



Prediction of coal and gas outburst risk by fuzzy rock engineering system

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Abstract

The sudden outburst of coal and gas is a complex and dynamic incident in the underground coal mines, resulting in the release of thousands of tons of coal and large amounts of gas into the working face within a short time. Due to a rise in the number of exploitations and the depth of extractions, the intensity, and frequency of explosions have increased in recent years. Consequently, these explosions have endangered miners' health and safety, brought about equipment loss and seriously affected coal production. To overcome these obstacles, the first step is to predict the occurrence of such incidents in the coal mines. There are a lot of factors playing a part in the sudden outburst of coal and gas, which can be categorized into natural and operational parameters, each of which has a different role. In this paper, a novel method is proposed to predict the possibility of gas outburst in coal seams. For this purpose, ten parameters are considered as the main variables influencing the outburst of coal and gas. To study the interrelation between these determining parameters as well as the uncertainty of the effect of one parameter on another, a fuzzy interaction matrix based on Fuzzy Rock Engineering System (FRES) has been employed. To evaluate the capability and efficiency of the proposed classification system, the C1 coal seam of Tabas coal mine is selected, and the proposed index is used to investigate the potential risk of the outburst in this mine. Index as mentioned earlier could be utilized as a basis through which one can decide on the possibility of the outburst of coal and gas in coal mines to reduce the risks of this incident.

Keywords Coal and gas outburst · Classification system · Rock engineering system · Fuzzy system

Introduction

The outbursts of coal and gas could be a significant hazard to the successful implementation of the mine plan. The gas outburst is the sudden release of a large volume of gas into the mine environment, whose sudden movements can break the coal and disperse its particles. This incident can be a serious threat to health, safety, equipment, and coal production. Ensuring a high level of safety and its maintenance is

an ideal goal in coal mining; therefore, the potential risks should be carefully assessed and predicted to be prevented and controlled (Hargraves 1983; Jin et al. 2018). The escalation of incidents caused by the sudden release of gas in various mines around the world calls for more attention of gas outburst prediction. The first recorded report of coal and gas outburst occurred in 1843 in the coal region of Isaac in France (Zhai et al. 2018). The largest outburst in a coal mine happened with the ejection of 14,500 tons of coal and 600,000 cubic meters of gas in the Gagarin Colliery of Donetsk, Ukraine (Lama and Bodziony 1998). Among all the countries in the world, China has the largest number of outbursts with the highest level of frequency (Guan et al. 2009). From the year 2004 to 2015, a total of 20,731 mine accidents occurred in China, with an average percentage of 1.7 deaths per accident (Sun and Qian 2016). Furthermore, 145 outbursts are recorded in Huainan from 1897 to 2016 (Yuan 2016). For example, in 2004, a violent outburst occurred in Henan coal mine, located in China which resulted in the death of 148 people (Zhang and

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Zhang 2005). Another outburst occurred in Sunjiawan coal mine in the Fuxin region in 2005, killing 214 people (Wang et al. 2013). The most catastrophic coal and gas outburst in the world occurred in 1992 at a depth of 560 m in the Kozlu coal mine in the Zonguldak Coal Basin, Turkey, as a result of which 263 miners died and 77 miners injured (Esen 2013). Although the number of gas outburst occurrences has declined in recent years thanks to technology development and advanced mining techniques, the gas outburst is still a dangerous incident in the underground coal mining industry. The developed methods for predicting the conditions of an instant outburst may be classified into some groups according to the various factors affecting the selected method. The type of method put to use depends on the local conditions. Several mines may use more than one method for constant prediction. Researchers have conducted some research on the mechanisms of coal and gas outburst and their determining factors. Wuyi and Ping (1999) have predicted gas explosion risk utilizing structural analysis of geology and coal structural features. Ji-sheng (2004) predicted the coal and gas outburst with regard to parameters of gas pressure, gas content, coal structure, and operational parameters employing the back propagation (BP) neural network. Wei-Hua and Hong-Wei (2009) have developed the method of outburst risk prediction through a pattern detection technique based on the systematic analysis of the factors affecting the outburst, ranging from one to several factors, such as gas content, permeability, stress gradient, petrology of the roof-rocks, and mining depth. Ni et al. (2010) have proposed an index system to assess gas and coal outburst using fault tree analysis (FTA). Tang et al. (2016) have studied the primary factors influencing coal and gas ejection, such as gas emission rate, seam depth, gas pressure, and used linear prediction to investigate the incident of sudden gas release. Zhao et al. (2017a, b) have predicted the gas outburst risk by detecting the changes in gas and stress distribution in the coal seam. Wang et al. (2018a, b) have utilized finite element methods (FEM) to simulate the stress field and predict gas and coal outburst in the mines of China. Kursunoglu and Onder used structural equation modeling (SEM) to evaluate the coal and gas seam outburst for an underground coal mine in Turkey (2019).

Generally, the outburst is predictable using experimental and mathematical methods such as analytical, simulation and numerical methods. Experimental methods are one kind of data collection that may be used to assess theoretical knowledge. Mathematical modeling is the art of translating problems from an application area into tractable mathematical formulations whose theoretical and numerical analysis provides insight, answers, and valuable guidance for the originating application. Analytical methods enable researchers to examine complex relationships between variables. Simulation methods are ways to imitate the operation of real-world

systems. It first requires that a model is developed representing characteristics, behaviors and functions of the selected system or process. The model represents the system itself, whereas the simulation represents the operation of the system over time. Numerical methods are those methods that can solve a problem numerically or they can be converted into a computer program.

Current methods of coal and gas outburst prediction mainly depend on the indices associated with drilling cutting, the initial velocity of gas emission from a borehole, soft layer thickness, acoustic emissions, coal temperature, gas content, and microseismic event counts.

To predict the gas and coal outburst, one should pay close attention to the interaction of the influential parameters in this incident since a rise in one parameter may increase or decrease the weight of the other parameters; therefore, it is necessary to consider the interaction of all the parameters. In all methods mentioned above, the interaction of parameters affecting the gas outburst has not been fully assessed and also the prediction methods cannot be effectively adapted to complex nonlinear interactions. Consequently, the prediction results are often not satisfactory. Hence, developing a new method to predict the possibility of gas and coal outburst considering the interaction of influential parameters is of vital importance. In such a system, the interaction of all parameters (geological and operational) must be observed simultaneously. The Rock Engineering System (RES) approach can analyze the mechanisms involved in rock engineering problems. In this method, the interaction matrix is utilized to list the effective parameters in a rock engineering project and show the interaction between them (Hudson 1992).

The purpose of this study is to present a new method for predicting gas outburst in coal seams using a fuzzy rock engineering system. Thus, the most influential parameters are determined through fuzzy RES, subsequently a new index is introduced to predict coal and gas outburst in the coal seams.

Influential parameters

The coal and gas outburst may occur during entry excavation and coal cutting processes or in dealing with various geological structures, including faults, folds, anticlines, synclines, and petrographic changes. Natural and operational parameters (resulting from mining) have different effects on this phenomenon with various levels of importance in the overall rate of gas emission.

Natural parameters

Geological structures, coal rank, gas content, gas pressure, permeability, coal strength, and stresses are natural factors that influence the gas outburst possibility. The description of these parameters is given below.

Geological structure

Geological structures play a preeminent role in gas outburst occurrence. The coal and gas outburst is usually found near geological structures, such as soft layers, faults, folds, shear regions, permeable igneous and coal layers of different thickness (Fisne and Esen 2014; Jia et al. 2018; Fusheng et al. 2007; Cao et al. 2001) Among all geological factors, two groups have been focused: the first group includes the factors directly related to the coal seams such as the dip, the thickness, the depth of the seam, and so on. These factors reflect the geometric and geological features of the coal seams and may be determined easily and accurately. The effects of coal seam dip and thickness in Zonguldak coal basin is shown in Figs. 1 and 2. It is clear that the most outburst phenomena has been occurred in coal seams thickness 2–3 m and dip angle of 30–70°. Hou et al. studied the effect of coal seam dip on the outburst in coal roadway by FLAC3D software. The results indicated that the increase of coal seam dip has a positive effect on the risk of outburst and the zone gradually moves upward along the coal seam with the potential of outburst (Hou et al. 2019).

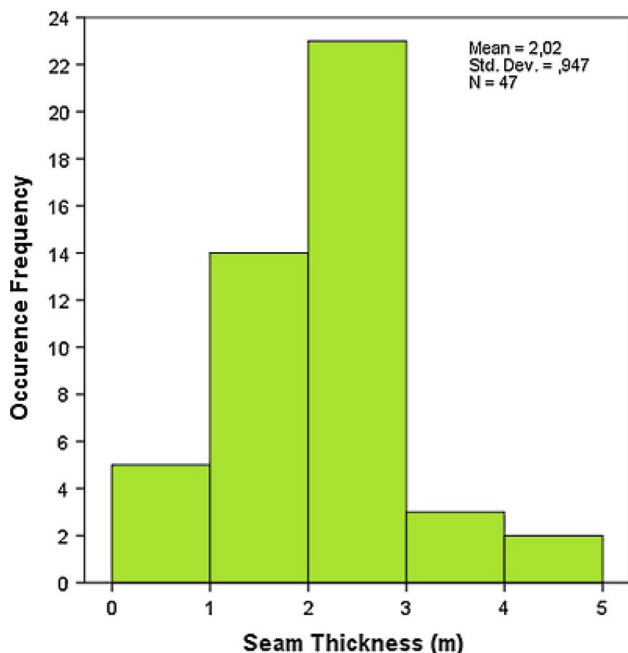


Fig. 1 The effect of coal thickness on outburst occurrence frequency in Zonguldak coal basin (Fisne and Esen 2014)

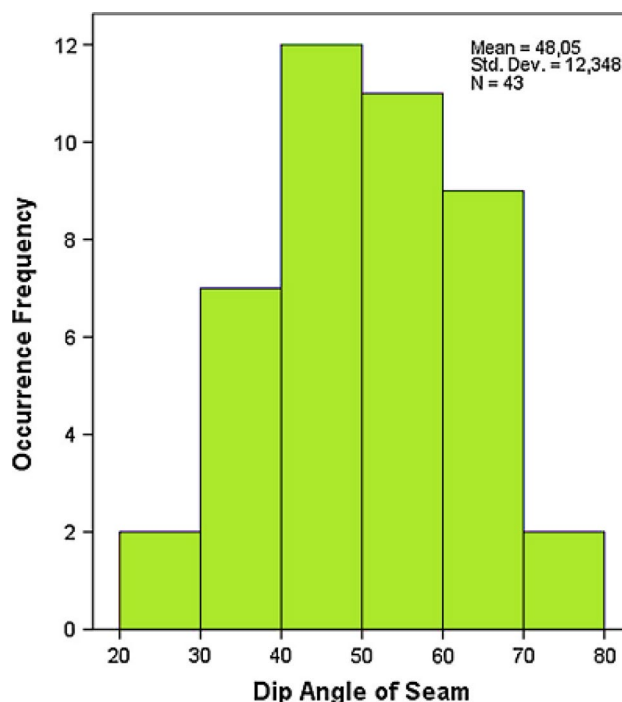


Fig. 2 The effect of coal seam dip on outburst occurrence frequency in Zonguldak coal basin (Fisne and Esen 2014)

The second group involves the factors describing the initial disturbances of the geometry of coal seams resulting from tectonic action and volcano. These factors include folds, fractures, faults, shear zones, layer thickness changes, and the penetration of magmatic networks. Faults play a vital role in outburst occurrence (Lama and Bodziony 1998). The risk of outburst occurrence is decreased with increasing distance from the fault zone (Fig. 3).

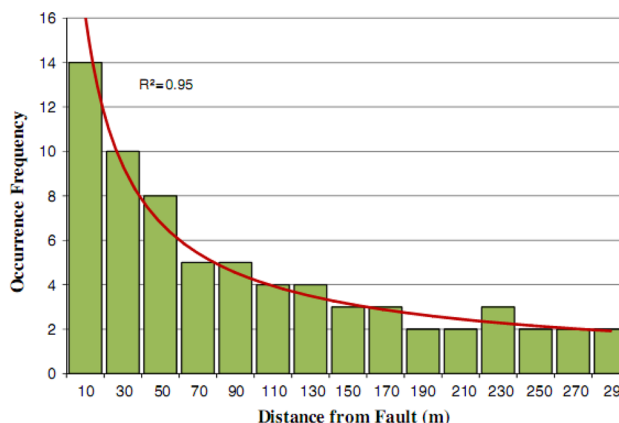


Fig. 3 The relation between the distance from the fault zone and outburst occurrence frequency in Zonguldak coal basin (Fisne and Esen 2014)

Lin et al. analyzed the effect of faults in the working face on coal and gas outbursts using 3DEC software. The modeling results revealed that when the small fault drop in the working face is more, the greater are the risk of coal and gas outburst (Lin et al. 2020).

Coal rank

The degree of change or alteration that occurs in coal is known as coal rank. The difference in coal rank is one of the critical factors to the storage of gas in the coal seam. Generally, there is no risk of outburst emergence in low-rank coal, and only high-rank brown bituminous coal has the potential for an outburst. As the rank of coal increases, the risk of an outburst occurrence is increased (Fisne and Esen 2014).

Gas content

The volume of absorbed gas per the coal mass unit is called gas content. The gas content of the coal seam is an essential factor for the outburst of gas, coal, and rock. The higher the content of gas, caused the higher the risk of gas and coal outburst (Fig. 4) (Lama and Bodziony 1998; Shi et al. 2017).

Liu et al. presented a method for estimation of the critical value of gas content for prediction of coal and gas outbursts in Xinzhuangzi coal mine of Huainan. The result shows that the critical gas content value is 11 m³/t (Liu et al. 2010).

Gas pressure

Gas pressure is the primary main source of sudden release gas. The gas pressure of the coal front face is dependent on the speed of mining. The gas pressure of more than

0.3 MPa in very soft coal seams can lead to the outburst (Zhao et al. 2019; Shi et al. 2017; Fisne and Esen 2014). The effect of coal seam gas pressure on coal outburst was shown in Fig. 5.

Zhi and Elsworth developed a numerical model to investigate the impact of gas desorption on gas outburst in a coal mine. The results showed that in 10–30 m front of working face the pore pressure increased which consequently escalated the risk of outburst (Zhi and Elsworth 2016).

Permeability

Permeability is an influential factor influences the formation of gas gradient and the rate of gas surface absorption. The outburst possibility decreases by an increase in permeability (Nie et al. 2014; Lama and Bodziony 1998). Jun et al. examined the effect of water jet slotting technology to reduce the risk of outburst. The experimental results indicated that high-pressure water jet slotting enhances coal seam permeability; also it reduces coal and gas outburst risk (Jun et al. 2019).

Coal strength

Coal strength affects the gas release into the coal seam. Coal strength depends on the maceral composition; hence the resistance of various layers is entirely varied. The risk of coal and gas outburst declines with an increase in coal strength (Nie et al. 2014; Sereshki 2005).

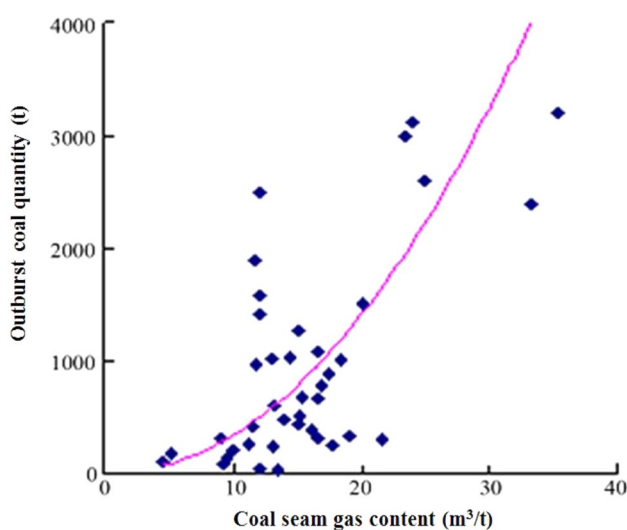


Fig. 4 The effect of coal seam gas content on outburst coal quantity (Shi et al. 2017)

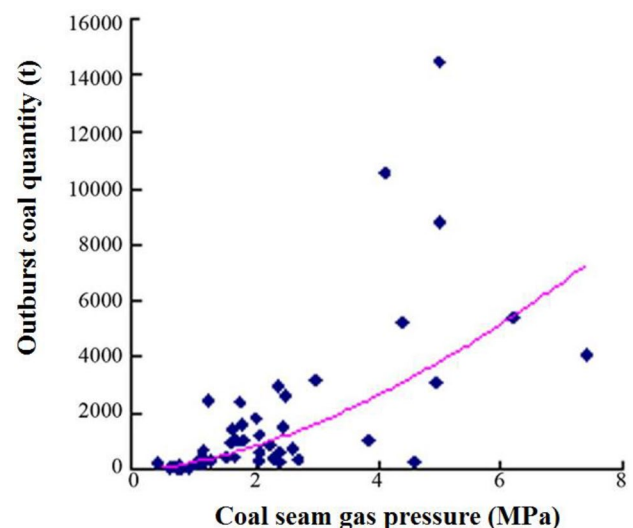


Fig. 5 The effect of coal seam gas pressure on outburst coal quantity (Shi et al. 2017)

Stress

Stress has the primary role in the occurrence of coal and gas outburst. The stress may be due to the depth of the coal seam or the induced stress caused by the mining operations which centralize stress at the corners of the in-situ coal, sides of the stope and pillars. The high tectonic stress decreases the coal strength, developing a large area of tectonic coal. The direction and size of the tectonic stress field intensely affect the stability of the roadway. When the direction of maximum stress is in the face advancement, the likelihood of an outburst occurrence is high. Vertical stresses and horizontal stresses play an essential role in the outburst (Fig. 6) (Zhang et al. 2008; Zhai et al. 2016; Yang et al. 2014). Han et al., by measuring the in situ stress of the Kailuan mining area, concluded that the stress in this area is larger than that of other areas (Han et al. 2007). An and Cheng studied the effect of tectonic stresses on the coal and gas outburst tendency by numerical modeling. Numerical modeling results demonstrated that the outburst intensifies due to increasing tectonic stresses (An and Cheng 2014).

High tectonic stress zones often cause irregularities in coal permeability, gas pressure and gas content, and an outburst usually occurs in this area.

Operational parameters

The operational factors including the extraction method, panel dimensions, and face advancement influence the outburst. One of the most critical parameters is face advancement. The extraction method and panel dimensions are affecting this parameter. For the underground coal mining method, the lower face advancement, the more gas can

naturally eject. The risk of outburst decreases in retreat-longwall mining due to drainage from inside the face, advancing corridors and degasification from the gob zone (Lama and Saghafi 2002; Fan et al. 2017; Beamish and Crosdale 1998; Zhai et al. 2016). Accordingly, it can be said that with increasing the face advancement, the induced stresses in front of the extraction face increase which can lead to the risk of an outburst (Wang et al. 2018a, b).

Rock engineering system

Rock engineering system is a method that can analyze the complex processes of rock engineering. The concept of the rock engineering system was first introduced by Hudson (1992) to solve complex engineering problems (Hudson 1992). This method is a fully engineered system that covers all the primary and secondary objectives of a problem. It is not only a highly reliable method to integrate current knowledge into the evaluations but also capable of applying in engineering projects for various purposes. In rock engineering systems, identification of critical parameters, influential paths, back loops, and evaluating the appropriate engineering techniques are made using the interaction matrix. The interaction matrix is a key element of rock engineering systems used to list the effective parameters and display the interaction between them in a rock engineering project. The general structure of an interaction matrix with two-elements (A and B) is shown in Fig. 7.

The interaction matrix is a square matrix, which bears the main parameters on its main diagonal and their interactions and the interrelations between each pair of parameters on its off-diagonal elements. As shown in Fig. 7, parameter

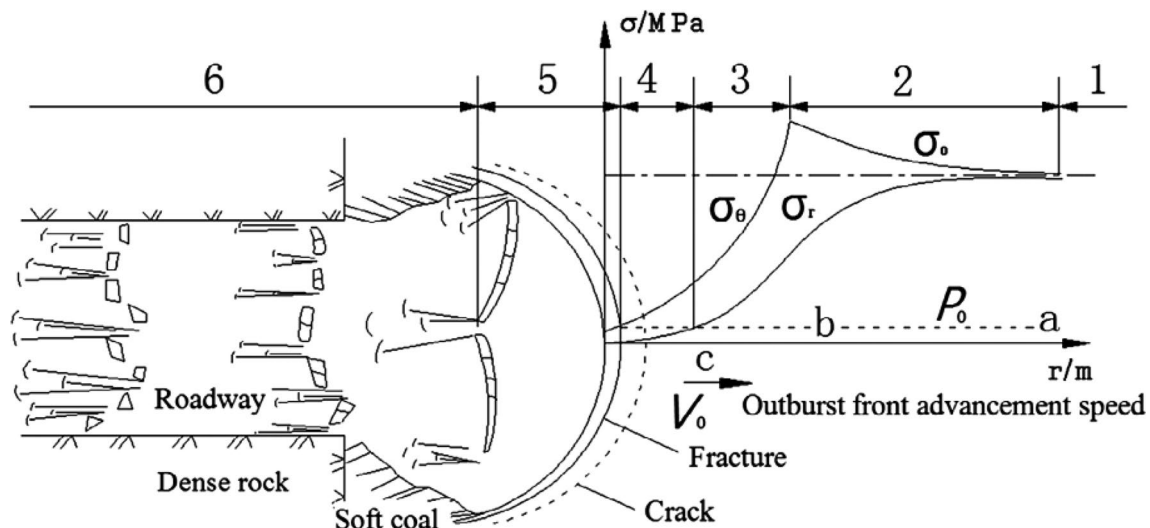


Fig. 6 The effect of stresses (in-situ and induced) in front of face on outburst occurrence (Chen et al. 2018)

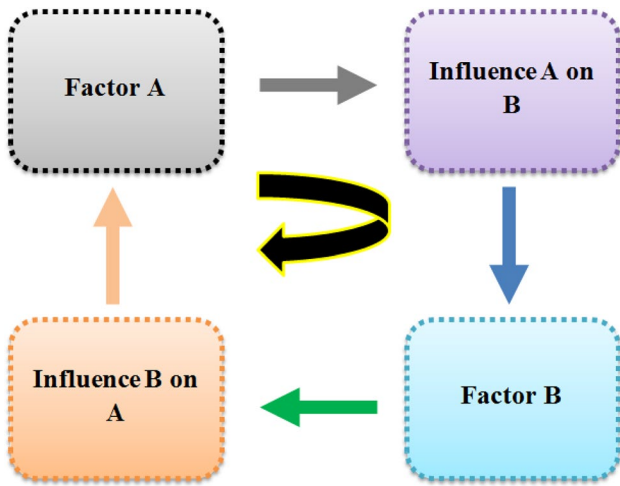


Fig. 7 The interaction matrix with two factors A and B (Hudson 1992)

A is located on the top left-hand entry and parameter B is located on the bottom right-hand entry of the matrix. The upper right-hand element represents the effect of A on band B and the bottom left-hand element represents the effect of B on A (Hudson 1992).

Interaction matrix coding

Several techniques have been proposed by Hudson for coding the interaction matrix to interpret the rock engineering systems (Hudson 1992). These techniques are shown in Fig. 8.

The Expert Semi-Quantitative (ESQ) method, is employed in most studies because of its ease of use (Rozos et al. 2008; Budetta et al. 2008; Younessi and Rasouli 2010; Frough and Torabi 2013; Naghadehi et al. 2013; Rafiee et al. 2019). This paper has adopted this method to code the interaction matrix.

Cause-and-effect diagram

The role of each parameter (weighted of coefficient influence) is revealed from a cause vs. effect diagram. After encoding the interaction matrix, the sum of each row and column can be calculated. The sum of the numerical values of each row (C) known as “cause” or the parameter effect on the system (indicating the effect that row parameter (Pi) has received from other parameters), and the sum of the values of each column (E) known as “effect” or the system effect on the parameter (indicating the effect that column parameter (Pi) has gained from other parameters). Figure 9 shows the generation of the cause and effect co-ordinate.

The position of each point in the cause and effect diagram determines the interaction state of that parameter. Obviously,

Matrix Coding Method	
1. Binary: Mechanism are switched on or off (0,1)	
2. Expert Semi-Quantitative (ESQ)	Main coding method in RES
0- No Interaction	
1- Weak Interaction	
2- Medium Interaction	
3- Strong Interaction	
4- Critical Interaction	
3. According to the slope of the P_i vs. P_j relation	
4. More numerically via solution to partial differential equation, e.g. solution to first order PDE is exponential or negative exponential	
5. Explicitly via complete numerical analysis of mechanism	

Fig. 8 The five basic coding methods (Hudson 1992)

the higher the numerical value (C + E) of the given parameter is, the more significant interaction with the whole system it shows, and the greater the differential value (C – E)

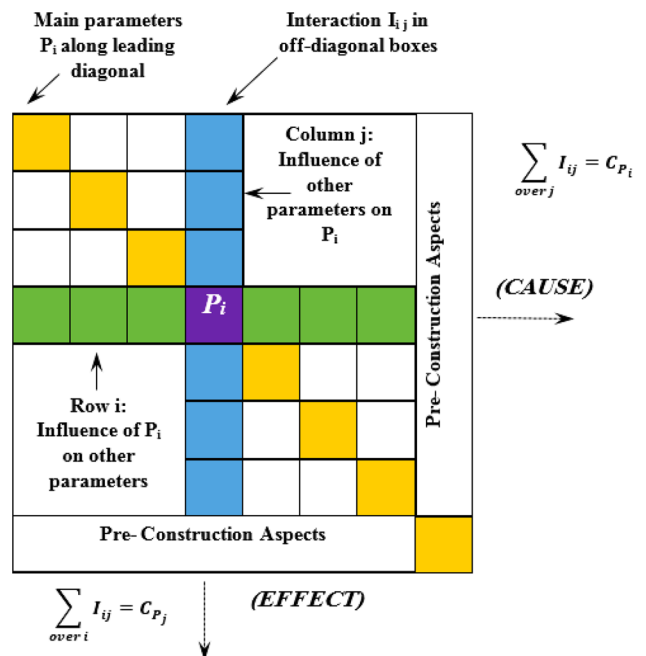


Fig. 9 Establish cause–effect co-ordinate (Hudson 1992)

(with regard to its sign) of the given parameter is, the more dominance the parameter has over the system. The negative value of $(C - E)$ indicates the dominance of the system over the parameter. In Fig. 10, the $C - E$ diagram is shown that is extended to N parameters (Hudson 1992).

Coal and gas outburst prediction index (CGOPI)

As mentioned in “Influential parameters” section, many parameters affect the outburst of coal and gas. In this research, based on engineering judgments of experienced experts and research conducted on the gas and coal outburst (Fisne and Esen 2014; Lama and Bodziony 1998; Zhai et al. 2016; Fusheng et al. 2007; Cao et al. 2001; Shi et al. 2017; Sereshki 2005; Zhao et al. 2019; Yang et al. 2014; Zhang and Dou 2006), ten parameters is evaluated as the main factors affecting this phenomenon and the values of their significance are presented in Table 1. Some parameters is represented qualitatively and some others quantitatively. It is not possible to directly enter actual values of the parameters in the calculation of the coal and gas outburst prediction index. It is notable that the values of the parameters are divided in to five classes and each class changes from 0 to 4.

Determination of coal and gas outburst prediction index (CGOPI)

As mentioned, in the encoding semi-quantitative (ESQ) method, a number (code) is considered for each

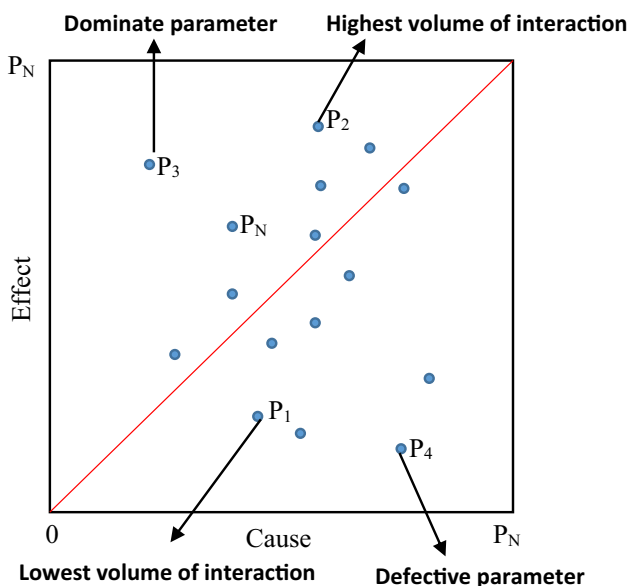


Fig. 10 The $C - E$ diagram comprising N influencing factors (Hudson 1992)

interaction. Since, in many cases, there are uncertainties in the features and interactions of parameters, choosing a single code cannot fully represent the corresponding interaction. Thus, to assess the uncertainty of a parameter effect on the others, a Fuzzy Expert Semi-Quantitative (FESQ) method has been employed (Rafiee et al. 2016). The first step in assessing the parameters is to form the interaction matrix of the effective parameters on the gas outburst. The ten main parameters are selected as influential parameters on the system located at the main diagonal of the interaction matrix. These parameters are: coal rank (P_1); gas content (P_2); permeability of coal (P_3); coal seam thickness (P_4); coal seam dip (P_5); coal strength (P_6); in-situ stress (P_7); gas pressure (P_8); geological structure of overburden (P_9); rate of face advancement (P_{10}) and the potential for outburst (P_{11}) that are placed in the main diagonal of the matrix for more accurate understanding and result.

Then, some questionnaires have been prepared and given to the experts to determine the interaction values between the parameters based on the ESQ method. Each expert should select from five alternatives of non-interaction (n_A), weak interaction (n_B), medium interaction (n_C), strong interaction (n_D), and critical interaction (n_E) for each entry of the matrix. These values were initially normalized and then considered as inputs entered into the fuzzy system via Matlab software. Therefore, each input of the fuzzy system is a numerical value within the $[0, 1]$ interval. For each input of the fuzzy system, two fuzzy sets as “Low” and “High” are considered, shown in Fig. 11. For example, if the n_A value is set to the “High” fuzzy set, it means that most experts believed that there is no interaction between the two parameters. In other words, the probability of the A option (non-interaction alternative) is greater than other options.

If the normalized values of inputs for each element in the interaction matrix are less than 0.4, the degree of membership of the “Low” fuzzy set is greater than the degree of membership of the “High” fuzzy set. This means that few experts have selected this option as the interaction of that element of the matrix. Nine fuzzy sets (m_1 to m_9) have been designed for the fuzzy system output. The reason for selecting nine fuzzy sets instead of five fuzzy sets is to provide better coverage of the intermediate values for representing the interaction between parameters more precisely. The output of the fuzzy system is shown in Fig. 12. As it is discussed, nine trapezoidal membership functions in range of $[0-4]$ are designed to cover the expert’s unsureness and disagreements.

After creating the membership function in the system, it is necessary to build a fuzzy rule base according to the fuzzy if-then rules. The designed fuzzy system consists of 5 inputs; each contains two sets. Consequently (2^5) , 32 rules are defined for the system.

Table 1 Proposed range of affecting parameters on the coal and gas outburst classification

Parameters	Rating				
	0	1	2	3	4
Coal rank	Lignite	Sub-bituminous	Anthracite	Semi-anthracite	Bituminous
Gas content (m ³ /t)	<5	5–10	10–15	15–20	>20
Permeability of coal (md)	<5	0.1–5	0.1–0.01	0.01–0.001	>0.001
Coal seam thicknesses (m)	<1	1–2	2–3	3–4	>4
Coal seam dip (°)	<5	5–10	10–15	15–30	>30
Strength of coal (MPa)	>12	12–10	10–4	4–2	<2
Gas pressure (MPa)	<0.4	0.4–0.74	0.74–1	1–2	>2
Rate of face advancement (m)	<2	2–5	5–7	7–9	>9
In-situ stress (MPa)	<3	3–6	6–12	12–20	>20
Geologic structure of overburden	Very low gas content and very high permeability of surrounding rocks, very low strength of hanging wall and footwall, high, permeable faults with low gas, very high permeability in synclinal and anticline of fold	Low gas content and high permeability of surrounding rocks, low strength of hanging wall and footwall, moderate permeable faults with low gas, high permeability in synclinal and anticline of fold	Moderate gas content and permeability of surrounding rocks, moderate strength of hanging wall and footwall, impermeable faults with low gas, moderate permeability in synclinal and anticline of fold	High gas content and low permeability of surrounding rocks, moderate strength of hanging wall and footwall, impermeable faults with moderate gas, low permeability in synclinal and anticline of fold	Very high gas content and very low permeability of surrounding rocks, high strength of hanging wall and footwall, impermeable faults with high gas, very low permeability in synclinal and anticline of fold

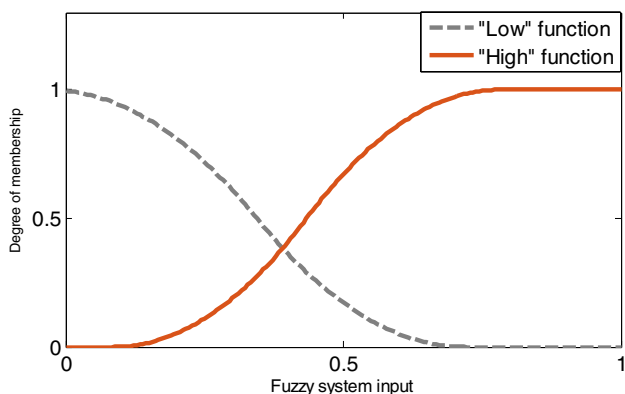


Fig. 11 Fuzzy set for each fuzzy system input

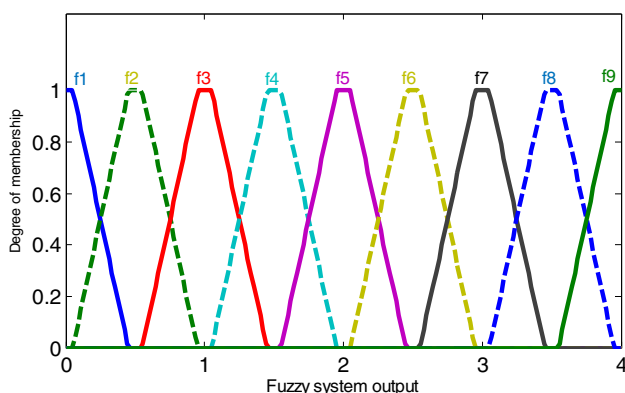


Fig. 12 Output of fuzzy system

RES interaction matrix is encoded regarding the fuzzy system. Using the values of parameters and their respective weights, the prediction index of gas and coal outburst is calculated. Hudson (1992) has suggested a method for determining the weight of each parameter.

For this purpose, in the first step, the cause (C_i) and effect (E_i) values for each parameter in the system is calculated by Eqs. 1 and 2 (Hudson 1992).

$$C_i = \sum_n I_{mn} \quad (\text{with } m \equiv i) \tag{1}$$

$$E_i = \sum_m I_{mn} \quad (\text{with } n \equiv i), \tag{2}$$

where I_{mn} represents the interaction matrix element. In these equations, C_i is the sum of the raw values and E_i is the sum of the column values for each parameter.

Then, the weight of each parameter is determined using the following equation (Hudson 1992).

$$a_i = \frac{C_i + E_i}{\sum_{i=1}^n C_i + \sum_{i=1}^n E_i} \tag{3}$$

The weight for parameter i , shown by a_i , is calculated by its ‘parameter interaction intensity’ ($C_i + E_i$) divided by the sum of interaction intensities of all parameters in the system (Hudson 1992).

After the weights for all parameters (a_i) were calculated, the coal and gas outburst prediction index (CGOPI) is calculated by Eq. 4.

$$CGOPI = \sum_{i=1}^{10} a_i \frac{P_i}{P_{Max_i}}, \tag{4}$$

where the a_i values are weights of parameters and P_i is the maximum values for each parameter which is considered for coal and gas outburst.

In the following section, the coal and gas outburst prediction index (CGOPI) is calculated for the Tabas coal mine.

Determination of CGOPI index for Tabas coal mine

Tabas coal mine is located in a Parvadeh coal deposit approximately 85 km south of Tabas city in the province of Khorasan in mid-eastern Iran and it is about 860 m above mean sea level (Fig. 13). The Parvadeh coal deposit lies in a basin between two major north–south trending fault systems, the Kalmard Fault to the west and the Nayband Fault to the East. A third major fault, termed the Hidden Fault, is thought to exist to the west. The Nayband Fault is still seismically active, a major earthquake occurring in 1978. Other faults in the area may also be active. Second-order structures trend east–west between these faults, including the Rostam, Zenowghan and Quri Chay Faults and the Parvadeh



Fig. 13 Location map showing the Tabas coal mine

Anticline. The Rostam Fault forms the northern boundary of the Parvadeh area. It is a reverse fault with a displacement of up to 700 m, down throwing to the north (Anon 2005).

There are five coal seams in the Parvadeh coal deposits, including D, C2, C1, B2 and B1. Only C1 seam is being considered for extraction by a mechanized longwall retreat mining method during this phase at Tabas mine, but other seams in the strata sequence affect the design of the mine. The thickness and dip of the C1 seam vary from approximately 2.2 m in the northeast to 1.5 m in the southwest and from 5 to 26°, respectively. The C1 coal seam gas content increased to the depth of 300 m in value of 19 m³ per ton

and then it will be constant. The gas content of surrounding rocks of the C1 seam is 3–5 m³ per ton at a depth of 500 m (Anon 2005). In this mine, post drainage will take the form of cross-measures boreholes originating in the long-wall gates to extract high-purity methane from gas horizons above and below the C1 seam. The holes will be cased at their outer end, and connected to dedicated pipe ranges, the drained gas being discharged at the surface (Anon 2005).

Tabas coal mine information for coal and gas outburst prediction was given in Table 2.

In the first stage to determine the CGOP index in the Tabas coal mine, by applying the FRES method, the fuzzy interaction matrix is developed. To this end, the judgment of 10 experts is collected, and by implementing fuzzy rules, the fuzzy interaction matrix is created, which is presented in Table 3.

In the second step, after encoding the matrix, the “Cause” and “Effect” values are calculated for each parameter. The C-E diagram shows the difference between high and low interaction effects (Fig. 14). The points in the lower right-hand side of the diagram called dominant and those parameters that are dominant on the system due to having larger (C–E). The parameters under the influence of the system are located in the upper left-hand side of the diagram with smaller (C–E) values and, in other words, they are dominated by the system.

It is clear from the C–E diagram that the P9, P3, P7 and P2 parameters, namely geological structure, in-situ stress, coal permeability, and gas content, have the highest degree

Table 2 The value of influencing parameters in Tabas coal mine for coal and gas outburst classification

Parameters		Value
P1	Coal rank	Anthracite
P2	Gas content (m ³ /t)	22
P3	Permeability of coal (md)	0.22
P4	Coal seam thicknesses (m)	2.16
P5	Coal seam dip (°)	11–26
P6	Strength of coal (MPa)	6.26
P7	In-situ stress (MPa)	15.9
P8	Gas pressure (MPa)	1
P9	Geologic structure of overburden	High gas content of surrounding rock
P10	Rate of face advancement (m)	3–4

Table 3 The fuzzy interaction matrix for coal and gas outburst

P₁	3	1.1	0.16	0.15	1.25	0.54	2	0.16	0.37	2.11	10.82	Cause
1.63	P₂	2.39	0.19	0.15	2	1.74	3.84	1	3	3.84	19.79	
1.75	2.39	P₃	0.15	0.15	3	1.63	3.84	0.16	2	3.64	18.72	
0.15	2.25	0.16	P₄	0.16	0.15	1.75	1.94	0.19	2.25	2	10.99	
0.15	0.19	0.19	0.15	P₅	0.15	2	1	2	2	2	9.83	
0.16	2	3	0.15	0.15	P₆	1	1	0.19	2.25	3	12.90	
0.16	2	3	0.15	0.15	3	P₇	3	2	3	3.49	19.96	
1.74	2.25	2	0.15	0.15	0.19	2.25	P₈	0.51	2.25	3.84	15.35	
0.16	2.25	2	2	2.25	2.25	3	2	P₉	0.15	3	19.05	
0.15	0.15	0.15	0.15	0.15	0.15	2	2.25	0.15	P₁₀	3	8.32	
0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	P₁₁	1.5	
6.20	16.64	14.14	3.41	3.63	12.30	16.06	21.02	6.50	17.42	29.93		
Effect												

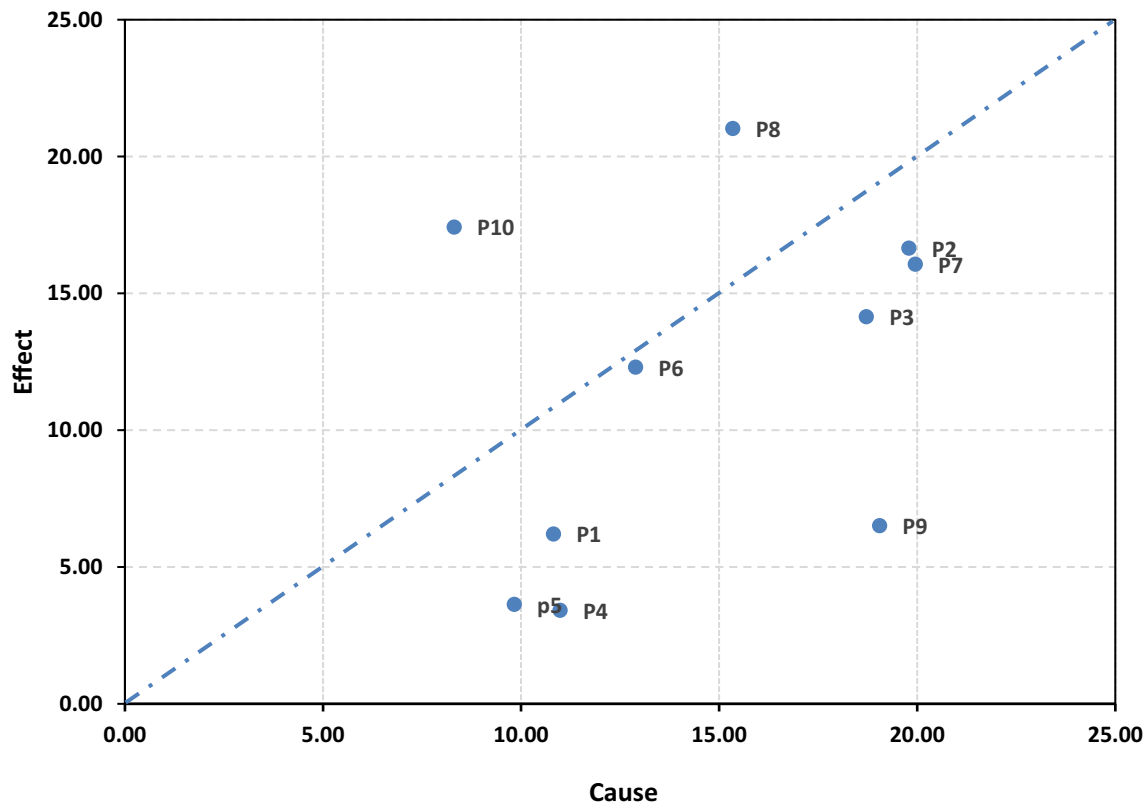


Fig. 14 Cause-effect diagram for coal and gas outburst

of dominance on the system. By calculating the cause and effect sum ($C + E$) for each parameter, the interaction significance histogram can be drawn (Fig. 15). The ($C + E$) value is selected as the factor of differentiation between parameters due to the focus on the role of system interactions. The parameters gas content, geographical structure, and in-situ stress involve the highest interactions in the system. When the interaction of the system is high, that system is potentially unstable. So a small change in a parameter's value, significantly affects the system behavior. Overall, some of the parameters will have a higher effect on the system than other parameters, as the system has more impact on some parameters than some others. Encoding of the interaction matrix is a method for determining the significance and dominance of parameters.

Based on the weight of each parameter (Table 4), the coal and gas outburst prediction index (CGOPI) is calculated.

As given in Table 4, the parameters of gas content, and gas pressure have the highest weight, and seam dip and thickness parameters have the least weight. The classification of the coal and gas outburst prediction index (CGOPI) is shown in Table 5. The CGOPI is between 0 and 100.

In summary, the flowchart of the steps to calculate the CGOPI index using of fuzzy rock engineering systems (FRES) for the Tabas coal mine is shown in Fig. 16.

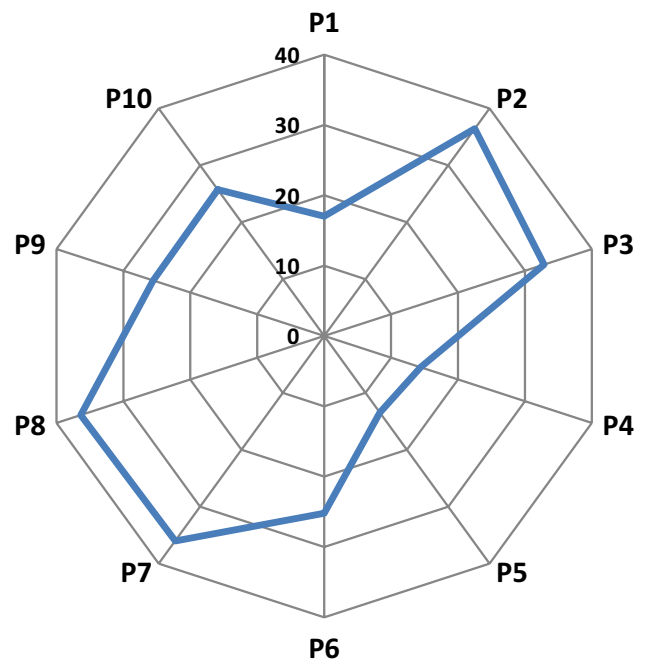


Fig. 15 The chart of the interactive intensity of parameters ($C + E$)

Table 4 The weighted coefficient

Parameters	C	E	C + E	C - E	a_i	
P1 Coal rank		10.82	6.2	17.03	4.62	0.058
P2 Gas content (m ³ /t)		19.79	16.64	36.44	3.15	0.124
P3 Permeability of coal (md)		18.72	14.14	32.86	4.58	0.112
P4 Coal seam thicknesses (m)		10.99	3.41	14.40	7.58	0.049
P5 Coal seam dip (°)		9.83	3.63	13.46	6.21	0.046
P6 Strength of coal (MPa)		12.9	12.3	25.19	0.6	0.086
P7 In-situ stress (MPa)		19.96	16.06	36.02	3.89	0.122
P8 Gas pressure (MPa)		15.35	21.02	36.37	-5.67	0.123
P9 Geologic structure of overburden		19.05	6.5	25.56	12.55	0.087
P10 Rate of face advancement (m)		8.32	17.42	25.74	-9.10	0.087
P11 CGOPI		1.53	29.93	31.46	-28.40	0.107
-		$\sum_{i=1}^{11} C_i = 147.26$	$\sum_{i=1}^{11} E_i = 147.26$	$\sum_{i=1}^{11} C_i = 294.52$	-	$\sum_{i=1}^{11} a_i = 1$

Table 5 The classification of coal and gas outburst intensity

Coal and gas outburst intensity	Classification
Very low risk	0 < CGOPI < 20
Low risk	20 < CGOPI < 40
Moderate risk	40 < CGOPI < 60
High risk	60 < CGOPI < 80
Very high risk	80 < CGOPI < 100

In this study, the CGOPI value for the C1 coal seam of Tabas coal mine has been obtained 60.

Evaluation of the index performance

To validate the proposed index for coal and gas outburst, the events of outburst in the Tabas coal mine has been studied. Outburst occurrence in Tabas coal mine is difficult to predict but is associated with areas of high gas content and high stress and may be exacerbated by zones of increased joint intensity (Anon 2005). The first outburst occurred in the Tabas coal mine in 2015. However, after that, many events of outburst incident has happened during entries development and caused the stop of excavation operation for some hours, the continuous miner backward and one man loss of life.

Moreover, during the panel extraction, many outburst incidents have happened. Figure 17 shows a summary outburst incident that has occurred in the E3 Panel in the Tabas coal mine. The gas associated with the outburst measured approximately 1200 m³, with the majority being related to zones of strike-slip faulting. It should be noted that outburst events have been related to geological structures and have occurred in areas where no substantial gas drainage has been undertaken.

These events of outburst incidents show that the risk of outburst is moderate and high in the Tabas coal mine.

Therefore, these events confirm the value of the proposed CGOP index (60), which is calculated using the FRES method.

Conclusions

In this study, a novel method is proposed to predict the possibility of coal and gas outburst. Therefore, after the preliminary studies, the most determining parameters (10 parameters) affecting the coal and gas outburst were selected. In the CGOPI approach, coal and gas outburst classification is based on a fuzzy rock engineering system. Accordingly, the interaction matrix is formed using the fuzzy system based on the experts' judgments and their viewpoints with regard to the fuzzy rules. Then, the cause-effect diagram is designed employing the cause and effect value of the parameters. By calculating the coefficient weights of each parameter and the sum of multiplying them by the values assigned to each input parameter, the prediction index for the possibility of coal and gas outburst was calculated. Based on the new approach, the following conclusions have been made.

- The results from the cause-effect diagram prove that the geological structure, in-situ stress, coal permeability, and gas content parameters have the most significant impact on the gas and coal outburst incident.
- The application of the new approach in the Tabas coal mine signified that the C1 seam is at high risk.

The offered method based on the fuzzy RES is suitable and provides a reliable result for the prediction of coal and gas outburst in coal seams.

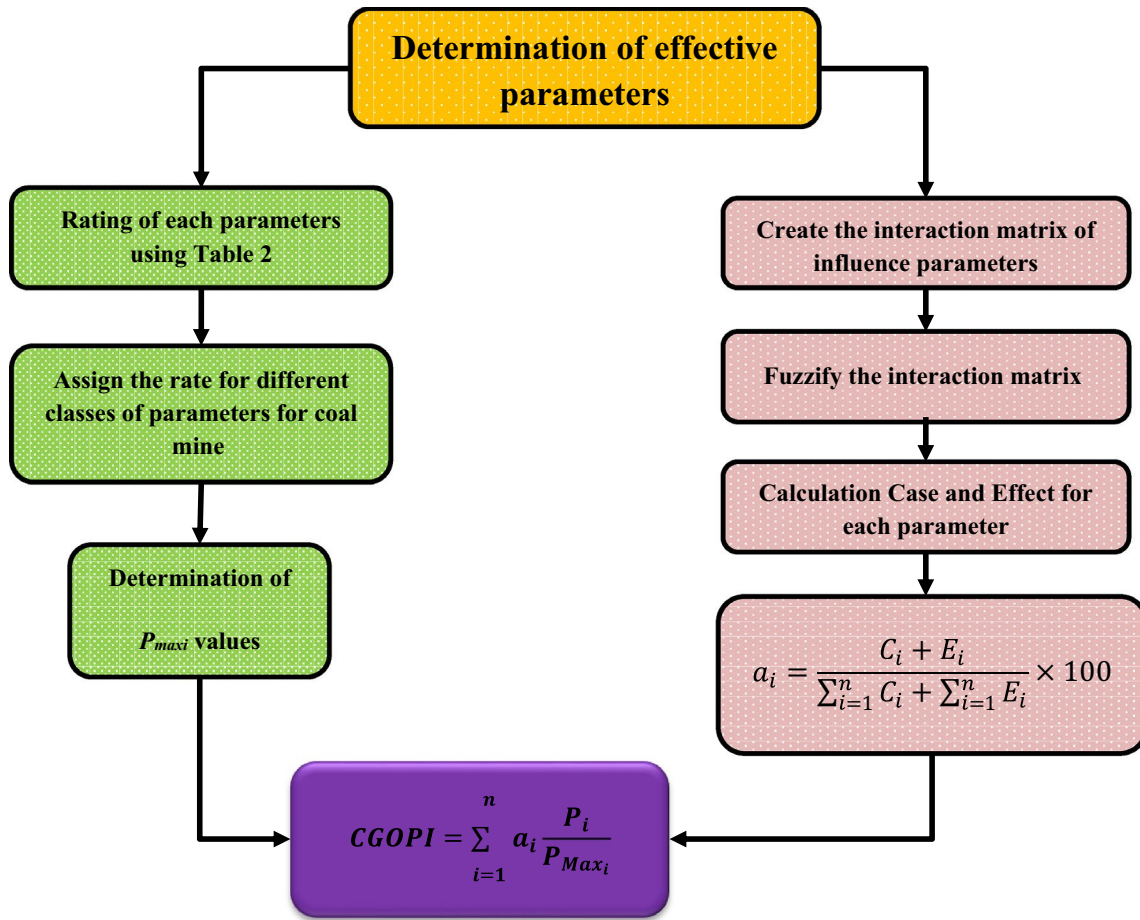


Fig. 16 Flowchart in prediction CGOPI using FRES

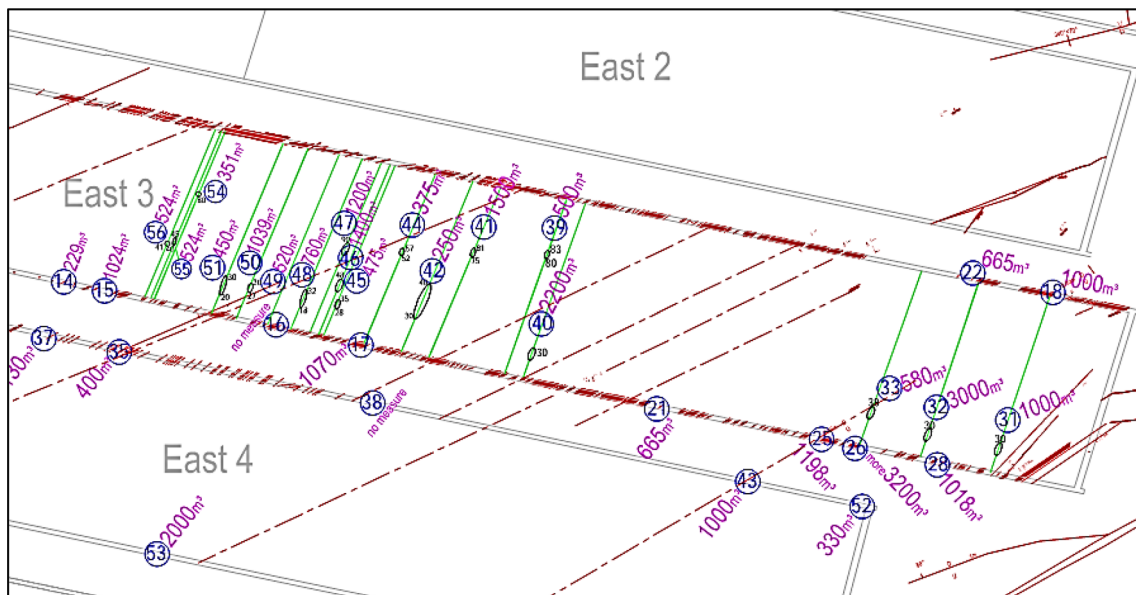


Fig. 17 Summary outburst in E3 Panel of Tabas coal mine (Tabas Coal Mine 2019)

Declarations

Conflict of interest The authors declare that there is no conflict of interest.

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