Volume 23 | Issue 3 Article 2

2024

A biocompatible hybrid approach for the selection of gas drainage methods in coal mines based on the Best-Worst Method and Analytic Network Process

Author(s) ORCID Identifier:
Amir Jafarpour: 0000-0002-5734-9970
Mehdi Najafi: 0000-0002-1609-3702
Ali Dabagh: 0000-0001-8084-0453

Recommended Citation

Jafarpour, Amir; Najafi, Mehdi; and Dabagh, Ali (2024) "A biocompatible hybrid approach for the selection of gas drainage methods in coal mines based on the Best-Worst Method and Analytic Network Process," *Journal of Sustainable Mining*: Vol. 23 : Iss. 3 , Article 2.
Available at: https://doi.org/10.46873/2300-3960.1414

A biocompatible hybrid approach for the selection of gas drainage methods in coal mines based on the Best-Worst Method and Analytic Network Process

Abstract

Methane drainage is one of the main steps in underground coal mining projects. The operation of methane extraction from coal mines/seams is important from the safety, economic, and technical points of view. Selecting the appropriate method for methane drainage is very difficult, and if the method is not chosen correctly, it will lead to environmental problems. The relationship between different influencing factors, parameters, and methods (and how they affect) is significant in choosing the method of gas drainage. In the current study, a hybrid algorithm is presented based on an Analytic Network Process (ANP) and a method based on the mathematical model (BWM). In the presented approach, the weighting of criteria by the BWM method and ranking of alternatives based on effective criteria is performed using the network analysis-based method. “Operating and capital costs” were the most effective criteria, and “in-situ stress” was the least effective factor in the selection process. The results show that the “post-drainage method using cross-measure boreholes” was ranked first with the highest score (0.249). Applying the selected method in the Tabas coal mine (case study) indicates that the proposed algorithm is compatible with real-world conditions and can have various applications in multi-criteria decision-making problems.

Keywords

Methane drainage, selection, Best-Worst Method, Analytic Network Process.

A biocompatible hybrid approach for the selection of gas drainage methods in coal mines based on the Best-Worst Method and Analytic Network Process

Amir Jafarpour, Mehdi Najafi*, Ali Dabagh

Department of Mining and Metallurgical Eng., Yazd University, Yazd, Iran

Abstract

Methane drainage is one of the main steps in underground coal mining projects. The operation of methane extraction from coal mines/seams is important from the safety, economic, and technical points of view. Selecting the appropriate method for methane drainage is very difficult, and if the method is not chosen correctly, it will lead to environmental problems. The relationship between different influencing factors, parameters, and methods (and how they affect) is significant in choosing the method of gas drainage. In the current study, a hybrid algorithm is presented based on an Analytic Network Process (ANP) and a method based on the mathematical model (BWM). In the presented approach, the weighting of criteria by the BWM method and ranking of alternatives based on effective criteria is performed using the network analysis-based method. "Operating and capital costs" were the most effective criteria, and "in-situ stress" was the least effective factor in the selection process. The results show that the "post-drainage method using cross-measure boreholes" was ranked first with the highest score (0.249). Applying the selected method in the Tabas coal mine (case study) indicates that the proposed algorithm is compatible with real-world conditions and can have various applications in multi-criteria decision-making problems.

Keywords: methane drainage, selection, Best-Worst Method, Analytic Network Process

1. Introduction

Today, one of the fundamental affairs in the design and implementation of industrial/mining projects is the study of the interaction of environmental and social (E&S) problems. The importance of these effects is very significant, and the need for governments to pay attention and sensitivity to the E&S moot point was presented in the form of international commitments, such as the Paris Agreement and Agenda 21 [1], and various conferences such as the United Nations Conference on Sustainable Development (UNCSD) [2].

In recent years, the need to achieve the goals of Sustainable Development (SD) and the problems associated with E&D by managers of the mining industry have caused even the literature and specialized vocabulary of the large-scale industry to undergo major changes. Paradigms such as carbon footprint [3–5], green lies [6,7], green blasting [8,9], green production scheduling [10–12], mining social responsibility [13,14], etc. are some of the most important idioms of this field.

On the other hand, societies' urgent need for energy and raw materials has led to the growth of the mining industry. Coal mining is no exception because coal is one of the main materials used in large-scale industries, especially for the iron smelting factories and steel production plants [15,16]. Consumerism in large-scale industries has increased the production of environmental pollutants and especially the release of large volumes of greenhouse gases. Also, coal mining in open pit and underground mines releases significant volumes of greenhouse gases such as carbon (CO and CO_2) and methane (CH_4) [5,17,18]. However, in addition to coal production, managing the production and storage of methane gas as a by-product makes the mine profitable and is very effective in increasing the mine's safety [19]. Methane extracted from underground coal mines can easily meet the energy needs of

Received 8 August 2023; revised 13 November 2023; accepted 13 November 2023.
Available online 7 April 2024

* Corresponding author at: Department of Mining and Metallurgical Eng., Yazd University, Safayieh, P.O. Box: 89195-741, Yazd, Iran.
E-mail addresses: jafarpour.a67@gmail.com (A. Jafarpour), mehdinajafi@yazd.ac.ir (M. Najafi), adabagh@yazd.ac.ir (A. Dabagh).

https://doi.org/10.46873/2300-3960.1414

the mining complexes. In some cases, this gas is also effective in meeting the needs of the population centers around the mine, which is in line with the goals of Corporate Social Responsibility (CSR) of mining [20].

So far, due to the diversity of natural and technical conditions of the underground coal mines and also the different capacities of gas drainage methods, several methods for gas extraction from the coal seams/mines have been presented, which are mentioned in Table 1. As can be seen in Table 1, the variety of gas-drainage methods has made it difficult to decide which method to choose. However, considering the various factors affecting the gas-drainage method, it becomes more difficult to choose the appropriate method for a coal mine/seam. On the other hand, so far, no effective solution has been proposed to select the method of gas drainage, which indicates the gap in this field of study. In this study, due to the simultaneous importance of environmental, social, and economic criteria in coal mining activities, a hybrid approach is presented based on multi-criteria decision-making methods.

2. Literature review

Not much research has been done on the choice of the best gas-degassing method from coal mines. As mentioned, one of the most important issues in the design and implementation of methane-drainage operations from underground coal mines is the choice of gas drainage method. So far, no special algorithm or practical approach has been proposed to select the gas drainage method appropriate to the conditions of each coal mine and its design.

Although extensive studies have been conducted to optimize the drilling pattern of drainage boreholes [25,36–38] and factors affecting the efficiency of gas drainage from the coal seam [39–42], the only solution proposed to select the method of gas drainage from underground coal mines has been done by Karacan [43]. He proposed the selection of a gas drainage system for coal mines that are extracted by the longwall mining method. In this research, using an expert classification system based on Artificial Neural Network (ANN), a mechanism is presented for selecting the type of methane drainage boreholes and their drilling angle. For this purpose, the factors affecting the choice of the gas drainage method include ash content, coal production rate, coal layer height, cutting height, zone width, zone length, overburden height, and several inputs and coal rank were considered as input criteria. In addition, data from 60 mines located in different coal basins of the United States of America have been used to create a database and model the selection method. In the study, an expert classification system has been developed as a decision tool. The system was constructed using an ANN structure and was trained using different geographical locations and coal properties as input and tested for classification. The results show that this model can be used as a decision tool to select a degassing system using the specific conditions of the area and the mine. Such a model can also be used as a screening tool to decide which gas-drainage method should be considered with more sophisticated numerical methods [43].

Therefore, it is necessary to provide a mechanism for selecting the method of gas drainage. This approach has been used in this study considering the capabilities of combined multi-criteria decision-making methods in solving various mining engineering problems. The proposed approach is based on mathematical formulation, and an important part of it is nonlinear mathematical modeling, which can be solved to achieve optimal results. Also, by reviewing the literature, 19 effective criteria were selected.

3. Methodology

In the current study, a hybrid approach has been used based on the Best-Worst Method (BWM) and the Analytic Network Process (ANP) has been used. For this purpose, to select the appropriate and desirable method for gas drainage of underground coal mines, taking into account the criteria affecting this decision, the combined method is used. The BWM is used to calculate the weight of effective criteria, and the ANP is used to rank the options. In the following, the research methodology is briefly described.

3.1. Best-Worst Method

The BWM is one of the new multi-criteria decision-making (MCDM) techniques that are among the MCDM and has been presented by Rezaei [44]. In this method, the best and worst criteria are determined by the decision-maker, and pairwise comparisons are made between each of these two indicators (best/worst) and other indicators. Then, a maximum-minimum problem (MAXI MIN) is formulated and solved to calculate the weight of different criteria. Also, in this method, a formula for calculating the incompatibility rate is considered to evaluate the validity of pairwise comparisons. One of the salient features of this method compared to other multi-factorial decision methods is that it requires less comparative data and leads to more robust comparisons. That is, it gives more reliable answers. In the following, the steps of implementing this method are briefly described.

Table 1. Deferent methods of gas-drainage in underground coal mines.

Method	Symbol	Description	Reference(s)
Pre-drainage using vertical surface boreholes	A_1	It contains one or more coal seams. Hydraulic fracturing and controlled blasting methods can be used in these boreholes.	[21,22]
Pre-drainage using horizontal in-seam boreholes	A_2	Long horizontal boreholes are drilled from inside the gates or from inside the boreholes into the coal seam and gas drainage is done according to the planned time.	[23,24]
Pre-drainage using surface to in-seam directional drilling	A_3	A vertical or sloping borehole is drilled. This borehole is then drilled by directional drilling to the target point. This drilling method can be used up to 1000 m.	[25,26]
Precautionary pre-drainage using short holes in the roof of headings	A_4	Vertical and short-length boreholes are drilled from inside the gates into the roof layers. In some cases, the boreholes are drilled at a slight angle to the roof of the working face.	[27,28]
Post-drainage using cross-measure boreholes	A_5	The boreholes are drilled from inside the return air gates of the longwall method with a high or low angle into the gob zone, and flammable gases are drained from these boreholes.	[29,30]
Post-drainage using surface goaf boreholes	A_6	Drainage boreholes are usually drilled inside the coal seam. Drilled boreholes can be effective up to 30 m above the coal seam. The borehole is sealed and cemented to the lowest production area.	[21]
Post-drainage using directionally drilled horizontal long holes above or below the worked seam	A_7	Using directional drilling, drainage boreholes are drilled up to 20 or 30 m above or below the extraction coal seam, and then drainage is performed.	[31]
Post-drainage from underlying or overlying galleries	A_8	Gates are created at the top or bottom of the extraction coal seam before mining. The mining operation in the gates is then stopped, and the drainage system is connected to the pipes network. Fan holes are used to increase the environment under the influence of the drainage system.	[32]
Post-drainage using surface to in-seam directional drilling	A_9	The gas drainage operation is similar to the pre-mining drainage method.	[33]
Post-drainage from chambers or pipes in longwall goafs	A_{10}	A space is created in the retreating longwall method. Simultaneously with the mining operation and the movement of gases into space, the gas is drained by placing pipes.	[34]
Post-drainage from cross-cuts into the longwall goaf (a variant of the above method)	A_{11}	The pipe network is installed from inside of shortcuts into the gob zone. Then, drained gas is directed to the surface or into the storage inside the shortcuts.	[35]

3.1.1. Determining the set of effective criteria

In the first step, the criteria affecting the purpose of the problem should be extracted and approved by experts and specialists. In this step, you can use the literature review or the Delphi method. The purpose of these methods is to confirm and screen the criteria that affect the problem. The set of criteria is defined as $\{c_1, c_2, \ldots, c_n\}$ required for decision-making. c_j represents the j^{th} criterion.

3.1.2. Determining the best criterion and the worst criterion

In this step, experts identify the best (most effective or most important) and worst (least effective or least important) criteria among all effective criteria based on previous experiences. No comparisons are made at this step.

3.1.3. Preference of the best criterion over other criteria

In this step, a pairwise comparison of the preference between the best criterion (B) and other criteria is provided using the 9-point scoring range provided by the Saaty [45,46]. The results of this step are displayed as $A_B = (a_{B1}, a_{B2}, \ldots, a_{Bn})$. This vector a_{Bj} indicates the superiority of the best criterion (B) over criterion j. Obviously, $a_{BB} = 1$.

3.1.4. Preference of other criteria over the worst criterion

Preference of other criteria over the worst criterion (W) is done and is shown as $A_W = (a_{1W}, a_{2W}, \ldots, a_{nW})^T$. In this vector, a_{jW} is the preference of the j^{th} criterion over the worst criterion. Obviously, $a_{WW} = 1$.

3.1.5. Creating a nonlinear programming model

To calculate the optimal weight of each criterion $(w_1^*, w_2^*, \ldots, w_n^*)$, $\frac{w_B}{w_j} = a_{Bj}$, and $\frac{w_j}{w_W} = a_{jW}$ pairs are formed. Then, to estimate these conditions in all j, a solution must be found to find the expressions, $\left|\frac{w_B}{w_j} - a_{Bj}\right|$, and $\left|\frac{w_j}{w_W} - a_{jW}\right|$ will be maximized, for all js when js are minimized. Given the non-negative weights and total weights, the nonlinear optimization model can be formulated as Equation (1):

$$\begin{aligned} & \min \max_j \left\{ \left|\frac{w_B}{w_j} - a_{Bj}\right|, \left|\frac{w_j}{w_w} - a_{jw}\right| \right\} \\ & s.t. \\ & \sum\nolimits_j w_j = 1 \\ & w_j \geq 0, \text{for all } j \end{aligned} \tag{1}$$

The above model can also be converted to Equation (2):

$$\begin{aligned} & \min \xi \\ & s.t \\ & \left|\frac{w_B}{w_j} - a_{Bj}\right| \leq \xi, \text{for all } j \\ & \left|\frac{w_j}{w_W} - a_{jW}\right| \leq \xi, \text{for all } j \\ & \sum_j w_j = 1 \\ & w_j = 0, \text{for all } j \end{aligned} \tag{2}$$

3.1.6. Solving the nonlinear model

The nonlinear model is solved by formulating, coding, and implementing in the environment of optimization software (such as Lingo or GAMS) and the optimal values of $(w_1^*, w_2^*, \ldots, w_n^*)$ and ξ^* are obtained.

3.1.7. Calculating consistency ratio

The adaptation rate is calculated using the obtained ξ^*. A larger value of ξ^* indicates a higher compatibility rate. The comparison is fully consistent when the following equation holds for all js:

$$a_{BW} = a_{Bj} \times a_{jW} \tag{3}$$

where: a_{Bj}, a_{jW}, and a_{BW} are the priorities of the best criterion over the j^{th} criterion, the priority of the j^{th} criterion over the worst criterion, and the priority of the best criterion over the worst criterion, respectively.

Since $a_{BW} = a_{Bj} \times a_{jW}$, the maximum value of ξ can be obtained. The compatibility rate can be calculated using the compatibility index of Table 2 and Equation (4). This compatibility rate is in the range [0, 1], and the closer it is to zero, the more consistent the comparisons are, and the closer it is to one, the less clear the comparisons are.

$$CR = \frac{\xi^*}{CI} \tag{4}$$

Where: CR is the consistency ratio, ξ^* is the maximum value of ξ and CI is the consistency index.

3.2. Analytic Network Process (ANP)

In recent years, multi-criteria decision-making (MCDM) methods have been widely used in all

Table 2. Consistency index (CI) table [44].

a_{BW}	1	2	3	4	5	6	7	8	9
Consistency index	0.00	0.44	1.00	1.63	2.30	3.00	3.73	4.47	5.23

sciences. Among these methods, the Analytic Network Process (ANP) is one of the most considered multi-factorial evaluation methods. ANP is the general state of the Analytic Hierarchy Process (AHP) and its broad form [45], in which issues of interdependence and feedback can be considered. For this reason, in recent years the use of ANP instead of AHP has increased in most areas. Although ANP was introduced by Saaty in 1996 [46], this network-based decision-making method begins with the experiences and personal judgment of experts for criteria in the form of linguistic propositions. Then, it provides a structure for a coherent, simpler, and more orderly decision-making process, which is very desirable for organizing criteria and evaluating their importance. The decision-making process of this method simplifies the preference of each criterion over the alternatives.

In the ANP method, unlike the AHP, a network is used instead of a hierarchy. The network can model the internal relationship between nodes (goal, criteria, and alternatives). Nodes are alternatives, criteria, or goals. The connection between the nodes is determined by the arrows, which is the effect between the nodes. The most important step in the ANP method is that the mutual relationships between nodes (between alternatives and criteria) are modeled correctly and accurately.

The steps of the network analysis method are as follows:

3.2.1. Problem configuration and model construction

At this step, first, the problem is defined completely and clearly. To make it easier to understand the problem and provide a logical solution, a network model should be formed. Therefore, the components of the problem become a hierarchical and orderly structure. This network model has logical connections between each level. Therefore, the criteria that affect the decision-making process should be identified. In the next step, the relationship between the criteria should be established based on their internal connections, which are indicated by arrows. The connection of network components shows the influence of elements on each other. In the ANP method, the relationships and influence of criteria and options on each other are also applied to the problem.

3.2.2. Formation of pairwise comparison matrices and calculation of weight vectors

Similar to the AHP method, pairwise comparison matrices of criteria and sub-criteria are formed, taking into account higher levels of network and internal communication, to be used to obtain the weight of elements. To calculate the weight and convert the experts' verbal expressions into numbers, the Saaty scale is used, which is presented in Table 3.

3.2.3. Super-matrix formation

Super-matrix is a matrix of relationships between network components obtained from the priority vectors of these relationships. This matrix provides a framework for determining the relative importance of options after pairwise comparisons. If the hierarchy has three levels of objective (G), criteria (C), and alternatives (A), the super-matrix will be, in the simplest case, as follows:

$$w = \begin{array}{c} \\ G \\ C \\ A \end{array} \begin{array}{c} \begin{array}{ccc} G & C & A \end{array} \\ \begin{bmatrix} 0 & 0 & 0 \\ W_{21} & 0 & 0 \\ 0 & W_{32} & I \end{bmatrix} \end{array} \tag{5}$$

In this matrix, W_{12} is a vector that shows the effect of the objective on each of the criteria. W_{32} is the matrix that shows the effect of each of the criteria on the alternatives. I is an identical matrix. The zero values of this matrix also indicate that the factors have no effect at the intersection of the rows and columns.

In general, the super-matrix will be as follows:

$$w = \begin{array}{c} \\ G \\ C \\ A \end{array} \begin{array}{c} \begin{array}{ccc} G & C & A \end{array} \\ \begin{bmatrix} W_{11} & W_{12} & W_{13} \\ W_{21} & W_{22} & W_{23} \\ W_{31} & W_{32} & W_{33} \end{bmatrix} \end{array} \tag{6}$$

The weights at adjective levels of the model are listed in the rows and columns of the matrix. Each w_{ij} of this matrix represents the weight vector of the pairwise comparison performed in the corresponding equation.

Table 3. The ratio scale and definition [45].

Intensity of importance	Definition
1	Equal importance
3	Somewhat more important
5	Much more important
7	Very much more important
9	Absolutely more important
2, 4, 6, 8	Intermediate values

3.2.4. Calculating the weighted super-matrix distribution

This is similar to the Markov chain process by obtaining the weighted super-matrix by a large number. That means:

$$\lim_{k\to\infty} W^k \tag{7}$$

W is the super-matrix that reaches the power of k to achieve convergence. k is always an odd number. If the final super-matrix converges to a final matrix, the calculation of the weight of the options based on the criteria is considered based on this final matrix. But if it does not converge to a final matrix, all the matrices with which the convergence is done periodically are averaged:

$$\lim_{k\to\infty} \left(\frac{1}{n}\right) W_i^k \tag{8}$$

3.2.5. Normalizing the obtained weight values

According to each cluster, the weight values obtained from the previous step are normalized.

3.2.6. Selecting the best option

In this step, the weight values obtained in the previous step will be used to determine the desired alternative.

3.3. BWM-ANP hybrid method

To decide on the choice of the appropriate method of gas drainage, it is necessary to create a model of effective criteria and available options, and according to the capabilities of different decision-making methods, the appropriate method is selected. As mentioned, the BWM-ANP method is the method of choice for solving the problem of choosing the appropriate gas-drainage method. According to this multi-criteria decision-making method, the weight of criteria is done using the BWM method, and the final ranking of options is done by the ANP method. The implementation steps of the hybrid method used are shown in Figure 1.

4. Case study: tabas coal mine

Tabas City is located in the west of the Southern-Khorasan province (Fig. 2). Tabas coal basin, with an area of 30,000 km^2 and exploration reserves of 75.2 billion tons of coking and thermal coal, is the richest and largest coal area in Iran. The Parvadeh zone, with an area of 1200 km^2 and geological reserves of 1.1 billion tons of coking coal, is one of the four coal areas of Tabas and the largest coking coal basin in Iran [47,48].

After conducting studies on the feasibility of mechanized mining in the Parvadeh mine and carrying out the operation of phase one of the equipment of the coal mine, this phase, with an annual production capacity of 5.1 million tons of raw coal and 750,000 tons of concentrate, operated by the longwall underground mining method. Then, Parvadeh was exploited in 2007 as the first mechanized coal mine in Iran [49].

The main honors of Tabas Parvadeh Coal Company (TPCCO), which are in line with SD goals, are: obtaining certificates of quality management (ISO 9001-2015), safety (OHSAS 18001-2007), occupational health (ISO 14001-2004), and safety management system (ISO 2015-45001). TPCCO has produced 9,000,000 tons of raw coal and 4,000,000 tons of concentrate by the end of 2019. In addition, the mentioned company as the most influential business unit in the region, has had a significant impact on the economic, social, and cultural growth of the region and has provided valuable services in the form of social responsibilities.

5. Implementation of the proposed algorithm

In the current study, the problem of selecting the methane-drainage method using the BWM-ANP combined multi-criteria decision-making method has been investigated. In this method, questionnaires were first prepared to use the opinions of experts and their experiences in weighting the effective criteria and performing pairwise comparisons for the available options for each criterion. Then, to implement the proposed algorithm, it was necessary to form the super-matrix of the ANP method first. As mentioned, this super-matrix is made up of matrices. Each matrix is also the result of pairwise comparisons. Suppose the matrix $[Z]$ is the same super-matrix we need:

$$[Z]_{31\times 31} = \begin{bmatrix} [a] & [b] & [c] \\ [d] & [e] & [g] \\ [h] & [i] & [j] \end{bmatrix} \tag{9}$$

The matrix $[Z]$ is the super-matrix of pairwise comparisons between goal levels, criteria, and alternatives. In the super-matrix, each of the components is a matrix, and the number of components in each of these matrices is different. The matrix $[a]$ is the result of a pairwise comparison between the goal level and itself. The matrix $[b]$ is the result of an even comparison between the goal and the criteria, which is a matrix of 1×19 (i.e. it has 19 components). The matrix $[c]$ is also the result of pairwise

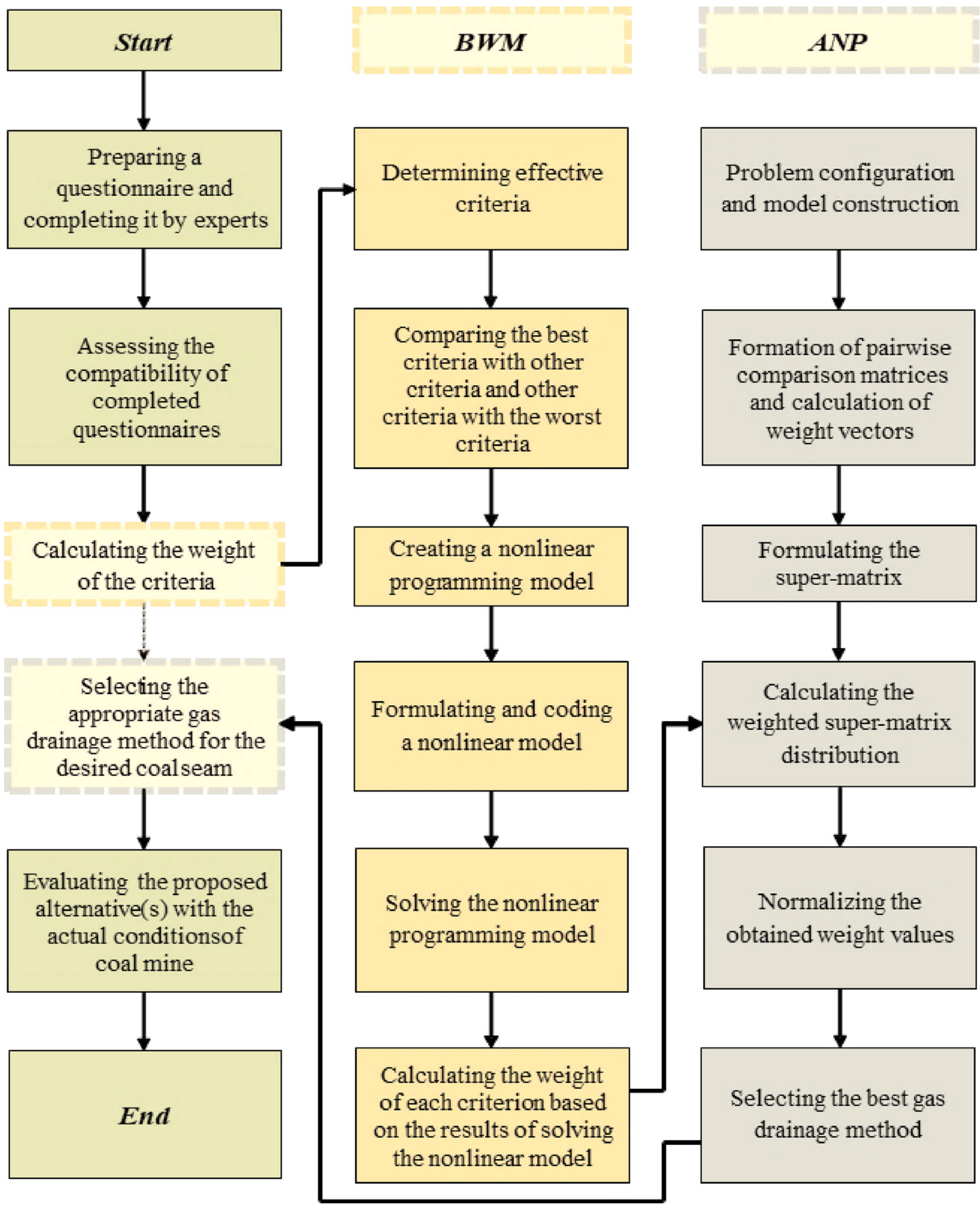

Fig. 1. Execution steps of the BWM-ANP hybrid algorithm.

comparisons between the goal and the alternatives, which consists of 11 components, i.e. the matrix is 1×11. In the current study, the value of these three matrices is equal to zero. The matrix [d] is the result of pairwise comparisons between the criteria and the goal and shows the effect of the criterion on the goal. This matrix has 19 components (19×1), and their values are calculated by the BWM method and show the weight of each criterion. The matrix [e] is a matrix with 19×19 components and shows the effect of the criteria on each other. Also, the matrix [g] has 19×11 components and shows pairwise comparisons between alternatives based on criteria. The matrices [h], [l], and [k] show the effect of the alternatives on the goal, criteria, and alternatives, and the values of the matrices are zero in the current study.

In the second step, the criteria influencing the process of selecting the methane drainage method must be identified. These criteria are in Table 4. In selecting effective criteria, in addition to studying credible scientific and technical sources, the

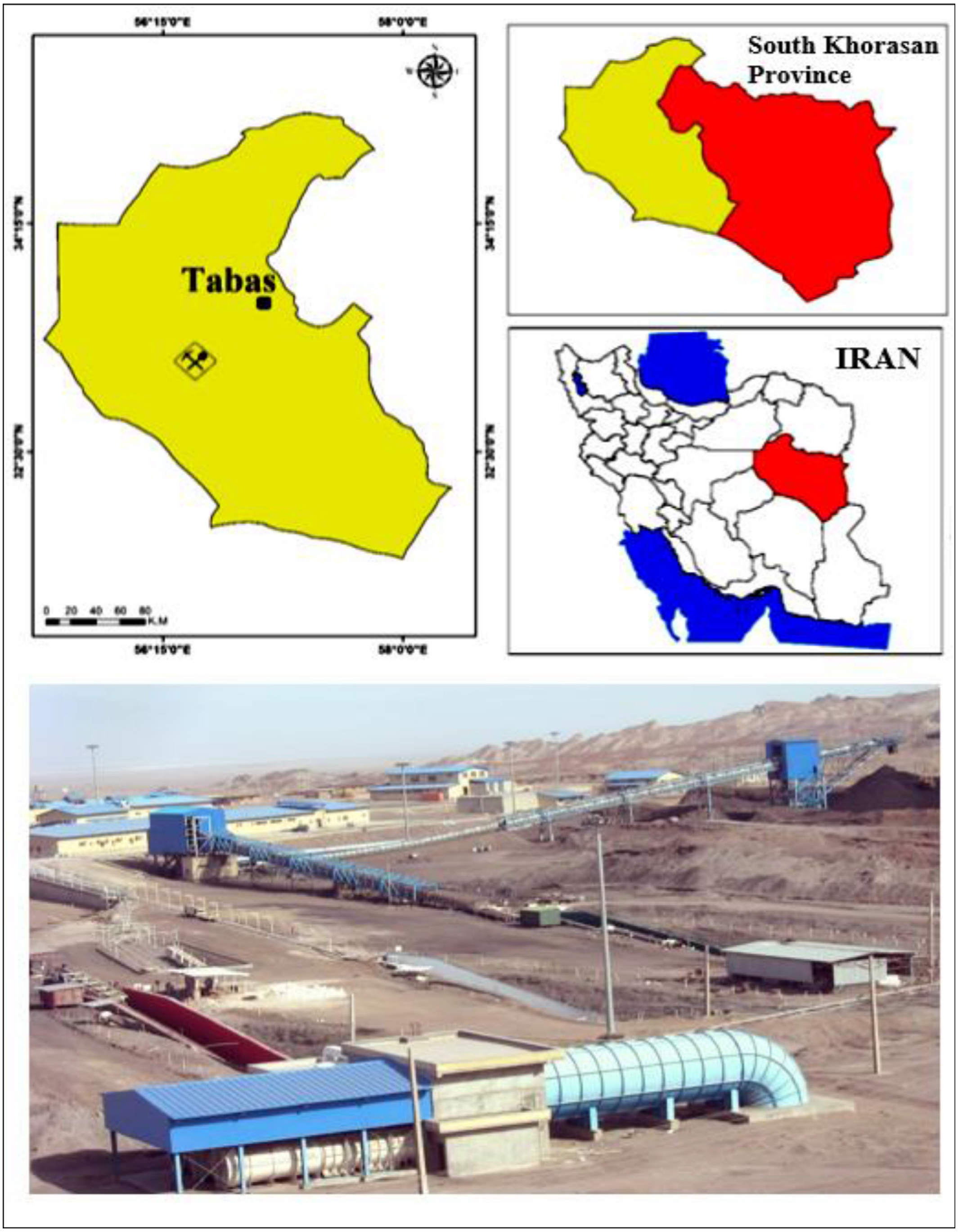

Fig. 2. Location of Tabas coal mine and a view of surface equipment [50].

experiences of experts from the Tabas Mine Gas Drainage Unit (TMGDU) have been used.

The parameters mentioned in Table 4 are described, briefly. The moisture content indicates the amount of water vapor in the coal seam. The permeability is the ability of a material to pass fluid through it (here, the material is a coal seam). The joints system and cleats actually indicate the condition of the joints and cleats of the coal seam, which play a significant role in the dispersion of gases. The coal ash is the percentage of ash in the coal seam, which is related to the amount of methane gas in the coal seam. The degree of saturation of the coal layer with methane gas is called gas saturation. It means the amount of saturated methane in the coal seam. The thickness of the coal seam is the vertical distance between the upper and lower surface of the coal layer. The coal rank has a great effect on the gas content of the coal seam. Special ranks of coal are suitable for gas drainage. Most of the methane

Table 4. Factors affecting the choice of gas drainage method in underground coal mines.

Criteria	Sub-criteria	Symbol
Natural characteristics of coal (C_1)	Moisture content	S_{11}
	Permeability	S_{12}
	Joint system and cleats	S_{13}
	Coal ash	S_{14}
	Gas saturation	S_{15}
	Thickness of coal seam	S_{16}
	Coal rank	S_{17}
	Condition of groundwater	S_{18}
	Gas content	S_{19}
Geological and geomechanical factors (C_2)	Geological structure of overburden of coal seam	S_{21}
	Effective stress	S_{22}
	In-situ stress	S_{23}
Executive and operational factors (C_3)	Length of borehole	S_{31}
	Diameter of borehole	S_{32}
	Angle of borehole	S_{33}
	Stability of boreholes	S_{34}
	Drilling density	S_{35}
	Operating and capital costs	S_{36}
	Gas drainage pressure	S_{37}

drainage projects produce methane gas from bituminous coals, but methane production from anthracite coals is currently implemented. The condition of underground water, the location of underground aquifers, sub-surface water flows and the amount of water available in the vicinity of the coal seam/mine are mentioned as the condition of underground water. Gas content is equal to the amount of gas per unit weight of coal (or rock), usually measured in standard cubic feet per ton. All the geological parameters, such as the condition of faults, joints, discontinuities and their effects, have been applied in the model as the geological structure of overburden of coal seam. Stresses resulting from mining and drilling activities are called effective stress. The stresses in the region (mine area) before the start of mining activities are called in-situ stress. All parameters related to methane drainage boreholes and their executive operations are considered in the form of executive and operational factors, which are known (borehole length, borehole diameter, drilling angle, etc.).

As can be seen, in addition to the main criteria, the effectiveness of the sub-criteria is also considered. The values of each criterion were taken from the engineering data and technical reports of the Tabas coal mine and were provided to the experts to use in completing the questionnaires. Some of the information on the Tabas coal mine is given in Table 5.

After completing the questionnaires by experts, the weight of each criterion was calculated by BWM method, which is presented in Table 6 (and Fig. 3), which is based on mathematical modeling. For this purpose, the mathematical model of the problem was formulated, which is based on the BWM method. Then, this model was solved using GAMS

Table 6. Weights of criteria calculated by the BWM (outputs of GAMS software).

Criteria	Weights	Criteria	Weights
S11	0.072	S22	0.031
S12	0.072	S23	0.018
S13	0.027	S31	0.031
S14	0.108	S32	0.031
S15	0.043	S33	0.043
S16	0.054	S34	0.054
S17	0.108	S35	0.036
S18	0.043	S36	0.126
S19	0.036	S37	0.031
S21	0.036		

Table 5. Some data of the Tabas coal mine.

Seam	Depth (m)	Thickness (m)	Cleats (joint/m)	Uniformity	Gas content (m^3/ton)	Roof quality (MPa)	Water condition (m^3/min)	Permeability (mDarcy)
D	313	0.3	13	0.7	15.1	88.7	106	38
C_2	348	0.6	17	0.8	16.2	91.4	91	40
C_1	364	1.9	20	0.75	16.3	95.1	83	45
B_2	387	0.9	18	0.8	20.87	85.4	64	30
B_1	399	0.75	16	0.7	21.69	86.1	80	41

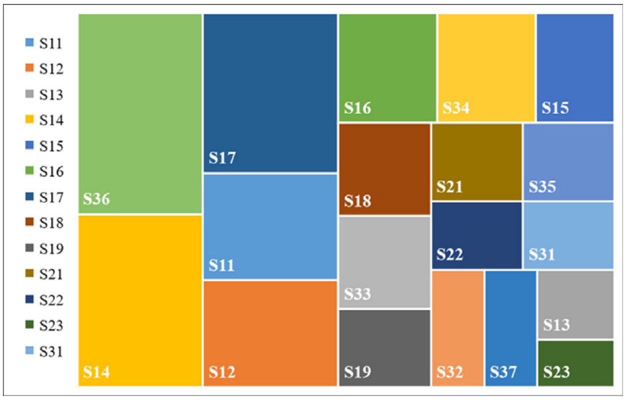

Fig. 3. Weights of criteria calculated by the BWM (outputs of GAMS software).

software, which is very efficient in solving mathematical models.

Due to the importance of economics in mining projects [51], the criterion "Operating and capital costs" has been identified as the most effective criterion. Criteria related to the intrinsic properties of coal and moisture content also scored higher. The least efficacy was related to in-situ stress, which has less effect on the degassing method, according to experts' opinion.

In the third step, the options were classified by performing the second step of the mentioned algorithm. At this step, the experts of the Tabas Coal Mine Exploitation Unit (TCMEU) performed the following pairwise comparisons:

- Pairwise comparisons between criteria,
- Pairwise comparisons between criteria and alternatives,
- Pairwise comparisons of criteria and sub-criteria,
- Pairwise comparisons between sub-criteria.

All calculations related to pairwise comparison matrices were formulated by Microsoft Excel software. Finally, the super-matrix was solved using coding in MATLAB software. Formulation of mathematical relationships between matrices was done based on the ANP calculation process. In addition, calculations related to converging the super-matrix were done based on the exponentiation of the super-matrix. The results of pairwise comparisons are in the form of a super-matrix, as shown in Table 7 (see supplemental content).

After solving the super-matrix obtained from pairwise comparisons, the classification of alternatives (methane drainage methods) based on the scores obtained from the calculations was obtained, as shown in Table 8 (see supplemental content). In addition, the percent for each option is shown in Figure 4.

As can be seen, alternative A_5 (post-drainage using cross-measure boreholes) was selected as the appropriate drainage method for the Tabas coal mine. Because that the weight obtained from the S_{36}, S_{14}, and S_{34} criteria for this option has relatively high values, the score calculated for this alternative is very different from other alternatives. Alternatives A_7 and A_9 were in the second place. Also, there is alternative A_3, selected in the third category with a slight difference from alternative A_6 (only one score). The results of the calculations show that most of the selected methods for methane drainage use cross-measure boreholes. Also, due to the importance of technical and financial problems of the project, gas drainage operations in all methods that have higher scores are performed simultaneously with underground mining operations.

This, in addition to the benefit from the coal extraction operation, is accompanied by the economic profit from the metamorphosis operation. It should be noted that methane drainage operations with selected methods solve the safety problems of personnel and equipment inside underground coal mines. It also significantly reduces the environmental problems caused by the direct emission of methane (and other greenhouse gases) in nature. Gas extraction with the selected method (A_5) has all the environmental, technical, managerial, and executive advantages and is accompanied by the least managerial, financial, and economic disadvantages.

It must be explained that, after weighing the effective criteria and ranking the alternatives, significant results were obtained, and the algorithm was able to solve the problem accurately. The use of mathematical modeling in a main part of the presented approach gave the algorithm the ability to obtain definitive results. The network analysis also simulated the relationships between effective

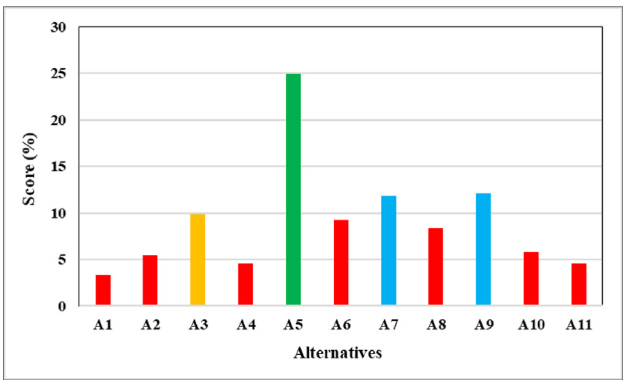

Fig. 4. Calculated scores of each alternative.

factors. The selected gas drainage methods are compatible with the conditions of the studied mine. Executive, operational and economic conditions of the selected methods show that the presented algorithm has the ability to solve complex problems. Choosing A_5 as the first priority by the algorithm shows that, based on the opinions of experts and managers, the input data was well analyzed and had a favorable output. Because the method chosen by the algorithm is the same method used in the Tabas coal mine for methane drainage.

6. Conclusion

The results of the present study show that it is possible to solve the appropriate methane drainage method in underground coal mines by using an algorithm based on a mathematical model (BWM) and a causal method (ANP). In the mentioned algorithm, safety and environmental problems, directly and indirectly, affect the process of selecting the appropriate method of gas drainage. Also, the effects of technical and executive factors on methane drainage operations and the impact of economic factors on the process of selecting the appropriate method of the gas drainage have been applied by considering the prevailing relationships between the effective criteria in the calculations. The results of the algorithm in one of the large mechanized coal mines of Iran show that gas drainage methods based on drilling diagonal boreholes are of higher priority. A comparison of the selected methods by the biocompatible algorithm presented with the opinions of consulting engineers and drainage specialists in the Tabas mine shows that the selected method has acceptable compatibility with the method proposed by consulting engineers, and the research method is currently implemented in the mine. It is suggested that in future research, the drilling pattern be optimized, and the technical characteristics of drainage boreholes are selected in the drainage method to optimize the whole methane drainage operation.

Ethical statement

The authors state that the research was conducted according to ethical standards.

Funding body

This research received no external funding.

Conflicts of interest

The authors declare no conflict of interest.

Supplementary data

Supplementary data to this article can be found on the article site at https://jsm.gig.eu/ (Vol. 23, Issue 3).

References

[1] Leicht A, Combes B, Byun WJ, Agbedahin AV. From Agenda 21 to Target 4.7: the development of education for sustainable development. In: Issues and trends in education for sustainable development, 25; 2018.

[2] Lal R, Bouma J, Brevik E, Dawson L, Field DJ, Glaser B, Hatano R, Hartemink A, Kosaki T, Lascelles B, Monger C. Soils and sustainable development goals of the United Nations (New York, USA): an IUSS perspective. Geoderma Regional; 2021. p. e00398.

[3] Muller S, Lai F, Beylot A, Boitier B, Villeneuve J. No mining activities, no environmental impacts? Assessing the carbon footprint of metal requirements induced by the consumption of a country with almost no mines. Sustain Prod Consum 2020;22:24–33.

[4] Hrůzová K, Matsakas L, Sand A, Rova U, Christakopoulos P. Organosolv lignin hydrophobic micro-and nanoparticles as a low-carbon footprint biodegradable flotation collector in mineral flotation. Bioresour Technol 2020;306:123235.

[5] Norgate T, Haque N. Energy and greenhouse gas impacts of mining and mineral processing operations. J Clean Prod 2010;18(3):266–74.

[6] Gatti L, Pizzetti M, Seele P. Green lies and their effect on intention to invest. J Bus Res 2021;127:228–40.

[7] Musiał M. Green lies in the operation of enterprises. Zeszyty Naukowe WSB w Poznaniu 2019;87(4):73–82.

[8] Bakhtavar E, Hosseini S, Hewage K, Sadiq R. Green blasting policy: simultaneous forecast of vertical and horizontal distribution of dust emissions using artificial causality-weighted neural network. J Clean Prod 2021;283:124562.

[9] Zhang Q, Wang J, Guo S, Gong W, Feng L, Wang H, Ming C, Ma Z. Shaped charge hydraulic blasting: an environmental, safe, and economical method of directional roof cutting. Geofluids; 2021. 2021.

[10] Afra AP, Behnamian J. Lagrangian heuristic algorithm for green multi-product production routing problem with reverse logistics and remanufacturing. J Manuf Syst 2021;58:33–43.

[11] Bakhtavar E, Jafarpour A, Yousefi S. Optimal production strategy of bimetallic deposits under technical and economic uncertainties using stochastic chance-constrained programming. J Min Environ 2017;8(3):475–85.

[12] Jafarpour A, Sharif JA, Eivazi A. Reducing destructive environmental impacts of sungun copper mine effluents with using of phytoremediation processes. Int J Pure Appl Biosci 2017;5(2):43–55.

[13] Tang P, Yang S, Yang S. How to design corporate governance structures to enhance corporate social responsibility in China's mining state-owned enterprises? Resour Pol 2020;66:101619.

[14] Lindman Å, Ranängen H, Kauppila O. Guiding corporate social responsibility practice for social license to operate: a Nordic mining perspective. Extr Ind Soc 2020;7(3):892–907.

[15] Mikaeil R, Gharahasanlou EJ, Jafarpour A. Ranking and evaluating the coal seam mechanization based on geological conditions. Geotech Geol Eng 2020;38(3):3307–29.

[16] Jafarpour A, Najafi M. Selection of compatible coal seam for methane drainage operation based on uncertain geological conditions: a hybrid fuzzy approach. Math Probl Eng 2022;2022:1–17. https://www.hindawi.com/journals/mpe/2022/4586979/.

[17] Liu LY, Ji HG, Lü XF, Wang T, Zhi S, Pei F, Quan DL. Mitigation of greenhouse gases released from mining activities: a review. Int J Miner Metall Mater 2021:1–9.

[18] da Silva MG, Muniz ARC, Hoffmann R, Lisbôa ACL. Impact of greenhouse gases on surface coal mining in Brazil. J Clean Prod 2018;193:206–16.

[19] Liu P, Fan J, Jiang D, Li J. Evaluation of underground coal gas drainage performance: mine site measurements and

parametric sensitivity analysis. Process Saf Environ Protect 2021;148:711–23.
[20] Abuya WO, Odongo G. Poisoned chalice or opportunity for positive impact? An analysis of the impact of 'inherited' corporate social responsibility (CSR) commitments in Kenya's titanium mining industry. Extr Ind Soc 2020;7(3):1002–10.
[21] Qu Q, Guo H, Loney M. Analysis of longwall goaf gas drainage trials with surface directional boreholes. Int J Coal Geol 2016;156:59–73.
[22] Sang S, Xu H, Fang L, Li G, Huang H. Stress relief coalbed methane drainage by surface vertical wells in China. Int J Coal Geol 2010;82(3–4):196–203.
[23] Karacan CÖ, Diamond WP, Schatzel SJ. Numerical analysis of the influence of in-seam horizontal methane drainage boreholes on longwall face emission rates. Int J Coal Geol 2007;72(1):15–32.
[24] Hummel JA, Ruiz FA, Kelafant JR. Quantifying the benefits of coal mine methane recovery and use projects: case study on the application of in-mine horizontal pre-drainage boreholes at gassy coal mines in India and the optimization of drainage system design using reservoir simulation. Environ Technol Innovat 2018;10:223–34.
[25] Wang Y, Yang W, Lin B, Yan F. Effects of different conductive ions on pore-structure evolution of medium-and high-rank coal bodies induced by electric pulses. Fuel 2021;293:120437.
[26] Flores RM, Wang G, Qin D, Xi Y, Rukstales LR. Advancing CMM drainage, quality, and utilization with horizontal directional-drilled boreholes in Duanshi Coal Mine, southern Qinshui Basin, China. Int J Coal Geol 2019;209:1–13.
[27] Oyler DC. Use of a sodium silicate gel grout for plugging horizontal methane drainage holes, vol. 8843. US Department of the Interior, Bureau of Mines; 1984.
[28] ECE ENERGY SERIES. Best practice guidance for effective methane drainage and use in coal mines. 2010.
[29] Liu Q, Cheng Y, Yuan L, Fang Y, Shi D, Kong S. A new effective method and new materials for high sealing performance of cross-measure CMM drainage boreholes. J Nat Gas Sci Eng 2014;21:805–13.
[30] Hu G, He W, Sun M. Enhancing coal seam gas using liquid CO2 phase-transition blasting with cross-measure borehole. J Nat Gas Sci Eng 2018;60:164–73.
[31] Frank H, Ting R, Naj A. Evolution and application of in-seam drilling for gas drainage. Int J Min Sci Technol 2013;23(4): 543–53.
[32] Tang B, Tang Y, Wang C, Li Y, Yu Y, Dai M, Wang Z. Rapid co-extraction of coal and coalbed methane techniques: a case study in Zhangji coal mine, China. In: IOP Conference Series: earth and Environmental Science. 446. IOP Publishing; 2020. p. 052012. No. 5.
[33] Wang F, Ren TX, Hungerford F, Tu S, Aziz N. Advanced directional drilling technology for gas drainage and exploration in Australian coal mines. Procedia Eng 2011;26:25–36.
[34] Moraru RI, Babut GB, Cioca LI. Study of methane flow in caved goafs ajacent to longwall faces in Valea Jiului coal basin. Int Multidiscip Sci GeoConference: SGEM 2013;1:731.
[35] Zheng C, Jiang B, Xue S, Chen Z, Li H. Coalbed methane emissions and drainage methods in underground mining for mining safety and environmental benefits: a review. Process Saf Environ Protect 2019;127:103–24.
[36] Chen Y, Xu J, Peng S, Yan F, Fan C. A gas–solid–liquid coupling model of coal seams and the optimization of gas drainage boreholes. Energies 2018;11(3):560.
[37] Guanhua N, Kai D, Shang L, Qian S, Dongmei H, Ning W, Yanying C. Development and performance testing of the new sealing material for gas drainage drilling in coal mine. Powder Technol 2020;363:152–60.
[38] Weston J, Ledroz A. All-attitude gyrocompass tool offers significant enhancement in survey accuracy over the highest performance MWD magnetic systems. In: SPE/IADC Middle East drilling technology conference and exhibition. Society of Petroleum Engineers; 2016.
[39] Xia T, Zhou F, Liu J, Gao F. Evaluation of the pre-drained coal seam gas quality. Fuel 2014;130:296–305.
[40] Lou Z, Wang K, Zang J, Zhao W, Qin B, Kan T. Effects of permeability anisotropy on coal mine methane drainage performance. J Nat Gas Sci Eng 2021;86:103733.
[41] Xue S, Zheng C, Kizil M, Jiang B, Wang Z, Tang M, Chen Z. Coal permeability models for enhancing performance of clean gas drainage: a review. J Petrol Sci Eng 2021:108283.
[42] Zhang XB, Shen SS, Feng XJ, Ming Y, Liu JJ. Influence of deformation and instability of borehole on gas extraction in deep mining soft coal seam. Adv Civ Eng 2021;2021:1–11. https://www.hindawi.com/journals/ace/2021/6689277/.
[43] Karacan CÖ. Degasification system selection for US longwall mines using an expert classification system. Comput Geosci 2009;35(3):515–26.
[44] Rezaei J. Best-worst multi-criteria decision-making method. Omega 2015;53:49–57.
[45] Saaty TL. How to make a decision: the analytic hierarchy process. Eur J Oper Res 1990;48(1):9–26. https://doi.org/10.1016/0377-2217(90)90057-I.
[46] Saaty TL. Fundamentals of the analytic network process. In: Proceedings of the 5th international symposium on the analytic hierarchy process; 1999. p. 12–4.
[47] Saffari A, Sereshki F, Ataei M. Evaluation effect of macerals petrographic and pyrite contents on spontaneous coal combustion in Tabas Parvadeh and Eastern Alborz coal mines in Iran. Int J Coal Prep Util 2019;42(1):12–29.
[48] Rajabzadeh MA, Ghorbani Z, Keshavarzi B. Chemistry, mineralogy and distribution of selected trace-elements in the Parvadeh coals, Tabas, Iran. Fuel 2016;174:216–24.
[49] www.tpc.co.ir.
[50] Soltani Khaboushan A, Osanloo M. Determination of an optimum interface between open-pit and underground mining activities in mazinu coal mine of Tabas power plant. J Min Environ 2021;12(1):139–49.
[51] Shojaei S, Jafarpour A, Shojaei S, Gyasi-Agyei Y, Rodrigo-Comino J. Heavy metal uptake by plants from wastewater of different pulp concentrations and contaminated soils. J Clean Prod 2021;296:126345.