i} + l_{\tilde{R}_i}}{\sum_{i=1}^{n} l_{\tilde{D}_i} + \sum_{i=1}^{n} l_{\tilde{R}_i}}, \frac{m_{\tilde{D}_i} + m_{\tilde{R}_i}}{\sum_{i=1}^{n} m_{\tilde{D}_i} + \sum_{i=1}^{n} m_{\tilde{R}_i}}, \frac{u_{\tilde{D}_i} + u_{\tilde{R}_i}}{\sum_{i=1}^{n} u_{\tilde{D}_i} + \sum_{i=1}^{n} u_{\tilde{R}_i}} \right) \tag{5}$$

In order to defuzzify weights, the Best Non-fuzzy Performance (BNP) method was used as Equation (6) [33].

$$BNP = l + \frac{(u - l) + (m - l)}{3} \tag{6}$$

where *l*, *m*, and *u* are the lower, middle, and upper bounds of TFN values, respectively.

2.1.2. Multi-attributive approximation area comparison (MABAC)

The MABAC method is a multi-criteria decision-making method; it was introduced in the research centre of the University of Defence, Belgrade. It was developed on the basis of computing the potential gain and loss values in order to increase the precise results. It has been used in different problem, especially in mining engineering such as assessing the risk of ruck burst and ranking the risk of dilution in underground mining [34, 35]. The MABAC steps are described in the following, as depicted in Figure 1 [36].

Step 1: Construct the initial evaluation matrix. In the first step, the initial evaluation matrix (X) forms by evaluating m alternatives according to n criteria. In this, the matrix columns are the criteria of the problem (C_i) and the rows are the alternatives (A_i). Elements of matrix X (x_{ij}) indicate the score of each alternative according to each criterion. This score can be given through definite numbers or through linguistic terms (i.e. Table 1) [36].

$$X = \begin{array}{c} \\ A_1 \\ A_2 \\ \dots \\ A_n \end{array} \begin{array}{c} \begin{array}{cccc} C_1 & C_2 & \dots & C_n \end{array} \\ \begin{bmatrix} x_{11} & x_{12} & \dots & x_{1n} \\ x_{21} & x_{22} & \dots & x_{2n} \\ \dots & \dots & \dots & \dots \\ x_{m1} & x_{m2} & \dots & x_{mn} \end{bmatrix} \end{array}$$

Step 2: Normalize the initial hybrid matrix. Since the criteria have different dimensions and units, the normalized matrix (N) should be calculated based on the matrix X. Elements of matrix N (n_{ij}) are computed using Eqs. (7) and (8) for the benefit (positive) and cost (negative) criteria, respectively [36].

$$n_{ij} = \frac{x_{ij} - x_i^-}{x_i^+ - x_i^-} \tag{7}$$

$$n_{ij} = \frac{x_{ij} - x_i^+}{x_i^- - x_i^+} \tag{8}$$

where x_{ij} is the elements of matrix X, x^+_i is the maximum value of the observed criterion according to the alternatives, and x^-_i is the minimum value of those.

Step 2: Attain the weighted decision matrix. Using the weights of parameters, which are determined by the fuzzy DEMATEL method, the weighted matrix (V) is calculated using Equation (9) [36].

$$V = \begin{bmatrix} v_{11} & v_{12} & \dots & v_{1n} \\ v_{21} & v_{22} & \dots & v_{2n} \\ \dots & \dots & \dots & \dots \\ v_{m1} & v_{m2} & \dots & v_{mn} \end{bmatrix} = \begin{bmatrix} w_1.(n_{11}+1) & w_2.(n_{12}+1) & \dots & w_n.(n_{1n}+1) \\ w_1.(n_{21}+1) & w_2.(n_{22}+1) & \dots & w_n.(n_{2n}+1) \\ \dots & \dots & \dots & \dots \\ w_1.(n_{m1}+1) & w_2.(n_{m2}+1) & \dots & w_n.(n_{mn}+1) \end{bmatrix} \tag{9}$$

where n_{ij} is the elements of the normalized matrix and w_i is the weight of the ith criterion.

Step 3: Establish the border approximation area (BAA) matrix. The value of BAA for each criterion is computed using Equation (10) [36].

$$g_i = \left(\prod_{i=1}^{m} v_{ij} \right)^{\frac{1}{m}} \tag{10}$$

In fact, the geometric mean is taken from the scores of each criterion in order to obtain the G vector as follows. In the G vector, g_i is the border approximate area for the C_i criterion [36].

$$\begin{array}{cc} & \begin{array}{cccc} C_1 & C_2 & \dots & C_n \end{array} \\ G = & \begin{bmatrix} g_1 & g_2 & \dots & g_n \end{bmatrix} \end{array}$$

Step 4: Calculation of the alternative distance from BAA. The distance matrix Q of the alternative from BAA is calculated using Equation (11) [36].

$$Q = V - G = \begin{bmatrix} v_{11} & v_{12} & \dots & v_{1n} \\ v_{21} & v_{22} & \dots & v_{2n} \\ \dots & \dots & \dots & \dots \\ v_{m1} & v_{m2} & \dots & v_{mn} \end{bmatrix} - \begin{bmatrix} g_1 & g_2 & \dots & g_n \\ g_1 & g_2 & \dots & g_n \\ \dots & \dots & \dots & \dots \\ g_1 & g_2 & \dots & g_n \end{bmatrix} = \begin{bmatrix} q_{11} & q_{12} & \dots & q_{1n} \\ q_{21} & q_{22} & \dots & q_{2n} \\ \dots & \dots & \dots & \dots \\ q_{m1} & q_{m2} & \dots & q_{mn} \end{bmatrix} \tag{11}$$

The A_i alternative can belong to the border approximation area (G), the upper approximation area (G^+) or the lower approximation area (G^-). Therefore, the A_i alternative belongs to the community of the mentioned areas. According to Figure 3, the upper approximation area (G^+) contains the ideal alternatives (A^+), while the lower approximation area (G^-) contains the anti-ideal alternatives (A^-). The A_i alternative belonging to the mentioned areas is determined based on Equation (12) [36].

$$A_i \in \begin{cases} G^+ & if \quad q_{ij} > 0 \\ G & if \quad q_{ij} = 0 \\ G^- & if \quad q_{ij} < 0 \end{cases} \tag{12}$$

The alternative A_i is required to have the maximum number of criteria belonging to the G^+ area in order to be selected as the best alternative among the other alternatives. The higher the number of criteria of the A_i alternative in the G^+ area, the closer it is to the ideal alternative. If $q_{ij} > 0$, then $q_{ij} \in G^+$, and then alternative A_i is near or equal to the ideal alternative. If $q_{ij} < 0$, then $q_{ij} \in G^-$, and then alternative A_i is near or equal to the anti-ideal alternative [36].

Step 5: Determine the risk level of each alternative. In this step, for each alternative, the value of S_i, which is the sum of the distance of the criteria to the border approximation area (G), is calculated using Equation (13). In other words, in this step, the sum of the elements in each row of the Q matrix is calculated. After calculating S_i, the final score of each alternative is determined, and the alternatives are ranked accordingly [36].

$$S_i = \sum_{j=1}^{n} q_{ij}, \qquad j = 1,2,...,n \qquad i = 1,2,...,m \qquad (13)$$

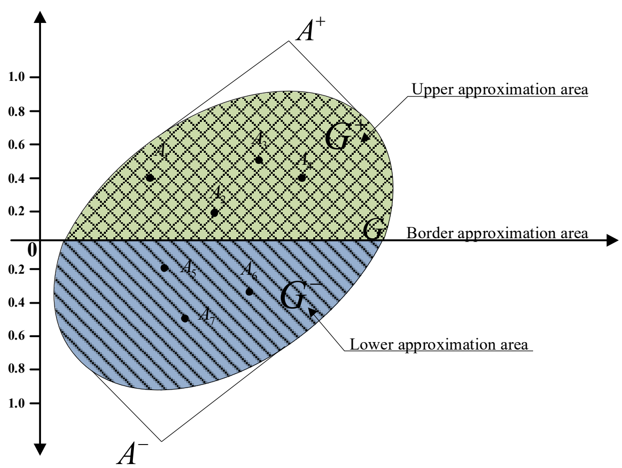


Figure 3. Presentation of the upper (G^+), lower (G^-), and border (G) approximation areas (modified from (selection transport) [36].

2.2 Case study

The Eastern Alborz coal mines, as the most important productive coal mines in the Eastern Alborz Mountains, includes two major mining areas in the Shahrood and Golestan regions (Figure 4). In this work, 7 mines of the Eastern Alborz coal basin including Qeshlaq, Razi, Malach Aram, Takht, Kelariz, Tazareh, and Razmja were selected as the case studies. All of these mines are exploited using the conventional (non-mechanized) longwall mining method. In order to establish a database, the roof rock properties and other characteristics of fifteen stopes in these mines were collected through laboratory investigations, underground surveying, and reviewing the literature.

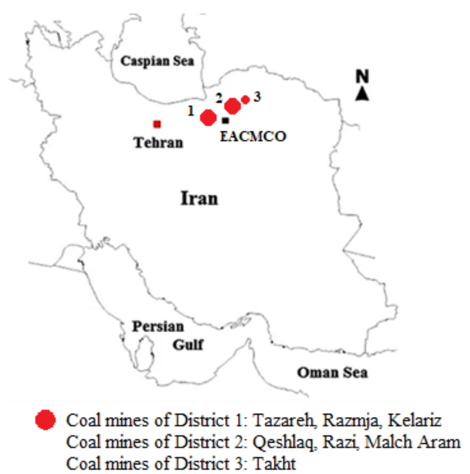


Figure 4. Location of the Eastern Alborz coal mines.

3. Results

3.1 Effective Parameters

Nine parameters affecting the potential of roof fall in coal mines were selected based on the CMRR method as well as considering the analysis performed in the study areas, ease of surveying, and access to numerical values. The role and type of data as well as their statistical information in the study areas are shown in Table 2.

Table 2. Effective Parameters and their statistical information.

No.	Parameter	Symbol	Benefit/Cost	Type	Min	Max	Mean	SD
1	Roof UCS (MPa)	C1	Cost	Quantitative	16	144	77..93	33.73
2	Roof BTS (MPa)	C2	Cost	Quantitative	1.4	12.5	4.98	2.73
3	Durability Index (%)	C3	Cost	Quantitative	26	98	71.4	23.15
4	Joint Dip (°)	C4	Benefit	Quantitative	40	85	71.53	12.99
5	Joint Spacing (m)	C5	Cost	Quantitative	0.15	1.5	0.56	0.38
6	Joint Persistence (m)	C6	Cost	Quantitative	0.25	2.5	0.87	0.78
7	Difference between direction of panel and joint orientation (°)	C7	Cost	Quantitative	0	83	39	32.85
8	Bedding Planes spacing (m)	C8	Cost	Quantitative	0.05	0.8	0.4	0.23
9	Groundwater Flow	C9	Benefit	Qualitative	Dry	Wet	-	-

3.2 Weighting of Parameters

In order to determine the effective parameter weight by incorporating fuzzy DEMATEL, 17 distributed questionnaires were collected and analyzed. Figure 5 shows the ultimate deterministic weight of parameters.

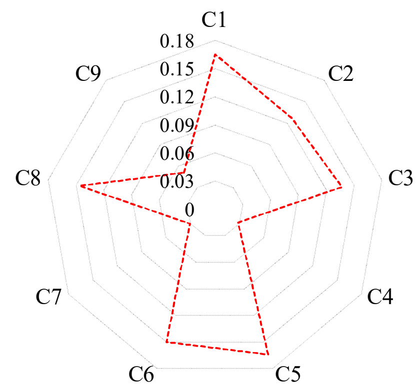


Figure 5. Ultimate deterministic weight of parameters.

3.3 Roof falling potential

Step 1: The initial evaluation matrix for the studied roofs is shown in Table 3. In this matrix, the CMRR classification method is used for fuzzification of the underground water flow, and the proportional fuzzy value is assigned to them according to Table 1. After that, these fuzzy values are defuzzified using Equation (6).

Table 3. Initial evaluation matrix.

X	C1	C2	C3	C4	C5	C6	C7	C8	C9
A1	82.00	3.40	0.75	40.00	0.40	0.40	3.00	0.20	0.08
A2	125.50	9.50	0.93	75.00	1.20	2.50	83.00	0.75	0.08
A3	74.50	4.40	0.78	80.00	0.40	0.30	30.00	0.30	0.08
A4	52.50	2.40	0.28	50.00	0.25	0.40	50.00	0.15	0.08
A5	144.00	12.50	0.98	84.00	1.50	2.50	75.00	0.80	0.25
A6	78.00	4.50	0.87	80.00	0.40	0.50	60.00	0.40	0.25
A7	40.00	2.25	0.50	61.00	0.15	0.25	0.00	0.05	0.25
A8	16.00	1.40	0.26	82.00	0.20	0.30	8.00	0.10	0.50
A9	63.50	3.50	0.63	85.00	0.30	0.40	60.00	0.60	0.50
A10	118.00	5.00	0.97	73.00	1.00	2.00	0.00	0.70	0.08
A11	80.00	4.60	0.90	78.00	0.60	0.80	0.00	0.40	0.08
A12	45.00	5.30	0.53	58.00	0.30	0.30	60.00	0.25	0.08
A13	72.50	4.50	0.70	71.00	0.40	0.45	0.00	0.30	0.08
A14	114.50	5.00	0.98	73.00	0.80	1.20	73.00	0.60	0.08
A15	63.00	6.50	0.65	83.00	0.50	0.75	83.00	0.40	0.08

Step 2: According to Eqs. (7) and (8), the normalized decision-making matrix can be obtained, as shown in Table 4.

Step 3: In this step, according to Equation (9), the weighted matrix (V) is calculated using the weights obtained for the parameters based on the fuzzy DEMATEL method (Figure 5) and presented in Table 5.

Step 4: The BAA matrix for each effective parameter is determined by Equation (10), which is shown in Table 6.

Step 5: The distance of each alternative from the BAA matrix is calculated by Equation (11), which is shown in Table 7.

Step 6: Using Equation (13), Figure 6 shows the S_i and the ranking of the alternatives (studied panel).

Table 4. Normalized hybrid matrix.

N	C1	C2	C3	C4	C5	C6	C7	C8	C9
A1	0.48	0.82	0.32	0.00	0.81	0.93	0.96	0.80	1.00
A2	0.14	0.27	0.07	0.78	0.22	0.00	0.00	0.07	1.00
A3	0.54	0.73	0.28	0.89	0.81	0.98	0.64	0.67	1.00
A4	0.71	0.91	0.97	0.22	0.93	0.93	0.40	0.87	1.00
A5	0.00	0.00	0.00	0.98	0.00	0.00	0.10	0.00	0.60
A6	0.52	0.72	0.15	0.89	0.81	0.89	0.28	0.53	0.60
A7	0.81	0.92	0.67	0.47	1.00	1.00	1.00	1.00	0.60
A8	1.00	1.00	1.00	0.93	0.96	0.98	0.90	0.93	0.00
A9	0.63	0.81	0.49	1.00	0.89	0.93	0.28	0.27	0.00
A10	0.20	0.68	0.01	0.73	0.37	0.22	1.00	0.13	1.00
A11	0.50	0.71	0.11	0.84	0.67	0.76	1.00	0.53	1.00
A12	0.77	0.65	0.63	0.40	0.89	0.98	0.28	0.73	1.00
A13	0.56	0.72	0.39	0.69	0.81	0.91	1.00	0.67	1.00
A14	0.23	0.68	0.00	0.73	0.52	0.58	0.12	0.27	1.00
A15	0.63	0.54	0.46	0.96	0.74	0.78	0.00	0.53	1.00

Table 5. Weighted decision-making matrix.

V	C1	C2	C3	C4	C5	C6	C7	C8	C9
A1	0.24	0.23	0.18	0.03	0.30	0.29	0.06	0.26	0.10
A2	0.19	0.16	0.15	0.05	0.20	0.15	0.03	0.16	0.10
A3	0.25	0.22	0.18	0.05	0.30	0.30	0.05	0.24	0.10
A4	0.28	0.24	0.27	0.03	0.32	0.29	0.04	0.27	0.10
A5	0.17	0.13	0.14	0.06	0.16	0.15	0.03	0.15	0.08
A6	0.25	0.22	0.16	0.05	0.30	0.28	0.04	0.22	0.08
A7	0.30	0.24	0.23	0.04	0.33	0.30	0.06	0.29	0.08
A8	0.33	0.25	0.27	0.05	0.32	0.30	0.06	0.28	0.05
A9	0.27	0.23	0.20	0.06	0.31	0.29	0.04	0.19	0.05
A10	0.20	0.21	0.14	0.05	0.23	0.18	0.06	0.17	0.10
A11	0.25	0.22	0.15	0.05	0.27	0.26	0.06	0.22	0.10
A12	0.29	0.21	0.22	0.04	0.31	0.30	0.04	0.25	0.10
A13	0.26	0.22	0.19	0.05	0.30	0.29	0.06	0.24	0.10
A14	0.20	0.21	0.14	0.05	0.25	0.24	0.03	0.19	0.10
A15	0.27	0.20	0.20	0.06	0.29	0.27	0.03	0.22	0.10

Table 6. BAA matrix.

G	C1	C2	C3	C4	C5	C6	C7	C8	C9
g_i	0.25	0.21	0.18	0.05	0.27	0.25	0.05	0.22	0.09

Table 7. Distance of each alternative from the BAA matrix.

Q	C1	C2	C3	C4	C5	C6	C7	C8	C9
A1	0.00	0.02	0.00	-0.02	0.02	0.04	0.01	0.04	0.01
A2	-0.06	-0.05	-0.04	0.00	-0.07	-0.10	-0.01	-0.06	0.01
A3	0.01	0.01	-0.01	0.01	0.02	0.04	0.00	0.02	0.01
A4	0.04	0.03	0.09	-0.01	0.04	0.04	0.00	0.05	0.01
A5	-0.08	-0.08	-0.05	0.01	-0.11	-0.10	-0.01	-0.07	-0.01
A6	0.00	0.01	-0.02	0.01	0.02	0.03	-0.01	0.00	-0.01
A7	0.05	0.03	0.05	-0.01	0.05	0.05	0.02	0.07	-0.01
A8	0.08	0.04	0.09	0.01	0.05	0.04	0.01	0.06	-0.04
A9	0.02	0.02	0.02	0.01	0.04	0.04	-0.01	-0.03	-0.04
A10	-0.05	0.00	-0.04	0.00	-0.05	-0.07	0.02	-0.05	0.01
A11	0.00	0.01	-0.03	0.00	0.00	0.01	0.02	0.00	0.01
A12	0.05	0.00	0.04	-0.01	0.04	0.04	-0.01	0.03	0.01
A13	0.01	0.01	0.01	0.00	0.02	0.03	0.02	0.02	0.01
A14	-0.04	0.00	-0.05	0.00	-0.02	-0.02	-0.01	-0.03	0.01
A15	0.02	-0.01	0.02	0.01	0.01	0.01	-0.01	0.00	0.01

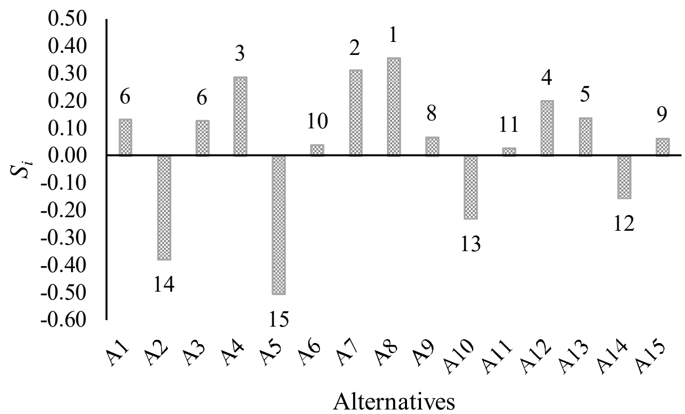


Figure 6. Values of S_i and ranking of alternatives.

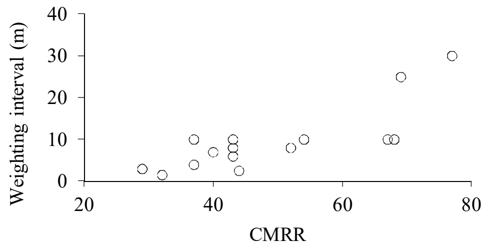
4. Discussion

In order to validate and compare the results of the proposed method (MABAC-DEMATEL) with the original CMRR method, the CMRR values were calculated and the ranking of collapse potential for these two methods along with the actual roof weighting interval were presented in Table 8.

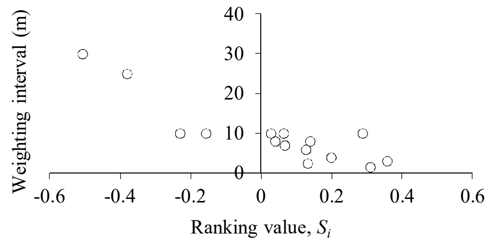
Table 8. Weighting interval value and ranking.

Case study (Alternative)	Weighting interval (m)	Actual ranking	Ranking by CMRR	Ranking by DEMATEL-MABAC
A1	2.5	2	6	6
A2	25	9	11	14
A3	6	5	5	7
A4	10	8	3	3
A5	30	10	12	15
A6	8	7	7	10
A7	1.5	1	2	2
A8	3	3	1	1
A9	7	6	4	8
A10	10	8	9	13
A11	10	8	8	11
A12	4	4	3	4
A13	8	7	5	5
A14	10	8	10	12
A15	10	8	5	9
A1	2.5	2	6	6

As it can be seen in Table 8, ranking by DEMATEL-MABAC is more in accordance with the actual ranking. However, a graphical comparison can provide a more clear insight into the results. Therefore, Figure 7 shows the correlation between the weighting interval and the calculated indices using the original CMRR and the proposed method. Contingent upon Figure 7, it can be seen that there is an increasing trend in the weighting interval with an increase in the CMRR value (Figure 7a). This shows that a higher weighting interval occurs when the roof has competent strata, which is indicated by a higher CMRR value. On the opposite side, Figure 7b illustrates that there is an indirect relationship between the weighting interval and the ranking index resulting from the DEMATEL-MABAC method. Such results are logical due to the nature of CMRR, which describes the quality of roof and ranking index of the proposed model, which indicate the potential of falling, and thus are opposite.



a. Correlation between weighting interval and CMRR value.



b. Correlation between weighting interval and Si value of DEMATEL-MABAC method.

Figure 7. Correlation between weighting interval and calculated indices.

In order to evaluate the correlation between the roof weighting interval and the original CMRR as well as the proposed index resulting from the DEMATEL-MABAC method, the ANOVA analysis was conducted. Table 9 summarizes the results of ANOVA analysis for different curve fittings.

Table 9. Results of ANOVA analysis.

Method	Model	R^2	SS	df	MS	F	P-value	Significance
CMRR	Linear	0.639	555.501	1	555.501	22.974	0.000	Sig.
	Logarithmic	0.584	508.267	1	508.267	18.275	0.001	Sig.
	Quadratic	0.709	617.046	2	508.523	14.646	0.001	Sig.
	Power	0.626	5.555	1	5.555	21.779	0.000	Sig.
	Exponential	0.619	5.486	1	5.486	21.080	0.001	Sig.
DEMATEL-MABAC	Linear	0.762	662.844	1	662.844	41.630	0.000	Sig.
	Logarithmic	Not available due to the existence of negative values						
	Quadratic	0.863	750.764	2	375.382	37.832	0.000	Sig.
	Power	Not available due to the existence of negative values						
	Exponential	0.664	5.891	1	5.891	25.705	0.000	Sig.

The ANOVA analysis to evaluate the correlation between the weighting interval and CMRR as well as the proposed index indicate that in both situations, a quadratic function can describe their relationship. However, comparison of R^2 shows that the relationship between the weighting interval and the DEMATEL-MABAC index possesses a higher coefficient of determination (0.86) when compared to that of weighting interval and CMRR value (0.71), and thus is the preferred model for the roof falling potential calculation with the prediction formula of weighting interval given by Equation (14).

$$L = 39.118 \times S_i^2 - 22.456 \times S_i + 8.0697 \qquad (14)$$

where L is the weighting interval (m) and S_i is the ranking value resulting from the DEMATEL-MABAC method.

It can be concluded that the proposed method has a more accuracy in comparison with the original CMRR method to quantify the roof falling potential. This results of the current work reveal that adopting the CMRR method with geo-mining condition from significant parameters and their importance can improve the reliability for characterization of the roof quality in terms of stability.

5. Conclusions

A new method was introduced to rank the roof falling potential and the risk of roof collapse based on the CMRR parameters by incorporating a hybrid MCDM technique. The main novelty of this work is to characterize the importance of the CMRR's parameters based on a given mining geo-condition using a systematic procedure. The proposed model was used to rank the weighting interval of 15 stopes of longwall coal mining in the Eastern Alborz Coal Mines Company from a falling potential viewpoint. The main conclusions of this investigation can be summarized as follow:

(a) Results of the DEMATEL method based on the expert judgments indicate that "UCS of roof" and "joint spacing" are the most important parameters involved in the roof stability and thus in the potential of roof falling; "joint persistence" was also found to be a quite significant parameter.

(b) Ranking the weighting interval to indicate the potential of roof falling using DEMATEL-MABAC was more in accordance to actual when compared to the original CMRR. A correlation between the weighting interval and the new index shows that the coefficient determination is 0.86, while it is 0.71 for correlation between the weighting interval and the CMRR value. The results obtained show that development of a new index based on the CMRR parameters and by incorporating proposed method, increase in the accuracy of prediction weighting interval more than 15%, and hence, confirming the validity and capability of the proposed approach.

(c) It was concluded that the adopting CMRR procedure with geo-mining condition of a given coal mine from the influencing parameters and weighting procedure viewpoints, increase its correlation with the roof falling potential.

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کمّی‌سازی پتاسیل ریزش سقف مبتنی بر روش CMRR با استفاده از تکنیک DEMATEL-MABAC- مطالعه موردی

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چکیده:

در این مقاله از تکنیک DEMATEL-MABAC برای کمّی‌سازی پتانسیل ریزش سقف در معادن زغال‌سنگ بر مبنای پارامترهای روش CMRR استفاده شده است. برای این منظور، با درنظر گرفتن گام تخریب به عنوان معیاری کمّی از مقدار پایداری سقف، پتانسیل ریزش سقف بلاواسطه در ۱۵ کارگاه شرکت زغالسنگ البرز شرقی کمّی‌سازی و رتبه‌بندی شده است. در این راستا، بر اساس قضاوت‌های خبرگان، تکنیک DEMATEL فازی برای وزن‌دهی به پارامترها و روش MABAC برای کمّی‌سازی پتانسیل ریزش سقف و رتبه‌بندی کارگاه‌ها مورد استفاده قرار گرفته‌اند. نتایج نشان داد که «مقدار UCS» و «فاصله‌داری درزه‌ها» در سقف بلاواسطه مهم‌ترین پارامترهای کنترل کننده ریزش سقف هستند؛ همچنین مشخص شد بعد از دو پارامتر ذکر شده، «پایایی درزه» پارامتری اساسی در این موضوع است. نتایج این مقاله مؤید این است که مقاومت کلی توده سنگ سقف کارگاه نقش اصلی را در پتانسیل ریزش ایفا می‌کند. مقایسه مدل پیشنهادی و روش اصلی CMRR نشان داد که مقدار ضریب تعیین (R^2) بین گام تخریب و مدل پیشنهادی ٪ ۱۵ بیشتر از ضریب تعیین بین گام تخریب و شاخص اصلی CMRR است که این موضوع بیانگر دقت بیشتر مدل ارائه شده برای کمّی‌سازی کیفیت سقف می‌باشد. این مقاله نشان داده است که استفاده از تکنیک ترکیبی DEMATEL-MABAC و همچنین ویژه‌سازی روش CMRR با توجه به شرایط معدن مورد نظر برای ارزیابی کیفیت سقف و پتانسیل ریزش آن دارای عملکرد بسیار بهتری نسبت به استفاده از روش اصلی CMRR می‌باشد.

کلمات کلیدی: ریزش سقف، CMRR، DEMATEL، MABAC، شرکت زغالسنگ البرز شرقی.