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Presenting an engineering classification system for coal spontaneous combustion potential

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Abstract The phenomenon of coal spontaneous combustion is one of the common hazards in coal mines and also one of the important reasons for the loss of coal in piles and mines. Based on previous researches, different types of coals have different spontaneous combustion characteristics. For coal loss prevention, a measure is necessary for prediction of coal spontaneous combustion. In this study, a new engineering classification system called ‘‘Coal Spontaneous Combustion Potential Index (CSCPI)’’ is presented based on the Fuzzy Delphi Analytic Hierarchy Process (FDAHP) approach. CSCPI classifies coals based on their spontaneous combustion capability. After recognition of the roles of the effective parameters influencing the initiation of a spontaneous combustion, a series of intrinsic, geological, and mining characteristics of coal seams are investigated. Then, the main stages of the implementation of the FDAHP method are studied and the weight of each parameter involved is calculated. A classification list of each parameter is formed, the CSCPI system is described, and the engineering classifying system is subsequently presented. In the CSCPI system, each coal seam can be rated by a number from 0 to 100; a higher number implies a greater ease for the coal spontaneous combustion capability. Based on the CSCPI system, the propensity of spontaneous combustion of coal can be classified into three potential levels: low, medium, and high. Finally, using the events of coal spontaneous combustion occurring in one of the Iranian coal mines, Eastern Alborz Coal Mines, an initial validation of the mentioned systematic approach is conducted. Comparison of the results obtained in this study illustrate a relatively good agreement.

Keywords Coal · Classification · Coal Spontaneous Combustion Potential Index (CSCPI) · Fuzzy Delphi Analytic Hierarchy Process (FDAHP) · Eastern Alborz Coal Mines

1 Introduction

Coal mining is a very intricate system and process. The rough working conditions and the hazardous environment are the most important factors that affect a coal mining process.

The hazards of underground mining are critical factors, which should be considered in the design and planning step of coal mines. Some significant hazards in underground coal mining can be summarized as subsidence, outburst, and spontaneous combustion. Therefore, it is necessary to accurately identify the risks involved and to find the ways to forecast, prevent, and control them.

Coal is a combustible material, which is applicable to a variety of oxidation scenarios with conditions ranging from the atmospheric temperature to the ignition temperature. One of the most frequent and serious causes of coal fires is spontaneous combustion or self-heating.

Spontaneous combustion is an oxidation reaction that occurs without an external heat source. This process changes the internal heat profile of the material, leading to

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a rise in the temperature. This can eventually lead to an open flame and burning of the material (Akgun and Arisoy 1994; Carras and Young 1994; Ren et al. 1999; Nugroho et al. 2000a; Wang et al. 2003; Smith and Glasser 2005; Beamish and Arisoy 2008b).

Oxidation of coal starts with exothermic chemical reactions, and it can be described as a process including three sequential steps. These steps are as what follow (Mohalik et al. 2009; Yuan and Smith 2012):

(1) Physical adsorption of oxygen on the coal surface;
(2) Chemical absorption (chemisorption), which leads to the formation of coal-oxygen complexes and oxygenated carbon-species;
(3) Chemical reaction.

The chemical reaction (step 3) breaks down the less stable coal-oxygen complexes, and results in the formation of gaseous products, typically carbon monoxide (CO), carbon dioxide (CO_2), and water vapor (H_2O).

Wang et al. (2003) also agreed that coal oxidation is a complicated process involving four phenomena (see Fig. 1), namely:

(1) Oxygen transport to the surfaces of coal particles;
(2) Oxygen transport within coal pores;
(3) Chemical interaction between coal and O_2;
(4) Release of heat and emission of gaseous products.

The inspection of events is a useful part of the risk assessment process in that it provides some information of the noxious impacts of spontaneous combustion, which include:

(1) Mortality of personnel;
(2) Psychic perturbations in survivors of calamity;
(3) Pollution of the air, water, and soil in the vicinity of the burning coal field; this is a hazard to the ecosystem of the region;
(4) Emissions from coal spontaneous combustion not only pollute the local atmosphere but also add substantial amounts of the greenhouse gases (CO_2 and CH_4) along with SO_x, NO_x, H_2S, and CO;
(5) Subsidence of land surface;
(6) Climate change and its contribution to global warming;
(7) Mine closures;
(8) Loss of equipment;
(9) Loss of production;
(10) Useless loss of a non-renewable energy resource;
(11) Loss of popularity and market position;
(12) Costs of therapeutic and recovery measures.

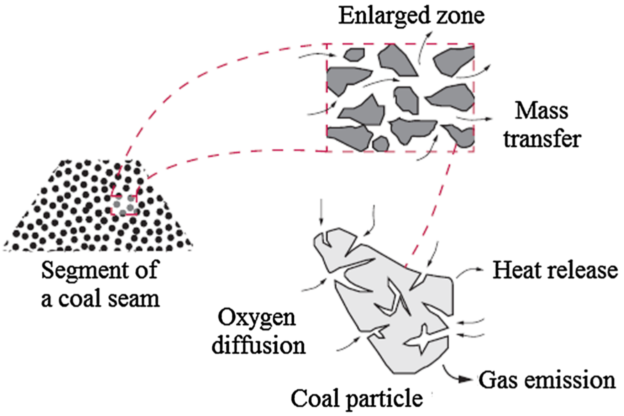


Fig. 1 Fundamental phenomena occurring in coal oxidation process (Wang et al. 2003)

As mentioned earlier, one of the risks that is a substantial amount occurring in the coal mines is ''spontaneous combustion''. Other terminologies of ''Coal Spontaneous Combustion'' are ''Coal Self-burning'', ''Coal Self-heating'' and ''Coal Self-ignition''. Coal spontaneous combustion can occur in underground mines, open pit mines, abandoned mines, coal storage locations, waste dumps, and during transports, especially on ocean-going vessels.

Evaluation of the coal spontaneous combustion hazards in coal mines should start in the first stage of design and carry on during their whole lifecycle, even after mine closure because the coal spontaneous combustion risks still remain as safety, economic, and environmental issues (Michaylov 2002).

In order to evaluate the spontaneous combustion capability of each coal seam, the effects of the important parameters involved should be recognized. The factors that appear to have an influence on the development of a spontaneous combustion event include, but are not limited to, pyrite content, ash content, humidity, coal rank, etc. These effective parameters that have specific effects on the spontaneous combustion phenomenon have different impacts from one to another. For this purpose, it is very important to know the qualitative and quantitative impacts of each parameter. The best method for surveying the coal spontaneous combustion capability is using a classification system based on the above-mentioned factors.

So far, many studies, mentioned in Table 1, have been carried out about intrinsic, geological, and mining characteristics of coal which, affecting coal spontaneous combustion, but until now, a comprehensive classification approach considering all the parameters affecting coal spontaneous combustion capability has not been developed. Also through analyzing the historical records of coal mine fires, it can be seen that the hazards of coal spontaneous combustion are influenced not only by the intrinsic characteristics of coal but also by a multiplicity of factors like geological and mining characteristics. To modify the traditional idea, the prediction of coal spontaneous

Table 1 The most famous and important studies with their used parameters

References	R	P	Mo	A	PS	GC	MSE	EM	AR	DS
Kuchta et al. (1980)	●									
Banerjee (1985)			●		●					
Ghosh (1986)		●								
Mitchell (1990)							●			
Arisoy and Akgun (1994)			●							
Bhat and Agarwal (1996)			●							
Ren et al. (1999)			●		●					
Sujanti and Zhang 1999	●				●					
Sujanti et al. (1999)	●				●	●				
Nugroho et al. (2000a, b)					●					
Jones (2001)			●							
Kadioğlu and Varamarz (2003)			●							
Kucuk et al. (2003)			●		●					
Beamish (2005)	●									
Beamish and Blazak (2005)				●						
Beamish and Jabouri (2005)						●				
Beamish et al. (2005)	●			●						
Ren et al. (2005)								●		
Cao et al. (2007)										●
Nelson and Chen (2007)	●	●								
Ramlu (2007)						●				
Singh et al. (2007)	●	●	●							
Beamish and Arisoy (2008a)	●			●						
Beamish and Sainsbury (2008)				●						
Beamish and Schultz (2008)			●							
Bo-tao et al. (2009)	●								●	
Beamish and Beamish (2010)			●							
Beamish and Beamish (2011)			●							
Beamish and Beamish (2012)			●							
Beamish et al. (2012)		●								
Beamish et al. (2013)	●									
Sasaki et al. (2014)	●		●							
Arisoy and Beamish (2015)		●	●							
Deng et al. (2015)		●								

R rank, *P* pyrite, *Mo* moisture, *A* ash, *PS* particle size, *GC* gas content, *MSE* multi-seam extraction, *EM* extraction method, *AR* advanced rate, *DS* deep seam

combustion should not be based on the unilateral identification of coal spontaneous combustion tendency, but on a comprehensive hazard evaluation system, which contains different factors and complicated interactions.

In this paper, according to a review of all the latest studies on the coal spontaneous combustion subject, the important, effective, and applicable parameters were identified and selected. It requires effort to make a comprehensive classification system that is an intelligent method for evaluation of coal spontaneous combustion potential in underground coal mines, especially mines extracted by the long wall method mining.

The most important step involved in providing a comprehensive classification system for evaluation of a phenomenon with a certain number of parameters is the determination of the weight of each parameter. The illustrious methods used for weighting parameters include the multi-criteria decision-making (MCDM) methods, rock engineering system (RES) method, and experimental-comparison method.

MCDM deals with the problem of helping the decision-maker to choose the best alternative according to several criteria (Chen and Klein 1997; Valls and Torra 2000).

Due to the fact that, depending on the problem, decision makers use different types of criteria (e.g. numerical, qualitative or stochastic values), different specializations of these methods have been developed in order to deal with these types of values (Valls and Torra 2000).

One of the newest processes used for weighting parameters in the MCDM methods is Fuzzy Delphi Analytic Hierarchy Process (FDAHP). The main objective of this paper is to present a new system for evaluating the factors affecting the coal spontaneous combustion capability using FDAHP. In this process, the opinions and experiences of a large number of experts are used, and thus it has a high efficiency. In this paper, according to the ability and reputation of FDAHP to determine the significance of each parameter in influencing the hazards and weighting parameters in the classification system, it is being used. This research work considers the coal spontaneous combustion classification as a group decision problem and applies the fuzzy logic theory as the tool for weighting calculations. Finally, a new classification system named ''Coal Spontaneous Combustion Potential Index (CSCPI)'' is presented.

2 Fuzzy Delphi Analytic Hierarchy Process (FDAHP)

Analytic hierarchy process (AHP) is a multiple-criteria decision-making (MCDM) technique that is suitable to deal with complex systems related to making a choice among several alternatives, and provides a comparison of the considered option, firstly proposed by Saaty (1980). It is a tool used to combine the qualitative and quantitative factors in the selection of a process, and is used for setting priorities in a complex, unanticipated, multi-criteria, and problematic situation. As Saaty has stated ''AHP is a measurement theory that prioritizes the consistency of the judgmental data provided by a group of decision-makers''. Furthermore, AHP provides a flexible and easy way to understand the analysis of complicated problems (Saaty 1980, 1990). The main advantage of AHP is its ability to handle complex and ill-structured problems that cannot be usually handled by rigorous mathematical models. AHP incorporates the evaluations of all decision-makers into a final decision without having to elicit their utility functions on subjective and objective criteria by pairwise comparisons of the alternatives (Saaty 1980).

The traditional AHP method is problematic in that it uses an exact value for the decision-maker's opinion in a

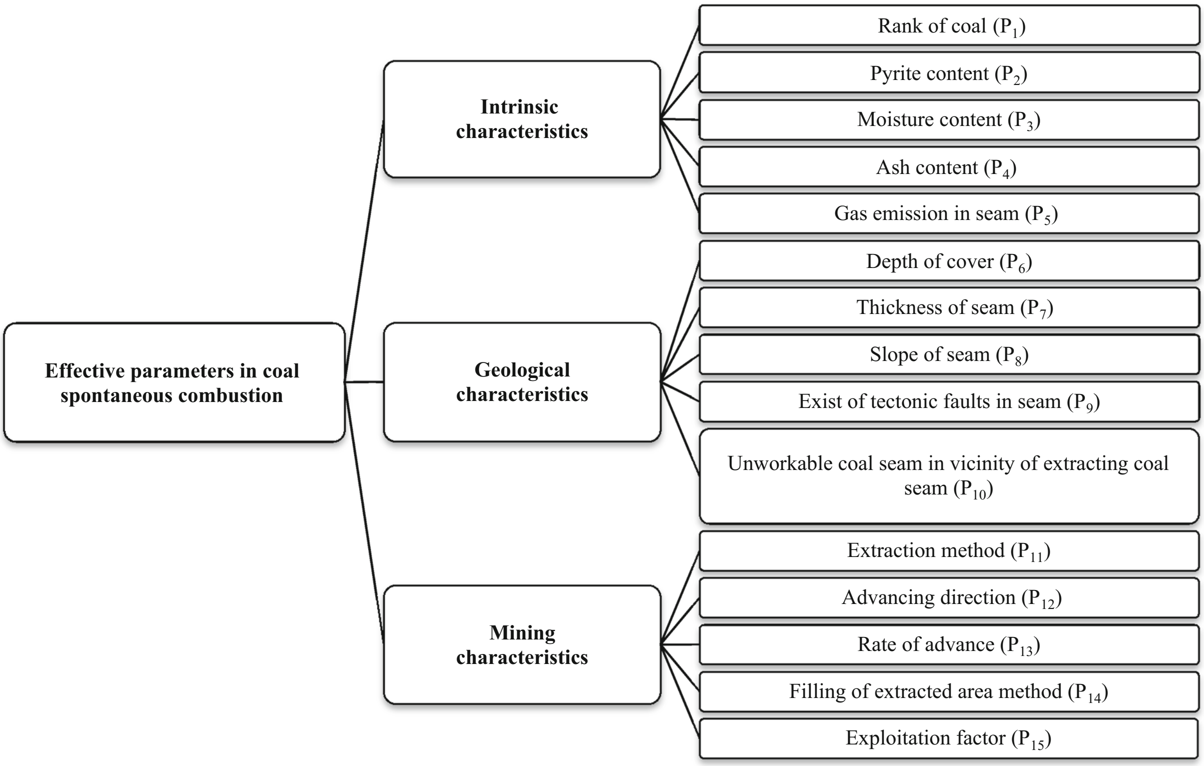


Fig. 2 Important characteristics influencing coal spontaneous combustion

Table 2 Fundamental scale of absolute numbers (Saaty 1980)

Intensity of importance	Definition
1	Equal importance
3	Moderate importance
5	Strong importance
7	Very strong importance
9	Extreme importance
2, 4, 6, 8	Preferences between above intervals

comparison of alternatives (Wang and Chen 2007). The AHP method is often criticized for the use of unbalanced scale of judgments and its inability to adequately handle the inherent uncertainty and imprecision in the pairwise comparison process (Deng 1999). To overcome all these shortcomings, FDAHP was developed for solving the hierarchical problems. Decision-makers usually find that it is more confident to give interval judgments than fixed value judgments.

The Delphi method is a technique used for structuring an effective group communication process by providing feedback of contributions of information and assessment of group judgments to enable individuals to re-evaluate their judgments. Since its development in the 1960s at Rand Corporation, the Delphi method has been widely used in various fields (Hoseinie et al. 2009; Mikaeil et al. 2013; Soltanmohammad et al. 2013).

On the other hand, the Delphi method uses the crisp number and a mean to become the evaluation criterion; these shortcomings might distort the experts' opinion. In order to deal with the fuzziness of human participants'

Table 3 A sample of questionnaire form main characteristics

No.	Main characteristics	Importance of each parameter				
		VW (1)	W (3)	M (5)	S (7)	VS (9)
1	Intrinsic characteristics					
2	Geological characteristics					
3	Mining characteristics					

VW very weak importance, *W* weak importance, *M* moderate importance, *S* strong importance, *VS* very strong importance

Table 4 A sample of questionnaire form intrinsic characteristics

No.	Intrinsic characteristics	Importance of each parameter				
		VW (1)	W (3)	M (5)	S (7)	VS (9)
1	Rank of coal					
2	Pyrite content (%)					
3	Moisture content (%)					
4	Ash content (%)'					
5	Gas emission in seam (ton/m^3)					

VW very weak importance, *W* weak importance, *M* moderate importance, *S* strong importance, *VS* very strong importance

Table 5 A sample of questionnaire form geological characteristics

No.	Geological characteristics	Importance of each parameter				
		VW (1)	W (3)	M (5)	S (7)	VS (9)
1	Depth of cover					
2	Thickness of seam					
3	Slope of seam					
4	Exist of tectonic faults in seam					
5	Unworkable coal seam in vicinity of extracting coal seam					

VW very weak importance, *W* weak importance, *M* moderate importance, *S* strong importance, *VS* very strong importance

Table 6 A sample of questionnaire form mining characteristics

No.	Mining characteristics	Importance of each parameter				
		VW (1)	W (3)	M (5)	S (7)	VS (9)
1	Extraction method					
2	Advancing direction					
3	Rate of advance					
4	Filling of extracted area method					
5	Exploitation factor					

VW Very Weak importance, *W* Weak importance, *M* Moderate importance, *S* Strong importance, *VS* Very Strong importance

Table 7 Experts' responses for main characteristics

Experts	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Experts' responses for main characteristics															
Intrinsic characteristics	9	7	9	9	9	7	9	9	5	9	9	9	7	9	9
Geological characteristics	5	7	7	9	5	7	5	5	7	9	7	5	5	5	3
Mining characteristics	7	5	5	7	9	7	7	7	7	7	9	7	7	7	7

Table 8 Experts' responses for intrinsic characteristics

Experts	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Experts' responses for intrinsic characteristics															
Rank of coal	9	7	9	9	9	9	9	7	7	9	7	7	7	7	9
Pyrite content	9	9	7	7	7	9	9	9	5	9	7	7	5	9	7
Moisture content	7	7	7	9	9	5	5	7	7	5	9	7	5	9	7
Ash content	7	7	7	9	7	5	5	5	7	5	5	7	5	9	5
Gas emission in seam	9	7	7	9	9	9	9	7	9	7	7	7	5	9	5

Table 9 Experts' responses for geological characteristics

Experts	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Experts' responses for geological characteristics															
Depth of cover	9	7	9	9	7	7	9	9	9	9	7	7	9	9	7
Thickness of seam	3	7	5	5	7	3	7	7	7	5	5	7	3	7	7
Slope of seam	3	5	5	5	5	1	5	1	5	1	5	3	3	5	1
Exist of tectonic faults in seam	7	9	5	9	5	5	9	7	9	7	7	5	5	7	9
Unworkable coal seam in vicinity of extracting coal seam	3	3	5	9	9	7	7	3	7	3	7	7	5	9	5

Table 10 Experts' responses for mining characteristics

Experts	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Experts' responses for mining characteristics															
Extraction method	9	7	7	9	9	7	9	7	7	9	7	9	7	9	9
Advancing direction	7	7	5	9	7	9	7	9	7	5	7	7	5	5	7
Rate of advance	7	7	9	9	7	9	9	7	7	7	7	7	7	7	7
Filling of extracted area method	7	7	5	9	9	7	7	7	7	7	9	7	7	7	7
Exploitation factor	7	7	7	9	7	7	7	7	7	7	7	5	7	7	7

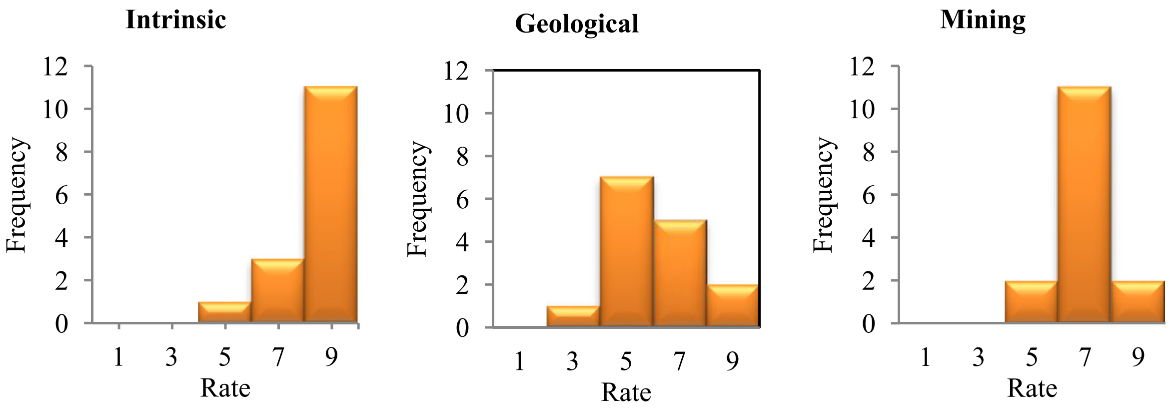


Fig. 3 Histograms of opinions of experts about main characteristics

judgments in the traditional Delphi method, Ishikawa et al. (1993) positioned ''fuzzy set theory'' proposed by Zadeh (1965, 1999) into the Delphi method to improve the time-consuming problems such as the convergence of the experts' options presented by Hwang and Lin (1987). The fuzzy Delphi method (FDM) is a methodology in which the subjective data of the experts is transformed into the quasi-objective data using the statistical analysis and fuzzy operations (Liu and Chen 2007a, b). The main advantages of FDM are that it can reduce the number of surveys to save time and cost, and it also includes the individual attributes of all experts (Kaufmann and Gupta 1988; Liu and Chen 2007a, b; Hoseinie et al. 2009). Thus it can effectively determine the weighting of each parameter.

It is known that group decision-making is a very important and powerful tool to accelerate the consensus of various opinions from the experts who are experienced in practices (Liu and Chen 2007a, b; Hoseinie et al. 2009). In this paper, FDM has been used to combine the opinions of experts. The main steps of the FDAHP method has been described in Sect. 3.1 with solving the problem in this research work.

The ultimate weights of each characteristic is obtained by multiplying the weight underhand characteristics in the weight overhand characteristics listed in Table 19 and shown in Fig. 8.

3 Methodology

3.1 Development of Fuzzy Delphi Analytic Hierarchy Process (FDAHP) method application for classification of coal spontaneous combustion potential

In order to develop a new classification for assessing the coal spontaneous combustion capability, five main steps must be taken into account as what follow.

3.1.1 Selection of most important parameters affecting coal spontaneous combustion potential (review of previous studies)

In the first step, identification of the parameters responsible for the occurrence of risks in the case of coal spontaneous combustion is necessary. According to the available literature and studies on the coal spontaneous combustion subject, a total of 15 important and influential parameters

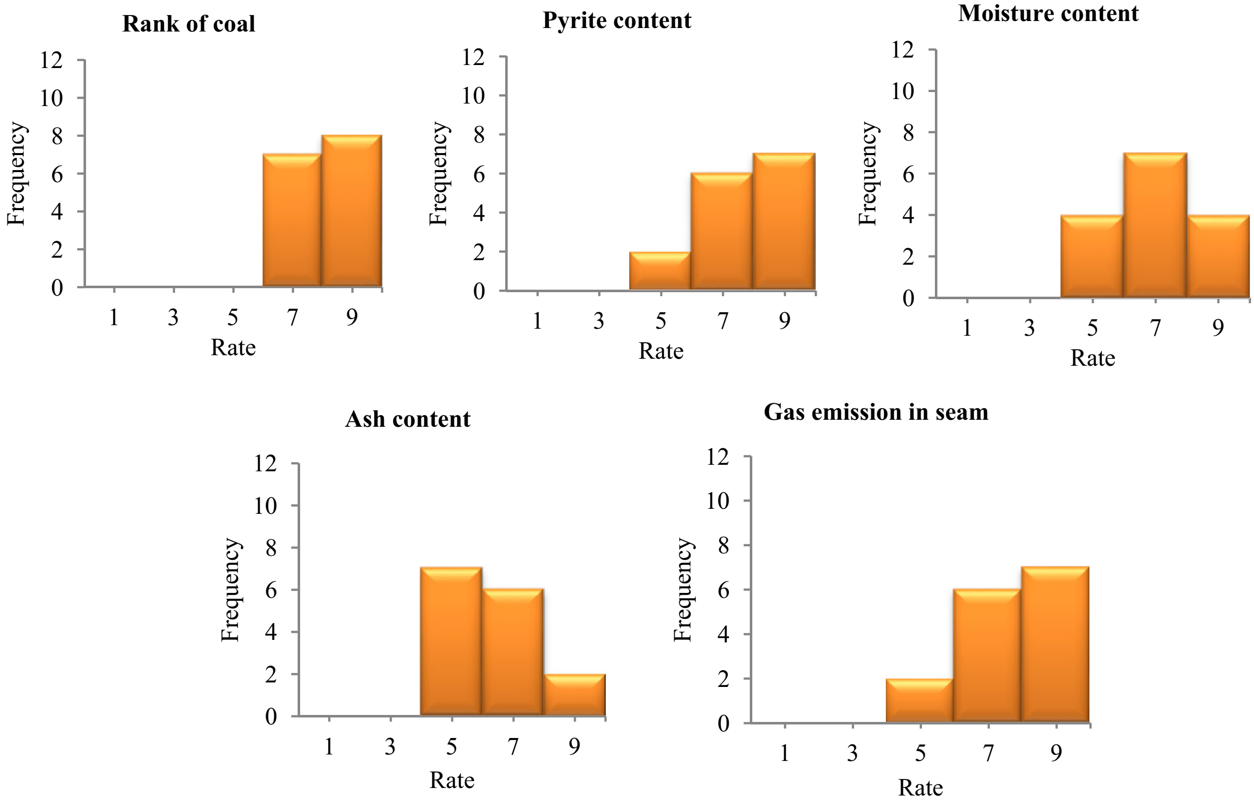


Fig. 4 Histograms of opinions of experts about intrinsic characteristics

were identified for the coal spontaneous combustion potential and classification, listed in Fig. 2.

Generally speaking, the important characteristics that influence the coal spontaneous combustion capability can be classified into three major categories: intrinsic, geological, and mining characteristics. Finally, as a result of this preview, all the mentioned parameters were selected for use in the FDAHP evaluation system and development of the CSCPI classification.

On the development of a new classification system, 3 basic principles were taken into consideration:

(1) The minimum number of parameters was used for classification.
(2) Utilization of the parallel and overlapping parameters was avoided.
(3) Using the parameters that did not have measurement abilities was avoided.

3.1.2 *Sending questionnaire to experts and experts' responses*

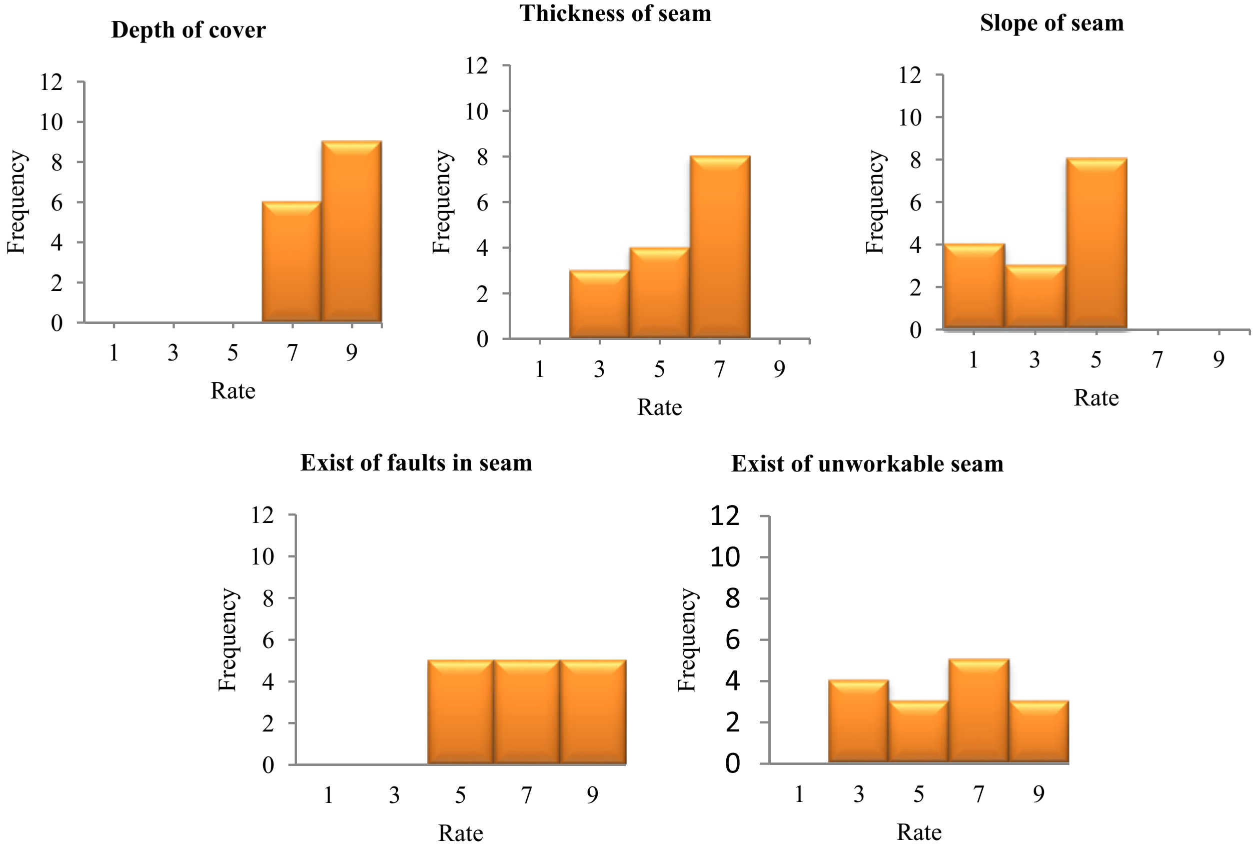
In the second step, after identification of the parameters affecting the coal spontaneous combustion, in order to use the FDAHP method and determine the weight of each parameter, technical questionnaires were prepared and sent to the experts. They were asked to mark in the questionnaires the importance of each parameter by Likert 5 point scale. In order to use the questionnaire data in the FDAHP method, for each important level, an intensity number from 1 to 9 was assigned (Table 2) based on the Saaty's method (Saaty 1980); questionnaire forms are shown in Tables 3, 4, 5, 6. The experts' responses (completed questionnaires) are shown in Tables 7, 8, 9 10. These opinions were used for the input FDAHP method.

The experts' opinion histograms (rates) about each parameter are illustrated in Figs. 3, 4, 5, 6. As it can be seen, the intrinsic characteristics have the highest frequency of rate 9. It shows that they are the most important characteristics of coal spontaneous combustion potential from the viewpoint of the experts' opinions.

3.1.3 *Calculation of relative fuzzy weights of parameters*

In the third step, relative fuzzy weights of parameters are calculated. The main steps are described as following.

3.1.3.1 Establishment of pairwise comparison matrices In order to establish the main pairwise comparison matrix using the FDAHP method, it is necessary to have the comparison matrix of the parameters based on each


Depth of cover

Thickness of seam

Slope of seam

Exist of faults in seam

Exist of unworkable seam

Fig. 5 Histograms of opinions of experts about geological characteristics

expert's opinion. For this purpose, according to the questionnaire, 4 comparison matrices were established for each expert (matrices 1, 2, 3, and 4 for main, intrinsic, geological, and mining characteristics, respectively; totally 60 comparison matrices).

Let C_1, C_2, …, C_n denote the set of elements, while a_{ij} represents a quantified judgment on a pair of elements C_i and C_j. The relative importance of two elements is obtained from the division rate of C_i on C_j based on the questionnaire. This yields an $n \times n$ matrix $\boldsymbol{A}$, as in Eq. (1) (Hoseinie et al. 2009):

$$\boldsymbol{A} = [a_{ij}] = \begin{array}{c} \\ C_1 \\ C_2 \\ \vdots \\ C_n \end{array} \begin{array}{c} \begin{array}{cccc} C_1 & C_2, & \ldots, & C_n \end{array} \\ \begin{bmatrix} 1 & a_{12} & \cdots & a_{1n} \\ 1/a_{12} & 1 & \cdots & a_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ 1/a_{1n} & 1/a_{2n} & \cdots & 1 \end{bmatrix} \end{array} \tag{1}$$

In this research work, there were four group characteristics (main, intrinsic, geological, and mining characteristics with 3, 5, 5, and 5 elements, respectively) and 15 experts. Therefore, there were fifteen 3×3, fifteen 5×5, fifteen 5×5, and fifteen 5×5 pairwise comparison matrices for the main, intrinsic, geological, and mining characteristics, respectively. Due to very high calculations, their details are avoided. The matrices were established for the following calculations.

3.1.3.2 Establishment of major pairwise comparison matrix For establishing the major pairwise comparison matrix in the FDAHP method and calculation of the relative fuzzy weights of the decision elements, three steps should be done, as follow (Liu and Chen 2007a, b; Hoseinie et al. 2009):

(a) Computation of triangular fuzzy numbers (TFNs); $\tilde{a}_{ij}$. In this work, the TFNs (as shown in Fig. 7 and Eq. (2)), which represent the pessimistic, moderate, and optimistic estimates were used to represent the opinions of the experts about each parameter.

$$\tilde{a}_{ij} = (\alpha_{ij}, \delta_{ij}, \gamma_{ij}) \tag{2}$$

$$\alpha_{ij} = \mathrm{Min}(\beta_{ijk}), \quad k = 1, 2, \ldots, \lambda \tag{3}$$

$$\delta_{ij} = \left(\prod_{k=1}^{\lambda} \beta_{ijk} \right)^{1/k}, \quad k = 1, 2, \ldots, \lambda \tag{4}$$

$$\gamma_{ij} = \mathrm{Max}(\beta_{ijk}), \quad k = 1, 2, \ldots, \lambda \tag{5}$$

where, $\alpha_{ij} \le \delta_{ij} \le \gamma_{ij}, \alpha_{ij}, \delta_{ij}, \gamma_{ij} \subseteq [1/9, 1] \cup [1, 9]$ (obtained from Eqs. (3)–(5); α_{ij} indicates the lower

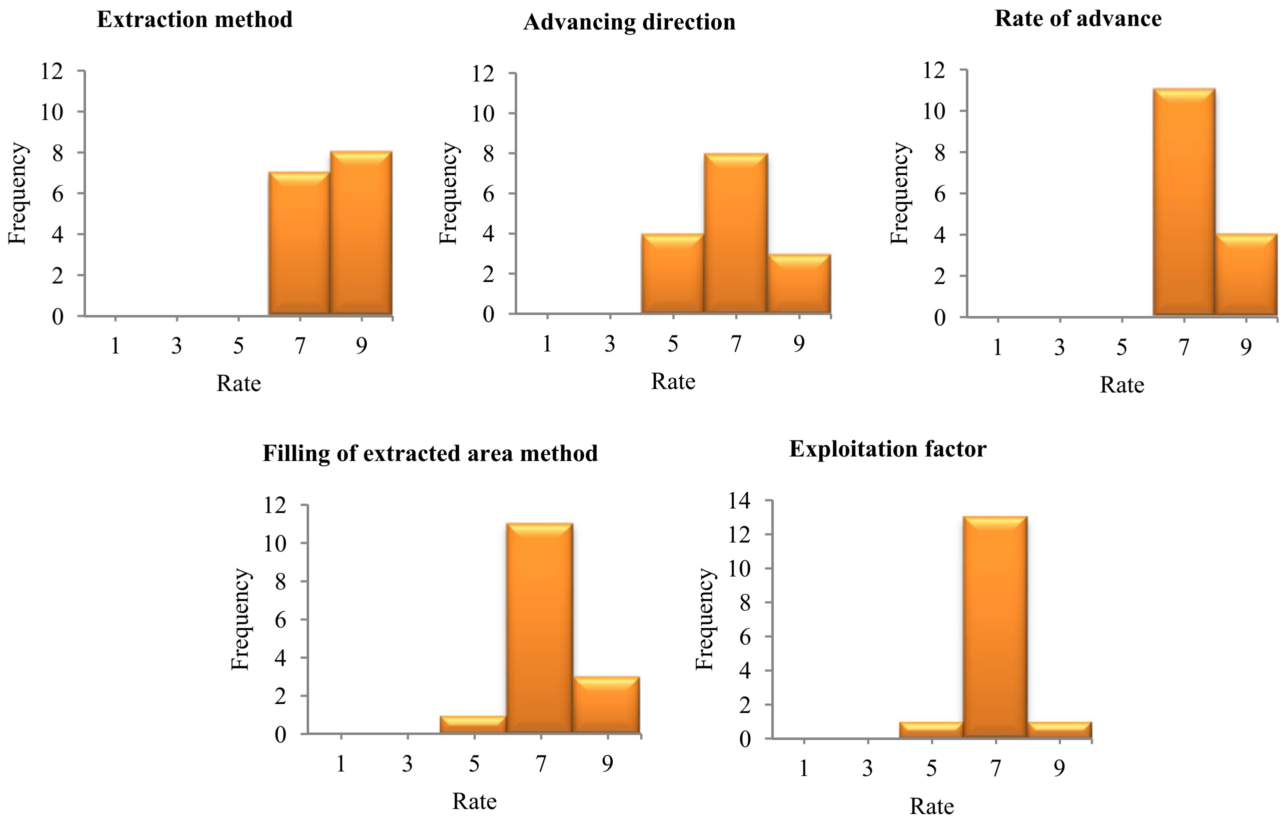


Fig. 6 Histograms of opinions of experts about mining characteristics

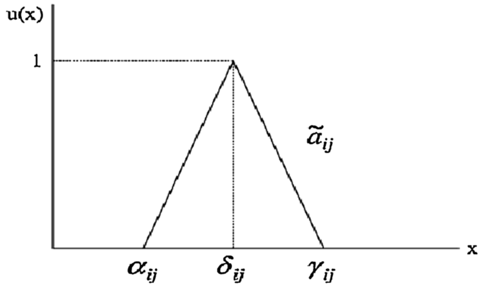


Fig. 7 Membership function of fuzzy Delphi method

bound, γ_{ij} indicates the upper bound, β_{ijk} indicates the relative intensity of importance of expert k between parameters i and j, and λ is the number of experts in the decision-making.

b) Following the above outlines, a fuzzy positive reciprocal matrix $\tilde{\boldsymbol{A}}$ can be calculated as Eq. (6):

$$\tilde{A}=[\tilde{a}_{ij}],\ \ \tilde{a}_{ij}\times\tilde{a}_{ji}\approx 1,\ \ \forall i,j=1,2,\ldots n$$

or

$$\tilde{A}=\begin{bmatrix}(1,1,1) & (\alpha_{12},\delta_{12},\gamma_{12}) & (\alpha_{13},\delta_{13},\gamma_{13})\\ (1/\gamma_{12},1/\delta_{12},1/\alpha_{12}) & (1,1,1) & (\alpha_{23},\delta_{23},\gamma_{23})\\ (1/\gamma_{13},1/\delta_{13},1/\alpha_{13}) & (1/\gamma_{23},1/\delta_{23},1/\alpha_{23}) & (1,1,1)\end{bmatrix} \tag{6}$$

(c) Calculation of relative fuzzy weights of the evaluation factors according to Eq. (7):

$$\tilde{\boldsymbol{Z}}_i=\left[\tilde{a}_{ij}\otimes\cdots\otimes\tilde{a}_{in}\right]^{1/n},$$
$$\tilde{\boldsymbol{W}}_i=\tilde{Z}_i\otimes(\tilde{Z}_i\oplus\cdots\oplus\tilde{Z}_n)^{-1}$$

where $\tilde{a}_1\otimes\tilde{a}_2=(\alpha_1\times\alpha_2,\delta_1\times\delta_2,\gamma_1\times\gamma_2)$; the symbol $\otimes$ here denotes the multiplication of fuzzy numbers, and the symbol $\oplus$ denotes the addition of fuzzy numbers. $\tilde{\boldsymbol{W}}_i$ is a row vector in consist of a fuzzy weight of the ith factor($\tilde{\boldsymbol{W}}_i=(\omega_1,\omega_2,\cdots,$

Table 11 Major pairwise comparison matrix between 3 main characteristics

Item	Intrinsic characteristics (IC)	Geological characteristics (GC)	Mining characteristics (MC)
IC	(1.000, 1.000, 1.000)	(0.714, 1.408, 3.000)	(0.714, 1.189, 1.800)
GC	(0.333, 0.710, 1.400)	(1.000, 1.000, 1.000)	(0.429, 0.845, 1.400)
MC	(0.556, 0.841, 1.400)	(0.714, 1.184, 2.333)	(1.000, 1.000, 1.000)

$\omega_n), i = 1, 2, \cdots, n)$. The defuzzification (changing the fuzzy number to a usual number) is based on the geometric average method (Eq. (8)):

$$W_i = \left(\prod_{i=1}^{3} \omega_j \right)^{1/3} \tag{8}$$

In this research work, 4 major pairwise comparison matrices, as shown in Tables 11, 13, 15, and 17, and the fuzzy and usual final weight of each group, as shown in Tables 12, 14, 16, and 18, were established by the procedure described.

Table 19 and Fig. 8 show that the parameters rank of coal, gas emission in seam, pyrite content, depth of cover, moisture content, extraction method, rate of advance, and filling of extracted area method have the highest weights in the system, and so a small change in these parameters will affect, to a considerable extent, the behavior of the system.

3.1.4 *Classification and rating of parameters*

In the fourth step, the rating of the parameter values was carried out based upon their effects on the coal spontaneous combustion. Totally, six classes of rating, from 0 to 5, were considered, where 0 shows the best case (most favorable condition) and the maximum value that indicates the worst position (most unfavorable condition).

In the case of coal spontaneous combustion, the rating of each parameter is presented in Table 20. The ranges of parameters in Table 20 were proposed based on the results obtained by other researchers (mentioned in Table 1).

Table 12 Fuzzy and usual final weight of 3 main characteristics

Item	$\tilde{\boldsymbol{Z}}_i$ (α, δ, γ)	$\tilde{\boldsymbol{W}}_i$ (Fuzzy weight)	Usual weight
Characteristics			
Intrinsic	(0.79906, 1.18732, 1.75441)	(0.1780, 0.3919, 0.8530)	0.3906
Geological	(0.52276, 0.84352, 1.25146)	(0.1164, 0.2785, 0.6085)	0.2704
Mining	(0.73485, 0.99848, 1.48378)	(0.1637, 0.3296, 0.7214)	0.3390
$(\tilde{Z}_i \oplus \cdots \oplus \tilde{Z}_n)^{-1}$	(0.22273, 0.33011, 0.48622)		$\Sigma = 1.000$

Table 13 Major pairwise comparison matrix between 5 intrinsic characteristics

Item	Rank of coal (RC)	Pyrite content (PC)	Moisture content (MC)	Ash content (AC)	Gas emission (GE)
RC	(1.000, 1.000, 1.000)	(0.778, 1.064, 1.400)	(0.778, 1.170, 1.800)	(0.778, 1.294, 1.800)	(0.778, 1.064, 1.800)
PC	(0.714, 0.940, 1.286)	(1.000, 1.000, 1.000)	(0.714, 1.100, 1.800)	(0.714, 1.216, 1.800)	(0.556, 1.000, 1.400)
MC	(0.556, 0.855, 1.286)	(0.556, 0.909, 1.400)	(1.000, 1.000, 1.000)	(1.000, 1.106, 1.800)	(0.556, 0.909, 1.400)
AC	(0.556, 0.773, 1.286)	(0.556, 0.822, 1.400)	(0.556, 0.904, 1.000)	(1.000, 1.000, 1.000)	(0.556, 0.822, 1.000)
GE	(0.556, 0.940, 1.286)	(0.714, 1.000, 1.800)	(0.714, 1.100, 1.800)	(1.000, 1.216, 1.800)	(1.000, 1.000, 1.000)

Table 14 Fuzzy and usual final weight of 5 intrinsic characteristics

Item	$\tilde{\boldsymbol{Z}}_i$ (α, δ, γ)	$\tilde{\boldsymbol{W}}_i$ (Fuzzy weight)	Usual weight
Characteristics			
Rank of coal	(0.81787, 1.11350, 1.52191)	(0.1182, 0.2218, 0.4171)	0.2220
Pyrite content	(0.72656, 1.04696, 1.42286)	(0.1050, 0.2086, 0.3899)	0.2044
moisture Content	(0.70281, 0.95195, 1.35311)	(0.1016, 0.1896, 0.3708)	0.1926
Ash content	(0.62486, 0.86067, 1.12475)	(0.0903, 0.1714, 0.3082)	0.1684
Gas emission	(0.77713, 1.04696, 1.49621)	(0.1123, 0.2086, 0.4100)	0.2126
$(\tilde{Z}_i \oplus \cdots \oplus \tilde{Z}_n)^{-1}$	(0.14453, 0.19920, 0.27403)		$\Sigma = 1.000$

Table 15 Major pairwise comparison matrix between 5 geological characteristics

Item	Depth (D)	Thickness (T)	Slope (S)	Faults (F)	Unworkable seam (US)
D	(1.000, 1.000, 1.000)	(1.000, 1.507, 3.000)	(1.400, 2.769, 9.000)	(0.778, 1.196, 1.800)	(0.778, 1.483, 3.000)
T	(0.333, 0.664, 1.000)	(1.000, 1.000, 1.000)	(1.000, 1.838, 7.000)	(0.429, 0.794, 1.400)	(0.429, 0.984, 2.333)
S	(0.111, 0.361, 0.714)	(0.143, 0.544, 1.000)	(1.000, 1.000, 1.000)	(0.111, 0.432, 1.000)	(0.143, 0.535, 1.667)
F	(0.556, 0.836, 1.286)	(0.714, 1.260, 2.333)	(1.000, 2.315, 9.000)	(1.000, 1.000, 1.000)	(0.556, 1.239, 3.000)
UC	(0.333, 0.675, 1.286)	(0.429, 1.016, 2.333)	(0.600, 1.868, 7.000)	(0.333, 0.807, 1.800)	(1.000, 1.000, 1.000)

Table 16 Fuzzy and usual final weight of 5 geological characteristics

Item	$\tilde{\boldsymbol{Z}}_i$ (α, δ, γ)	$\tilde{\boldsymbol{W}}_i$ (Fuzzy weight)	Usual weight
Characteristics			
Depth	(0.96731, 1.49228, 2.70864)	(0.0959, 0.2829, 0.9150)	0.2928
Thickness	(0.57199, 0.99038, 1.87000)	(0.0567, 0.1877, 0.6317)	0.1895
Slope	(0.19066, 0.53886, 1.03549)	(0.0189, 0.1021, 0.3498)	0.0881
Faults	(0.73904, 1.24749, 2.40822)	(0.0732, 0.2365, 0.8136)	0.2425
Unworkable seam	(0.49112, 1.00656, 2.06775)	(0.0487, 0.1908, 0.6985)	0.1872
$(\tilde{Z}_i \oplus \cdots \oplus \tilde{Z}_n)^{-1}$	(0.09911, 0.18955, 0.33782)		$\Sigma = 1.0000$

Table 17 Major pairwise comparison matrix between 5 mining characteristics

Item	Extraction method (EM)	Advancing direction (AD)	Rate of advance (RA)	Filling method (FM)	Exploitation factor (EF)
EM	(1.000, 1.000, 1.000)	(0.778, 1.189, 1.800)	(0.778, 1.069, 1.286)	(0.778, 1.112, 1.400)	(1.000, 1.150, 1.800)
AD	(0.556, 0.841, 1.286)	(1.000, 1.000, 1.000)	(0.556, 0.899, 1.286)	(0.714, 0.935, 1.286)	(0.714, 0.967, 1.400)
RA	(0.778, 0.935, 1.286)	(0.778, 1.112, 1.800)	(1.000, 1.000, 1.000)	(0.778, 1.040, 1.800)	(1.000, 1.075, 1.400)
FM	(0.714, 0.899, 1.286)	(0.778, 1.070, 1.400)	(0.556, 0.962, 1.286)	(1.000, 1.000, 1.000)	(0.714, 1.034, 1.400)
EF	(0.556, 0.870, 1.000)	(0.714, 1.034, 1.400)	(0.714, 0.930, 1.000)	(0.714, 0.967, 1.400)	(1.000, 1.000, 1.000)

Table 18 Fuzzy and usual final weight of 5 mining characteristics

Characteristics	$\tilde{\boldsymbol{Z}}_i$ (α, δ, γ)	$\tilde{\boldsymbol{W}}_i$ (Fuzzy weight)	Usual weight
Extraction method	(0.86003, 1.10218, 1.42286)	(0.1323, 0.2200, 0.3670)	0.2203
Advancing direction	(0.69094, 0.92662, 1.24369)	(0.1063, 0.1850, 0.3208)	0.1849
Rate of advance	(0.86003, 1.03073, 1.42286)	(0.1323, 0.2058, 0.3670)	0.2155
Filling method	(0.73904, 0.99112, 1.26505)	(0.1137, 0.1979, 0.3263)	0.1944
Exploitation factor	(0.72656, 0.95846, 1.14407)	(0.1118, 0.1913, 0.2951)	0.1849
$(\tilde{Z}_i \oplus \cdots \oplus \tilde{Z}_n)^{-1}$	(0.15388, 0.19964, 0.25796)		$\Sigma = 1.0000$

3.1.5 Definition of CSCPI and vulnerability index ranges

In the fifth step, rating of Coal Spontaneous Combustion Potential index (CSCPI) for each coal seam can be calculated according to Eq. (9) (modified after Hudson 1992).

$$CSCPI_j = \sum_{i=1}^{15} a_i \frac{P_{ij}}{P_{\mathrm{Max}i}} \tag{9}$$

where, i refers to parameters (1 to 15); j refers to number of seams; a_i is the weighting of each parameter (%) (obtained from Table 19); P_{ij} is the rating assigned to different

Table 19 Ultimate weights of characteristics in coal spontaneous combustion potential resulting from FDAHP method

Parameter	Ultimate weight	Ultimate weight (%)
Rank of coal	0.0867	8.67
Pyrite content	0.0798	7.98
Moisture content	0.0752	7.52
Ash content	0.0658	6.58
Gas emission in seam	0.0830	8.30
Depth of cover	0.0792	7.92
Thickness of seam	0.0512	5.12
Slope of seam	0.0238	2.38
Exist of tectonic faults in seam	0.0656	6.56
Unworkable coal seam in vicinity of extracting coal seam	0.0506	5.06
Extraction method	0.0747	7.47
Advancing direction	0.0627	6.27
Rate of advance	0.0730	7.30
Filling of extracted area method	0.0659	6.59
Exploitation factor	0.0627	6.27

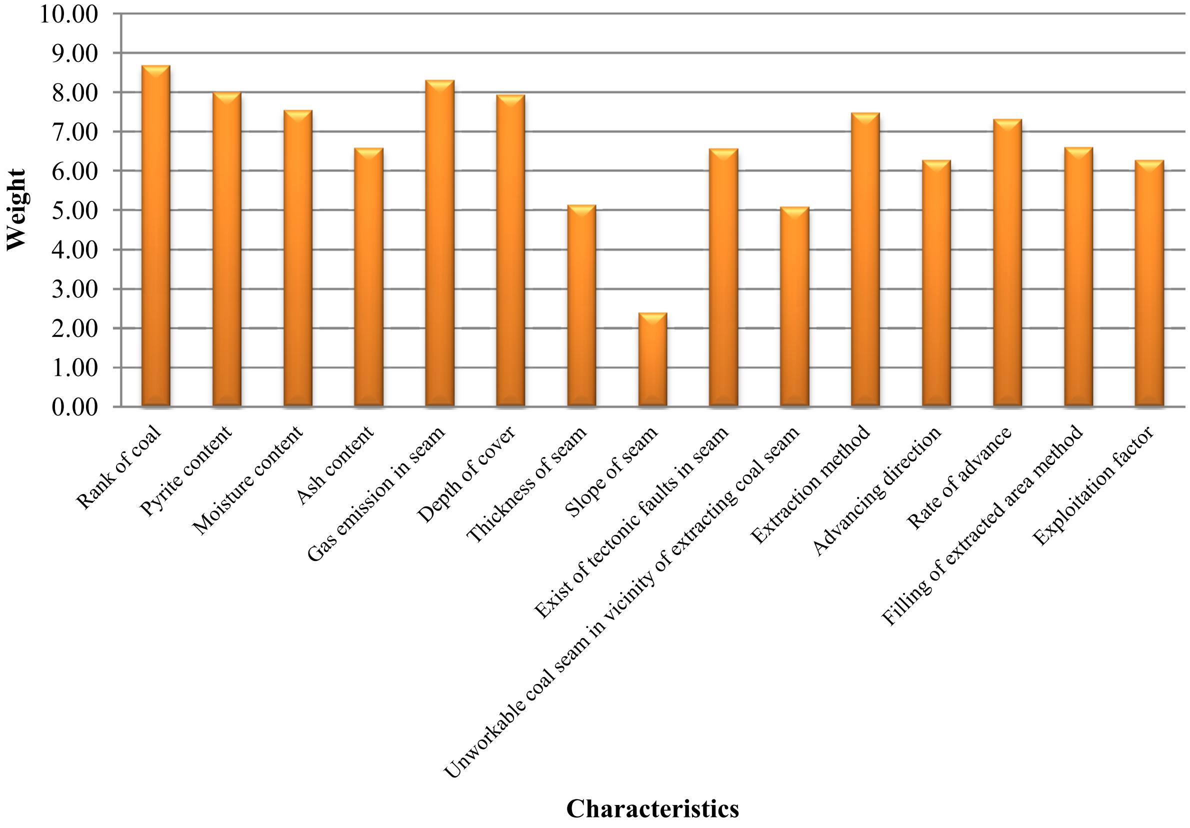


Fig. 8 Histogram ultimate weights of characteristics in coal spontaneous combustion potential resulting from FDAHP method

Table 20 Proposed ranges and ratings for effective parameters in coal spontaneous combustion

Parameter	Suggested ranges and ratings					
	0	1	2	3	4	5
Rank of coal	Anthracite groups	Bituminous groups	Lignite	Sub-bituminous groups	–	–
Pyrite content (%)	$P_2 < 1$	$1 \leq P_2 < 2$	$2 \leq P_2 < 5$	$5 \leq P_2 < 8$	$8 \leq P_2 < 10$	$P_2 \geq 10$
Moisture content (%)	$P_3 < 3$	$3 \leq P_3 < 5$	$5 \leq P_3 < 7$	$7 \leq P_3 < 12$	$12 \leq P_3 < 24$	$P_3 \geq 24$
Ash content (%)	$P_4 \geq 60$	$40 \leq P_4 < 60$	$20 \leq P_4 < 40$	$10 \leq P_4 < 20$	$P_4 < 10$	–
Gas emission in seam (m^3/ton)	$P_5 \geq 15$	$10 \leq P_5 < 15$	$5 \leq P_5 < 10$	$P_5 < 5$	–	–
Depth of cover (m)	$50 \leq P_6 < 200$	$200 \leq P_6 < 400$	$400 \leq P_6 < 600$	$600 \leq P_6 < 800$	$P_6 < 50$ $P_6 \geq 800$	–
Thickness of seam (m)	$P_7 < 1.2$	$1.2 \leq P_7 < 2.4$	$2.4 \leq P_7 < 3.2$	$3.2 \leq P_7 < 5$	Thick seam with multi-cut	
Slope of seam (degree)	$P_8 < 15$	$15 \leq P_8 < 30$	$30 \leq P_8 < 45$	$45 \leq P_8 < 60$	$60 \leq P_8 \leq 90$	–
Exist of tectonic faults in seam	Not available	Less than 2 small fault/500 m	More than 2 small fault/500 m	Big fault with great failures	–	–
Unworkable coal seam in vicinity of extracting coal seam	Not available	Spacing of 2 seams is more than 30 times extraction seam thickness	Spacing of 2 seams is between 20-30 times extraction seam thickness	Spacing of 2 seams is between 10-20 times extraction seam thickness	Spacing of 2 seams is between 5-10 times extraction seam thickness	Spacing of 2 seams is less than 5 times extraction seam thickness
Extraction method	Mechanized long wall with shearer loader	Short wall mining	Semi-mechanized long wall with Plow	Room and pillar mining	Traditional long wall	
Advancing direction	Retreat	Advance	–	–	–	–
Rate of advance (m/d)	$P_{13} \geq 5$	$4 \leq P_{13} < 5$	$3 \leq P_{13} < 4$	$2 \leq P_{13} < 3$	$1 \leq P_{13} < 2$	$P_{13} < 1$
Filling of extracted area method	Hydraulic filling	Pneumatic filling	Mechanical filling	Gravity stowing	Hand stowing	Caving method
Exploitation factor	$P_{15} \geq 80$	$65 \leq P_{15} < 80$	$50 \leq P_{15} < 65$	$30 \leq P_{15} < 50$	$P_{15} < 30$	–

Table 21 Classification of coal spontaneous combustion potential index (modified after Mazzoccola and Hudson 1996)

Risk significance	Low	Medium	High
Category	I	II	III
Coal Spontaneous Combustion Potential index (CSCPI)	$0 \leq CSCPI > 33$	$33 \leq CSCPI > 66$	$66 \leq CSCPI \leq 100$

classes of parameter i value, different for different seams j (obtained from Table 20); P_{Maxi} is the maximum value rating of parameter i (obtained from Table 20); $P_{\mathrm{Max}i}$ is for normalization by dividing with the maximum rating; $CSCPI_j$ is the coal spontaneous combustion potential index of each seam; the maximum value of the index is 100 that refers to the most unfavorable conditions, and the minimum index is 0 that refers to the most favorable conditions.

Vulnerability index is in a range of 100 points that can be divided into five or three areas. In this range, high levels of classification, indicating the vulnerability of

Fig. 9 Location map showing position of Tazareh coal mines in Eastern Alborz, Iran

inappropriate conditions, and by reducing the amounts of index, improved conditions (Mazzoccola and Hudson 1996). In this study, Based on the CSCPI system, the propensity of spontaneous combustion of coal can be classified into three potential levels: low, medium and high risk significance, as shown in Table 21.

3.2 Case study: Eastern Alborz Coal Mines

The eastern Alborz coal mines are located in the Alborz Mountains. They include two major mining areas including Tazareh (including Pashkalat, Kelariz, and Razmja mines) and Olang. In order to classify the coal spontaneous combustion potential in the Eastern Alborz coal mines by means of the FDAHP approach, the Pashkalat, Kelariz, and Razmja coal fields of Tazareh were selected (Fig. 9).

4 Results

Each seam of coal fields should be rated to calculate the intrinsic, geological, and mining characteristic-related CSCPI. The rating of each seam is presented in Table 22. It should be noted that obtaining the intrinsic, geological, and mining characteristics of each seam under study involves field sampling and laboratory works. For short, the details are avoided, and just the category is provided, assigned according to Table 20.

After calculating CSCPI for each seam, based on value ranges which presented in Table 21, each coal seam was classified. The proposed classification is given in Table 23. It is noteworthy that at present this classification and indexing in order to determine the scope of the index on each class, of the evidence and the events occurred in each class in the past has been used. The comparison demonstrated relatively good concordance. That indicate use of a systematic approach in analyzing of the potential of coal spontaneous combustion seams in large scale and in the issues of multiple factors can be very useful.

5 Discussion and conclusions

One of the biggest challenges to safety, economic, and environment in coal mines is coal spontaneous combustion, which depends on many parameters. Therefore, prediction of coal spontaneous combustion considering all the effective parameters is very difficult.

In this research work, after primary studies, the most important parameters affecting coal spontaneous combustion (15 parameters) in underground coal mines were selected, the whole Fuzzy Delphi Analytic Hierarchy Process (FDAHP) method was formulated the weight of characteristics affecting the coal spontaneous combustion was evaluated, and the effect of each parameter on the spontaneous combustion potential was estimated. In this paper, a new classification was developed based on the fuzzy Delphi analytic hierarchy process (FDAHP) technique and using the intrinsic, geological, and mining characteristics, named CSCPI. The CSCPI method can be widely used in the evaluation of coal spontaneous combustion studies and industrial applications.

Information has an important practical use, and, for instance, has implications on site characterization since it allows the designer to identify parameters that should be characterized in more detail in any particular case. For example, the results obtained showed that the parameter "rank of coal" had the highest expected interaction with the system. Similarly, "gas emission in seam", "pyrite content", "depth of cover", "moisture content", "extraction method", "rate of advance", and "filling of extracted area method" have the highest weight in the system, and so a small change in these parameters will affect, to a considerable extent, the behavior of the system.

In this study, the rating of each coal seam based on CSCPI was calculated. The CSCPI results indicate that the K5 seam of Pashkalat Coal Mines was in the high risk state (Category III). Comparison between the results of CSCPI and spontaneous combustion events shows that there is a relatively good concordance. Thus the resulting

Table 22 Calculation of CSCPI for seams of coal fields

Item	Rating of parameters															
Weight of each parameter $a_i(\%)$	8.67	7.98	7.52	6.58	8.30	7.92	5.12	2.38	6.56	5.06	7.47	6.27	7.30	6.59	6.27	$\sum_{i=1}^{15} a_i = 100$
$P_{\mathrm{Max}i}$	3	5	5	4	3	4	4	4	3	5	4	1	5	5	4	–
Parameters Seam	P_1	P_2	P_3	P_4	P_5	P_6	P_7	P_8	P_9	P_{10}	P_{11}	P_{12}	P_{13}	P_{14}	P_{15}	CSCPI
Pashkalat																
P18	1	0	0	2	3	0	0	1	0	0	4	1	5	5	1	44.3
P15	1	2	0	2	3	0	0	2	0	0	4	1	5	5	1	48.1
P10	1	1	0	2	3	1	0	1	1	0	4	1	5	5	1	50.0
P3	0	0	0	2	3	1	0	2	0	3	4	1	5	5	1	47.0
K25	0	0	0	2	3	3	0	1	1	0	4	1	5	5	1	49.5
K23	0	0	0	2	3	3	0	2	1	0	4	1	5	5	1	50.1
K21	0	0	0	2	3	3	0	1	1	0	4	1	5	5	1	49.5
K19U	0	2	0	1	3	3	0	2	1	0	4	1	5	5	1	51.7
K19L	0	2	1	2	3	3	0	1	1	0	4	1	5	5	1	54.2
K14	0	0	0	2	3	3	0	2	1	0	4	1	5	5	1	50.1
K13	0	2	0	2	2	3	0	2	1	0	4	1	5	5	1	50.5
K12	0	2	0	1	3	3	0	1	1	0	4	1	5	5	1	51.1
K10	0	2	0	4	3	3	2	3	3	0	4	1	5	5	1	64.1
K9	0	0	0	2	2	3	0	2	0	0	4	1	5	5	1	45.2
K8	0	2	0	2	3	3	0	2	1	0	4	1	5	5	1	53.3
K6	0	2	0	2	3	4	0	2	1	0	4	1	5	5	1	55.3
K5	0	3	0	4	3	4	4	3	3	0	4	1	5	5	1	70.3
Razmja																
K21	0	1	0	2	2	0	0	2	0	0	4	1	5	5	1	40.8
K20	0	2	1	2	2	0	0	2	2	0	4	1	5	5	1	48.3
K19	0	0	1	2	2	0	1	2	0	3	4	1	5	5	1	45.0
K17	0	2	0	2	1	0	2	2	0	4	4	1	5	5	1	46.3
K10	0	4	1	2	1	1	3	2	0	0	4	1	5	5	1	50.2
K8	0	2	2	2	1	1	2	2	2	0	4	1	5	5	1	51.6
K5	0	2	3	2	2	1	3	2	2	0	4	1	5	5	1	57.1
Kelariz																
P18	1	1	0	2	3	0	0	4	0	0	4	1	5	3	1	45.0
P15	1	2	0	2	3	1	0	4	0	0	4	1	5	3	1	48.6
P10	0	1	0	2	3	1	1	4	0	0	4	1	5	3	1	45.4
K28	0	0	0	2	3	3	0	4	0	0	4	1	5	3	1	46.5
K25	0	0	0	2	3	3	1	4	0	0	4	1	5	3	1	47.8
K23	0	1	0	2	3	3	1	4	0	0	4	1	5	3	1	49.4
K19	0	2	0	2	3	3	1	4	0	0	4	1	5	3	1	50.9
K10	0	3	0	2	3	3	1	4	0	0	4	1	5	3	1	52.5
K8	0	2	0	2	2	3	0	4	0	0	4	1	5	3	1	46.9
K6	0	2	0	2	3	4	0	4	0	0	4	1	5	3	1	51.6
K5	0	2	0	3	3	4	1	4	0	0	4	1	5	3	1	54.6
K4	0	2	0	2	3	4	0	4	0	0	4	1	5	3	1	51.6

Table 23 Final ranking obtained for seams of coal fields

Seam	CSCPI	Category	Risk description	Status of coal spontaneous combustion
Pashkalat				
P18	44.3	II	Medium	No spontaneous combustion.
P15	48.1			
P10	50.0			
P3	47.0			
K25	49.5			
K23	50.1			
K21	49.5			
K19U	51.7			
K19L	54.2			
K14	50.1			
K13	50.5			
K12	51.1			
K10	64.1			
K9	45.2			
K8	53.3			
K6	55.3			
K5	70.3	III	High	In 2006, spontaneous combustion occurred.
Razmja				
K21	40.8	II	Medium	No spontaneous combustion.
K20	48.3			
K19	45.0			
K17	46.3			
K10	50.2			
K8	51.6			
K5	57.1			
Kelariz				
P18	45.0	II	Medium	No spontaneous combustion.
P15	48.6			
P10	45.4			
K28	46.5			
K25	47.8			
K23	49.4			
K19	50.9			
K10	52.5			
K8	46.9			
K6	51.6			
K5	54.6			
K4	51.6			

classification by this method is reliable and could present a comprehensive view of the situation about the case study.

The results of this research work indicate that utilization of the systematic approach in analyzing the coal spontaneous combustion seams potential in a large scale can be very useful.

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