Journal of Engineering Science and Technology Review 15 (3) (2022) 139 - 146

JOURNAL OF
Engineering Science and Technology Review

www.jestr.org

Research Article

Risk Assessment Model of Residual Coal Spontaneous Combustion Using Combination Weighting and Set Pair Analysis Method

Jiaqi Ge[1], Yun Qi[2, 3,*], Jinzhang Jia[3], Wei Wang[2,3] and Qingjie Qi[3,4]

[1]*Tashan Coal Mine, Jinneng Holding Coal Industry Group, Datong Shanxi 037000, China*
[2]*College of Coal Engineering, Shanxi Datong University Datong 037000, China*
[3]*College of Safety Science and Engineering, Liaoning Technical University, Fuxin Liaoning 123000, China*
[4]*China Coal Technology Engineering Group, Emergency Research Institute, Beijing, 100013, China.*

Received 5 May 2022; Accepted 12 July 2022

Abstract

In order to solve the problem of low accuracy of autogenous risk assessment in mined-out areas, which has caused several risk factors, such as ambiguity, arbitrament, uncertainty, variability, and diversity, a combination weighting-set pair analysis (SPA) coupling evaluation was put forward. First, on the basis of the mechanism and occurrence conditions of coal spontaneous combustion, 11 influencing factors were identified and extracted from three aspects, namely, coal spontaneous combustion tendency, extraction conditions, and air leakage and heat storage conditions. Second, a Euclidean measure was introduced to ensure the degree in the difference between the subjective and objective weights and compromising modulus. Then, the combined weights of each index were obtained. Third, on the basis of SPA theory, a combined weighting–SPA coupling mining model was constructed. Lastly, three mined-out areas affected by gas drainage conditions were set in Pingdingshan No. 10 Coal Mine of China as an example. The set pair association degree expression of the evaluation index and corresponding standard was obtained, and the risk level was determined. Results show that the combination weighting method ensures the reasonable distribution of the weights of each index factor for the prediction of spontaneous combustion risk in goaf. After analysis, the main factors affecting the spontaneous combustion risk in goaf are ranked as $U_{21} > U_{13} > U_{11} > U_{22} > U_{31}$.The prediction results on the spontaneous combustion risk in No. 1, No. 2, and No. 3 mined-out areas are consistent with the measured results, and the prediction accuracy of the model is high. The obtained conclusions are of great significance for the rational prevention and control of spontaneous combustion in goaf and the prevention of similar disasters.

Keywords: Prediction of spontaneous combustion risk, Comprehensive weight, Compromise coefficient, Improved combination weight–SPA evaluation model, Maximum membership

1. Introduction

As the basic energy and an important raw material of human society, coal plays a vital role in industrial development. With the development and progress of science and technology, although the energy structure is constantly changing and the total consumption of coal is decreasing, coal consumption still accounts for more than 90% of fossil energy resources [1]. According to statistics, as the world's largest economy, the United States' coal industry is not a mainstream industry, but coal mining provides 27% of all jobs, coal resource consumption accounts for 91%, and the economic value created accounts for 26% of the entire GDP. The proportion of coal consumption in EU countries is also as high as 80%. In 2020, China's coal resource consumption accounted for 60%, which was much lower than that of developed countries. On the whole, the dominant position of coal in human development will not change in the near future. In recent years, although China's coal industry has achieved rapid development and the energy structure has gradually become clean and low-carbon [2], the trend wherein coal occupies the dominant position in China's fossil energy resources has not changed. Therefore, countries around the world still need to exploit a large amount of coal resources.

With the increase in coal mining depth, the geological conditions of coal mines are becoming increasingly complex, and disasters, such as water, fire, gas, ground temperature, and ground pressure, are becoming more serious than before. The safety production of coal mines is facing considerable challenges [3]. With the large-scale exploitation of coal resources, the spontaneous combustion tendency of most coal seams is obvious spontaneous or easy spontaneous combustion, and coal spontaneous combustion disaster is becoming increasingly prominent. In coal mining, leakage stoppage, pressure equalization, grouting, inert gas injection, and other methods are generally adopted to prevent coal spontaneous combustion [4]. However, after long-term development, coal is easily oxidized again, resulting in re-ignition, fire, damage to underground mining equipment, heavy casualties, and property losses, which seriously restrict the rapid development of China's economy. At present, China mainly uses grouting, nitrogen injection, three-phase foam, and other means to control coal spontaneous combustion, but these methods often entail certain blindness and danger [5]. The factors that affect coal spontaneous combustion in goafs mainly include the spontaneous combustion tendency of broken floating coal, continuous contact with oxygen, temperature and thermal storage environment, and time of coal oxidation reaction. In the actual process of coal combustion, many factors influence coal spontaneous combustion, and these factors

*E-mail address: qiyun_sx@163.com
ISSN: 1791-2377
doi:10.25103/jestr.153.14

interact and restrict each other, resulting in the complexity of coal spontaneous combustion in the process of mine production [6-7]. Determining the cause and risk degree of coal spontaneous combustion in time is difficult, so targeted treatment measures must be adopted to prevent the spread of fire and the expansion of disasters. Therefore, the prediction of coal spontaneous combustion risk in goafs has become one of the main problems to be solved in China's coal mine safety production and even in the world's coal production [8]. Predicting coal spontaneous combustion in goafs can clarify the status of coal spontaneous combustion and reveal the signs of coal spontaneous combustion as soon as possible [9]. Many studies have shown that analyzing the factors of coal spontaneous combustion by using fuzzy mathematical principles, intelligent algorithms, and cloud computing can effectively predict the coal spontaneous combustion status, but these methods have many shortcomings, such as loss of the original information and massive subjective impact.

Given this background, the author intends to combine the improved analytic hierarchy process (AHP) method with the entropy weight method (EWM). Meanwhile, the spontaneous combustion of residual coal in goafs is regarded as a system that can exert a mutual influence on certainty and uncertainty. In accordance with the extensibility of set pair analysis (SPA) theory, the traditional SPA method is optimized, and a risk evaluation model of spontaneous combustion in goafs is established based on combination weighting SPA coupling. The goaf of the F group coal seam in No. 10 mine of Pingdingshan Coal Mine is employed as the research object, and the gas drainage effect is investigated. To lay a foundation for implementing scientific and reasonable measures to prevent spontaneous combustion in goafs, the influence of gas drainage on spontaneous combustion in goafs is analyzed, and the risk of spontaneous combustion of residual coal in goafs is predicted.

2. State of the art

Spontaneous combustion of residual coal in goafs is a latent and uncertain complex physical and chemical process, and its inducement often has a strong nonlinear effect [10]. When a fire occurs, the risk expansion speed is very high because the ignition location is relatively hidden, so accurately determining the ignition status in the goaf is difficult [11]. Therefore, local and international scholars have conducted extensive research on the risk prediction methods of coal spontaneous combustion from different angles. With regard to the risk factors of spontaneous combustion in goafs, Kursunoglu et al. [12] employed polynomial logistic regression technology, comprehensively considered the effective parameters of underground coal mines in Turkey, predicted the spontaneous combustion trend of coal mines, successfully identified gas concentration and wind speed as the factors that affect coal spontaneous combustion, and divided the fire risk into normal and potential combustion. Brodny et al. [13] conducted a coal spontaneous combustion test at Silicon University of Technology on the basis of the business model of the open innovation concept then determined the potential location of underground fire to help limit the occurrence of fire. Lsab et al. [14] studied the oxidation characteristics of coal samples under different gas environments through isothermal adsorption, scanning electron microscopy, and industrial analysis and pointed out that the fixed carbon content in coal affects the adsorption capacity for methane. Their research results provide a theoretical basis for the prevention and control of spontaneous combustion in goafs. Li et al. [15] used gas data on the goaf of a beam tube to determine the natural dangerous area in the goaf via the oxygen volume fraction method and conducted a simulation analysis with FLUENT software to verify the accuracy of using the oxygen volume fraction method in determining the dangerous spontaneous combustion area in the goaf. Cao et al. [16] used the new optical fiber sensing temperature measurement technology to accurately judge the high-temperature area in a goaf. They compared and analyzed the optical fiber temperature measurement results with the beam tube monitoring results and discussed the reliability of using pipeline temperature measurement in determining the dangerous area in the goaf. Luo et al. [17] analyzed the influence of pore development of raw and saturated coal on the coal oxidation process and confirmed through a coal sample low-temperature oxidation test that coal soaking changes the spontaneous combustion tendency of coal.

With regard to the prediction method of spontaneous combustion risk in goafs, Sahu et al. [18] proposed a fuzzy c-means method based on the principle of the fuzzy expert system and artificial neural network and applied it to the prediction of coal spontaneous combustion tendency to verify the model's accuracy. Prabhakaran et al. [19] explored the combustion characteristics of lignite through thermogravimetric analysis under non-isothermal conditions and analyzed the spontaneous combustion risk of coal by using the artificial neural network and the best fitting model; their results provide a new idea for determining the risk level of spontaneous combustion in goafs. Zhao et al. [20] used the principal component analysis (PCA) AdaBoost model to predict the risk of coal spontaneous combustion in goafs under unbalanced data to improve the prediction accuracy. They found that the prediction result of the PCA AdaBoost model is better and more effective than the result of the particle swarm optimization–support vector machine model. Xiao et al. [21] applied the adaptive step method and annealing algorithm to improve the evaluation model of the backpropagation (BP) neural network and provided a great contribution to improving the accuracy of spontaneous combustion risk prediction for mining seams. Wang et al. [22] established the G2-TOPSIS decision-making model of borehole spontaneous combustion risk on the basis of the approximate ideal solution and modified G2 weighting method by introducing the difference driving method. Chen et al. [23] referred to the theory of partial order set, used the partial order set evaluation model to construct a hazard Hasse diagram of spontaneous combustion in goafs, and analyzed the hazard degree of spontaneous combustion in the goaf. Li et al. [24] established an SPA model to predict the risk of spontaneous combustion of residual coal in goafs. Yue et al. [25] adopted a coal spontaneous combustion test device to measure the parameters, such as heat release intensity and oxygen consumption rate, of coal samples; they established a division method for dangerous areas in goafs and improved the current situation of on-site fire prevention and extinguishment in goafs.

However, the above-mentioned prediction models have drawbacks. For example, although the BP neural network method can avoid the subjective influence of artificially determining the weight coefficient, the difficulty of obtaining sample information still affects the quality of the solution. Additionally, although the SPA method can make full use of the interaction between certainty and uncertainty, the risk level classification is unclear, and the evaluation result is distorted. In the current study, the improved AHP method and the EWM method are combined to obtain the combination weight, and the traditional SPA method is optimized in accordance with the extensibility of SPA theory. As a result, the influence of the subjectivity and objectivity of the traditional prediction model is reduced, and the accuracy of the model is improved. The results are expected to lay a foundation for implementing scientific and reasonable preventive measures against spontaneous combustion in goafs.

The rest of this study is organized as follows. The third section introduces the process of determining the combination weight. The fourth section shows the construction of the evaluation model of combination weighting SPA coupling. The fifth section applies the model to actual production to verify the accuracy of the model. The last section summarizes this study and presents relevant conclusions.

3. Methodology

3.1 Determination of the combination weight

3.1.1 Combination weighting principle

To avoid the fact that the decision-maker's subjectivity influences the risk of spontaneous combustion in goafs and that objective survey data are easily affected by discrete extreme values, two or more methods to determine the weight should be combined; in this manner, the methods' respective advantages can be used to obtain the combined weight [26]. In this study, the Euclidean measure is introduced to merge the subjective weight determined by the AHP method with the objective weight determined by the EWM method to ensure that the difference between the subjective and objective weights is consistent with the corresponding compromise coefficient. Then, the calculation method of "AHP + EWM" coupling is established to determine the ideal weight of the goaf spontaneous combustion risk assessment index.

3.1.2 Combination weighting principle

AHP is a decision-making method that can comprehensively analyze complex multi-objective decision-making problems by combining qualitative and quantitative analyses [27]. The basic idea is as follows. First, the system decision-making objectives are analyzed, and a multi-factor hierarchical structure model that describes the system functions or characteristics is established. Second, the relative importance of each factor is determined using the comparative scaling method to construct the judgment matrix of the relative importance of each index. Lastly, the maximum eigenvalue and its corresponding eigenvector are calculated, and the consistency of the importance judgment matrix is verified. The feature vector is the weight vector of the evaluation index after standardization. The main steps of using AHP to calculate the index weight are as follows:

Step 1) A hierarchical structure model of the spontaneous combustion risk assessment system is established. The relationship of and influence on the basic elements in the goaf spontaneous combustion risk assessment system are analyzed. Additionally, expert opinions are combined to divide the indices into index, criterion, and target layers.

Step 2) The judgment matrix is constructed. In accordance with the comparative scaling method, the importance of each index factor relative to a certain criterion of the upper layer is compared and analyzed. Judgment matrix $\boldsymbol{A}=(a_{ij})_{m\times n}$ is constructed as follows:

$$\boldsymbol{A}=\begin{bmatrix} a_{11} & a_{12} & \cdots & a_{1n} \\ a_{21} & & \cdots & a_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ a_{m1} & a_{m2} & \cdots & a_{mn} \end{bmatrix} \tag{1}$$

Step 3) The index factors are ranked in hierarchy. The square-root method is used to calculate the weight, which corresponds to the relative importance of each index factor in the judgment matrix under the criterion. The obtained vector $\beta=(\beta_1,\beta_2,\ldots,\beta_n)$ is normalized to derive eigenvector w corresponding to the maximum eigenvalue $\lambda_{\max}$ of judgment matrix $\boldsymbol{A}$, that is, the importance weight of each index factor in the same layer relative to a certain index in the upper layer.

$$\beta_i=\sqrt[n]{\prod_{j=1}^{n} a_{ij}},\ i=1,2,3,\ldots,n \tag{2}$$

$$w_i=\frac{\beta_i}{\sum_{j=1}^{n}\lambda_i},\ i=1,2,3,\ldots,n \tag{3}$$

We derive $w=(w_1,w_2,\ldots,w_n)^{\mathrm{T}}$, which is the approximate value of the normalized eigenvector, where w_i is the weight corresponding to the i^{th} factor and $\sum_{i=1}^{n} w_i=1$

Step 4) A consistency test is performed on the judgment matrix. Generally, evaluating whether the judgment matrix meets the requirements of complete consistency in the construction process is difficult. Therefore, a series of measurement standards is necessarily established. When the judgment matrix meets these standards, it is approximately regarded as having complete consistency, and the weight of each level index, which is calculated by the judgment matrix with complete consistency, is reasonable.

$$\lambda_{\max}=\frac{1}{n}\frac{(A\cdot w)_i}{w_i} \tag{4}$$

$$CR=\frac{CI}{I}R \tag{5}$$

$$CI=\frac{|\lambda_{\max}-n|}{\delta-1} \tag{6}$$

where CR is the consistency ratio; CI is the consistency index; and RI is the random consistency index, which can be determined by referring to the chart [10]. Only when $CR < 0.1$ is established can the judgment matrix meet the requirement of consistency. Otherwise, it needs to be rebuilt until the requirement of consistency is met.

3.1.3 Determination of subjective weight by the EWM method

EWM is an objective weighting method that uses the effective information contained in the measured data of various factors affecting the decision-making objectives to determine the degree of dispersion. When the variation degree of the evaluation index of the spontaneous combustion risk in goafs is high and the entropy value is small, the amount of effective information provided by the evaluation index and the weight in the comprehensive evaluation of the spontaneous combustion risk are both large. The weight calculation steps of the EWM method are as follows:

Step 1) Decision matrix $\boldsymbol{R}$ is constructed. By combining the principles of qualitative and quantitative analyses, m samples can be nondimensionalized and standardized, which are related to the spontaneous combustion risk assessment, so the original data matrix of n spontaneous combustion risk evaluation indicators can be obtained.

$$r_{ij}=\begin{cases}\dfrac{b_{ij}-\min b_j}{\max b_j-\min b_j}, \text{ income-type index}\\ \dfrac{\max b_j-b_{ij}}{\max b_j-\min b_j}, \text{ cost-type index}\end{cases} \tag{7}$$

where $\min b_j$ and $\max b_j$ are the best and worst values of each evaluation factor relative to a certain index, respectively.

Step 2) The entropy value of the evaluation index is determined. To avoid the fact that the index characteristic proportion value is zero, ensure that the evaluation index entropy has mathematical significance, and control the influence of $r_{ij}\cdot\ln r_{ij}$ on index entropy within a reasonable range, some factors in the decision matrix must be modified. Then, the evaluation index entropy value is determined as follows:

$$x_{ij}=\begin{cases}\dfrac{r_{ij}}{\sum\limits_{i=1}^{n} r_{ij}}, r_{ij}\neq 0\\ \dfrac{r_{ij}+\psi}{\sum\limits_{i=1}^{n}(r_{ij}+\psi)}, r_{ij}=0\end{cases} \tag{8}$$

$$e_j=-\sum_{i=1}^{m} r_{ij}\cdot\ln r_{ij} \tag{9}$$

where x_{ij} is the characteristic proportion of rating indicators, ψ is the correction factor, and e_j is the entropy weight of the j^{th} index .

Step 3) The information weight of index i is calculated as

$$w_j=\frac{1-e_j}{\sum\limits_{j=1}^{n}(1-e_j)}, \text{ where } \sum w_j=1 \tag{10}$$

3.1.4 Using the "AHP + EWM" method to determine the combination weight

To ensure that the decision-makers' subjective understanding of the risk factors of spontaneous combustion in goafs and the objective investigation data can truly reflect the law, the compromise coefficient is introduced to couple the subjective and objective weights of each index factor. The Euclidean measure in n-dimensional space is also introduced to ensure the consistency of the difference between the subjective and objective weights and the compromise coefficient.

$$w=\alpha w_{\mathrm{A}}+(1-\alpha)w_{\mathrm{E}} \tag{11}$$

$$D(w_{Aj},w_{Bj})=\sum_{j}^{n}(w_{Aj}-w_{Bj})^2 \tag{12}$$

$$D(w_{Aj},w_{Bj})^2=(\alpha-1)^2 \tag{13}$$

where α is the weight compromise coefficient, $D(w_{Aj},w_{Ej})$ is a Euclidean metric, and $D(w_{Aj},w_{Ej})^2$ is the degree of difference between subjective and objective weights and the compromise coefficient.

3.2 Construction of combination weighting and SPA coupling model

3.2.1 Construction of SPA model

Given the requirements in safety evaluation accuracy in engineering practice, the identical discrepancy contrast connection degree model in traditional SPA theory is too rough and simple to distinguish the grade difference when the evaluation index is in the adjacent position or interval [28]. Therefore, the expansibility of the traditional connection degree must be optimized.

Step 1) Suppose that the set of multifactor evaluation is $U=\{u_1,\ u_2,\ \ldots,\ u_n\}$, and many experts are invited to grade the evaluation index of evaluation factor $u_s(1\leq s\leq n)$ to form the grade vector $V=\{v_1,v_2,\ldots,v_m\}$. Additionally, the evaluation target toward identical discrepancy contrast evaluation of evaluation factor u_s is $r_{s1}+r_{s2}i+\cdots+r_{sm-1}i+r_{sm}j$, where $r_{s1}+r_{s2}+\cdots+r_{sm-1}+r_{sm}=1$. Then, the initial identical, dissimilar, inverse evaluation matrix $\boldsymbol{R}$ is obtained as follows:

$$\boldsymbol{R}=\begin{pmatrix} r_{11} & r_{12} & \cdots & r_{1m}\\ r_{21} & r_{22} & \cdots & r_{2m}\\ \vdots & \vdots & \ddots & \vdots\\ r_{n1} & r_{n2} & \cdots & r_{nm}\end{pmatrix} \tag{14}$$

where i is the difference coefficient, $i\in[-1,1]$, and j is the coefficient of opposition ($j=-1$).

Step 2) The matrix of multiple coefficients $\boldsymbol{E}=\begin{pmatrix}1 & i_1 & i_2 & \cdots & i_{m-2} & j\end{pmatrix}^T$ is built by evaluating the set or set pair on the coefficients of degree of identity, degree of difference, and degree of opposition of the evaluation set or set pair under certain background conditions. The weight vectors $W=\begin{pmatrix} w_1 & w_2 & \cdots & w_n \end{pmatrix}$ of all index factors in evaluation set U are combined together, so the same, different, and opposite evaluation model is constructed as follows:

$$\mu=W\cdot R\cdot E=\begin{pmatrix} w_1 \\ w_2 \\ \vdots \\ w_n \end{pmatrix}^T \cdot \begin{pmatrix} r_{11} & r_{12} & \cdots & r_{1m} \\ r_{21} & r_{22} & \cdots & r_{2m} \\ \vdots & \vdots & \ddots & \vdots \\ r_{n1} & r_{n2} & \cdots & r_{nm} \end{pmatrix} \cdot \begin{pmatrix} 1 \\ i_1 \\ \vdots \\ i_{m-2} \\ j \end{pmatrix}$$

that is,

$$\mu=\sum_{s=1}^{n} w_s r_{s1} + \sum_{s=1}^{n} w_s r_{s2} i_1 + \sum_{s=1}^{n} w_s r_{s1} i_2 + \cdots + \sum_{s=1}^{n} w_s r_{s1} i_{m-1} + \sum_{s=1}^{n} w_s r_{sm} j \tag{15}$$

3.5 Constructing the evaluation model of combination weighting SPA coupling

Connection degree u_{sk} is obtained by assuming that connection degree u_s is the s^{th} evaluation object and by analyzing the set pair of the k^{th} index in the evaluation index. Combined with the calculation of the combination weight, an SPA model is constructed as

$$\mu_s = w_k u_{sk} \tag{16}$$

By combining Formulas (11), (15), and (16), we derive the following:

$$\mu=\sum_{s=1}^{n} wr_{s1} + \sum_{s=1}^{n} wr_{s2} i_1 + \sum_{s=1}^{n} wr_{s1} i_2 + \cdots + \sum_{s=1}^{n} wr_{s1} i_{m-1} + \sum_{s=1}^{n} wr_{sm} j \tag{17}$$

The combination weighting–SPA coupling evaluation model makes full use of SPA theory and considers the uncertainty characteristics of evaluation indexes. A combined weight is introduced to quantify the evaluation indexes, optimize the evaluation model of goaf spontaneous combustion, and improve the accuracy of the evaluation results. The research framework is shown in Figure 1.

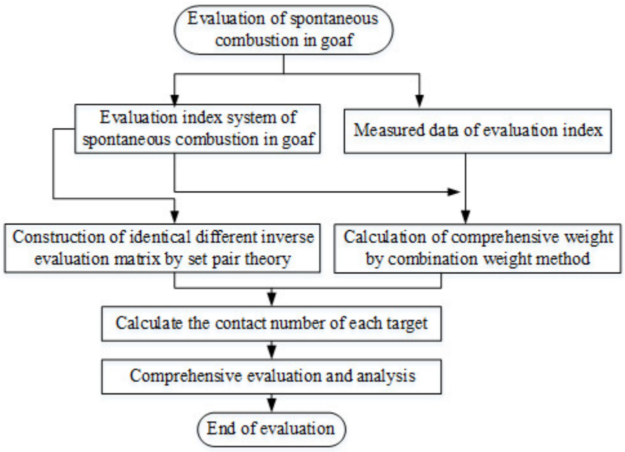

Fig. 1. Improvement of the SPA evaluation process of portfolio weight

4 Result analysis and discussion

4.1 Evaluation index of spontaneous combustion grade in a goaf

Goaf spontaneous combustion is the result of multiple factors. Generally, spontaneous combustion is believed to be caused only by the accumulation of enough heat under the condition of continuous air leakage and oxygen supply in goaf residual coal. Affected by the extraction conditions, the conditions of air leakage and oxygen supply in the goaf and heat storage in the coal seam change dynamically with strong uncertainty. In accordance with the actual situation of the coal seams in No. 10 Coal Mine of Pingdingshan Coal Mine, an evaluation index system of the spontaneous combustion risk of a goaf with 11 single indices is established with the spontaneous combustion tendency of coal, extraction conditions, air leakage conditions, and heat storage conditions as the main factors, as shown in Table 1, by considering the factors that affect the spontaneous combustion risk of goaf comprehensively.

Table 1. Prediction system of spontaneous combustion risk in goaf

First level index of spontaneous combustion risk U_i	Single index of spontaneous combustion risk U_{ii}	Measured parameter value		
Spontaneous combustion tendency U_1	Oxygen absorption capacity of coal U_{11}	0.58	0.47	0.38
	Unit temperature rise rate of CO U_{12}	4.55	3.79	4.23
	Temperature difference of redox ignition point U_{13}	30	27	22
Extraction conditions U_2	Distance from top cutting line U_{21}	32.7	26.25	27.45
	Pumping negative pressure U_{22}	3.3	2.8	4.2
	Average pumping capacity U_{23}	14	11	17
Air leakage and heat storage conditions U_3	Air leakage time U_{31}	13.44	12.86	14.06
	Air leakage intensity U_{32}	0.15	0.21	0.11
	Residual coal thickness U_{33}	0.476	0.38	0.54
	Surrounding rock temperature U_{34}	34	37	38
	Buried depth of coal seam U_{35}	419.6	890	754

In Reference [6], the risk degree of goaf spontaneous combustion is divided into five levels, namely, I (safe), II (relatively safe), III (generally safe), IV (relatively unsafe), and V (unsafe), as shown in Table 2. The identical discrepancy contrast evaluation of the evaluation object relative to evaluation factor u_s is $r_{s1}+r_{s2}i+r_{s3}i+r_{s4}i+r_{s5}j$, in which $r_{s1}+r_{s2}+r_{s3}+r_{s4}+r_{s5}=1$. On the basis of the principle of average distribution, $i_1=0.5$, $i_2=0$, $i_3=0.5$,and $j=-1$ are considered in the expression of connection degree, and the corresponding risk level can be obtained by calculating the value of the connection degree.

Table 2 . Grade division and judgment interval

Danger level	I	II	III	IV	V
Level description	Security	Safer	General safety	Less secure	Insecure
Judgment interval	(0.6,1]	(0.2,0.6]	(-0.2,0.2]	(-0.6,-0.2]	(-1,-0.6]

4.2 Determination of comprehensive weight by "AHP+EWM"

In accordance with the comparison method for the importance degree of Group F goaf of Pingdingshan No. 10 Coal Mine, the 1–9 scale method is used to quantitatively construct the judgment matrix. According to Formulas (1)–(3), the eigenvector corresponding to λ_{max} is obtained as follows: W=(0.333, 0.333, 0.333), W_1=(0.3873, 0.1698,0 .4429), W_2=(0.4905, 0.3119, 0.1976), W_3=(0.3362, 0.2656, 0.2212, 0.0885, 0.0885). By using Formulas (4)–(6) to test the consistency of eigenvalues, we find that the *CR* values of each judgment matrix meet $CR < 0.1$. Therefore, if the judgment matrix and eigenvector meet the requirements, the weight vector corresponding to the AHP method is as follows: w_{A1}=(0.3873, 0.1698, 0.4429), w_{A2}=(0.4905, 0.3119, 0.1976), w_{A3}=(0.3362, 0.2656, 0.2212, 0.0885, 0.0885). Then, in accordance with the data in Table 1, the original data of the evaluation object are treated via dimensionless normalization, and the weight corresponding to the EWM method of the goaf spontaneous combustion risk factor is obtained through Formulas (8)–(10) as follows: w_{E1}=(0.3021, 0.3413, 0.3566), w_{E2}=(0.2968, 0.3294, 0.3738), w_{E3}=(0.1796, 0.1666, 0.2008, 0.2303, 0.2227).

The Euclidean measure is introduced to combine the subjective weight of the AHP method with the objective weight of the EWM method. According to Formulas (11)–(13), the compromise coefficient α is 0.73. Hence, the ideal comprehensive weight of each evaluation index is obtained as w_1=(0.3643, 0.2161, 0.4196), w_2=(0.4382, 0.3166, 0.2452), w_3=(0.2939, 0.2389, 0.2157, 0.1268, 0.1247). The comparison of comprehensive weights indicates that the different evaluation indices have different effects on the spontaneous combustion risk of the goaf. The primary and secondary factors that affect the spontaneous combustion risk of the goaf are $U_{21} > U_{13} > U_{11} > U_{22} > U_{31}$, which can be used as the main criterion for the prevention and control of the spontaneous combustion risk of the goaf.

4.3 Determination of comprehensive weight by "AHP+EWM"

Using the evaluation index system and the goaf data of Pingdingshan No. 10 Coal Mine collected in Reference [1], experts with solid theoretical knowledge and rich practical experience are invited to score the three goaf evaluation index factors to be predicted, and the evaluation results are normalized, as shown in Table 3.

Table 3. Goaf to be evaluated and single index evaluation results

Index	Goaf	Evaluation results				
oxygen absorption capacity of coal	NO.1	0.07	0.45	0.28	0.16	0.04
	NO.2	0.05	0.33	0.46	0.10	0.06
	NO.3	0.24	0.43	0.16	0.13	0.04
unit temperature rise rate of CO	NO.1	0.05	0.39	0.36	0.16	0.04
	NO.2	0.08	0.33	0.42	0.11	0.06
	NO.3	0.28	0.46	0.17	0.06	0.03
temperature difference of the redox ignition point	NO.1	0.07	0.42	0.30	0.14	0.07
	NO.2	0.1	0.35	0.39	0.09	0.07
	NO.3	0.24	0.46	0.18	0.07	0.05
distance from top cutting line	NO.1	0.06	0.42	0.36	0.12	0.04
	NO.2	0.09	0.34	0.37	0.12	0.08
	NO.3	0.23	0.44	0.17	0.12	0.04
pumping negative pressure	NO.1	0.06	0.46	0.27	0.12	0.09
	NO.2	0.07	0.29	0.45	0.13	0.06
	NO.3	0.24	0.52	0.13	0.07	0.04
pumping capacity	NO.1	0.13	0.37	0.36	0.12	0.02
	NO.2	0.07	0.32	0.42	0.14	0.05
	NO.3	0.26	0.45	0.13	0.09	0.07
air leakage time	NO.1	0.37	0.38	0.12	0.09	0.04
	NO.2	0.44	0.12	0.34	0.07	0.03
	NO.3	0.43	0.27	0.18	0.03	0.09
air leakage intensity	NO.1	0.12	0.38	0.35	0.12	0.03
	NO.2	0.08	0.33	0.42	0.13	0.04
	NO.3	0.43	0.13	0.35	0.06	0.03
residual coal thickness	NO.1	0.05	0.43	0.37	0.11	0.04
	NO.2	0.08	0.35	0.38	0.12	0.07
	NO.3	0.22	0.45	0.17	0.12	0.04
surrounding rock temperature	NO.1	0.06	0.38	0.37	0.15	0.04
	NO.2	0.08	0.35	0.40	0.11	0.06
	NO.3	0.26	0.48	0.17	0.06	0.03
buried depth of coal seam	NO.1	0.38	0.38	0.11	0.09	0.04
	NO.2	0.42	0.14	0.34	0.07	0.03
	NO.3	0.42	0.28	0.18	0.03	0.09

In accordance with Table 3, the initial similar, different, and reverse evaluation matrix is obtained. By combining Formulas (15) and (17), the connection degree expression of the evaluation result of the No. 1 goaf is constructed as follows:

$$\mu_{11}=\left(w_1,w_2,\cdots,w_n\right)\cdot\begin{pmatrix} r_{11} & r_{12} & r_{13} & r_{14} & r_{15} \\ r_{21} & r_{22} & r_{23} & r_{24} & r_{15} \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ r_{n1} & r_{n2} & r_{n3} & r_{n4} & r_{n5} \end{pmatrix}\cdot\begin{pmatrix} 1 \\ i_1 \\ i_2 \\ i_3 \\ j \end{pmatrix}$$

$$=(0.3643,2161,0.4196)\cdot\begin{pmatrix} 0.07 & 0.45 & 0.28 & 0.16 & 0.04 \\ 0.05 & 0.39 & 0.36 & 0.16 & 0.04 \\ 0.07 & 0.42 & 0.3 & 0.14 & 0.07 \end{pmatrix}\cdot$$

$$\begin{pmatrix} 1 \\ i_1 \\ i_2 \\ i_3 \\ j \end{pmatrix}=0.0657+0.4244i_1+0.3057i_2+0.1515i_3+0.0526j$$

In the same way,

$$\mu_{12}=0.0772+0.4204i_1+0.3315i_2+0.12i_3+0.0509j$$

$$\mu_{13}=0.2032+0.3908i_1+0.2593i_2+0.1091i_3+0.0376j$$

Similarly, the relation degree expression of the No. 2 goaf evaluation result is as follows:

$$\mu_{21}=0.0775+0.3384i_1+0.4220i_2+0.0980i_3+0.06420j$$

$$\mu_{22}=0.0787+0.3193i_1+0.4076i_2+0.1281i_3+0.0663j$$

$$\mu_{23}=0.2282+0.2514i_1+0.3754i_2+0.1002i_3+0.0448j$$

The relation degree expression of the No. 3 goaf evaluation result is as follows:

$$\mu_{31}=0.2486+0.4490i_1+0.1706i_2+0.0897i_3+0.0421j$$

$$\mu_{32}=0.2405+0.4678i_1+0.1475i_2+0.0968i_3+0.0474j$$

$$\mu_{33}=0.3619+0.3032i_1+0.2172i_2+0.0604i_3+0.0573j$$

By calculating the evaluation results of each goaf, the average connection degree values of the No. 1 and No. 3 goafs are determined to be 0.2138 and 0.3712, respectively, and their evaluation grade is grade II (relatively safe). The average connection degree of the No. 2 goaf is 0.1708, and its evaluation grade is grade III (general safety). The evaluation results of goaf spontaneous combustion risk are shown in Table 4. The results are consistent with the actual goaf spontaneous combustion risk, and the accuracy of the evaluation model is close to 100%. Therefore, the evaluation model has certain universality and guiding significance.

Table 4. Evaluation of rock burst tendency

No. of goaf	Average connection degree	Forecast results	Measured results
NO. 1	0.2138	II	II~III
NO. 2	0.1708	III	III
NO. 3	0.3712	II	II

5. Conclusions

An improved combined weight–SPA goaf spontaneous combustion risk assessment model is proposed to solve the uncertainty of each index factor and the interaction between the certainty and uncertainty of each factor in goaf spontaneous combustion risk assessment. The compromise coefficient and the Euclidean distance function optimization decision model are introduced to reduce the impact of subjectivity, experience of the AHP method, and the objectivity of the EWM method on the assessment results. Then, the comprehensive connection degree parameters of SPA are obtained. The following conclusions are obtained:

1) The combination weighting method is used to ensure the reasonable distribution of the weight of each index factor in goaf spontaneous combustion risk prediction, but analysis of the weight value of each index shows a difference in the degree of influence of goaf spontaneous combustion risk factors on spontaneous combustion risk. The main factors that affect the spontaneous combustion risk of goafs in Pingdingshan No. 10 coal mine are $U_{21}>U_{13}>U_{11}>U_{22}>U_{31}$.

2) The goaf spontaneous combustion risk prediction results of the combination weighting–SPA coupling model for No. 1, No. 2, and No. 3 goafs are basically consistent with the measured results, and only the No. 2 goaf evaluation results are relatively conservative. However, from the risk point of view, the evaluation results are reliable, which may be consistent with the phenomenon that the measured results on coal spontaneous combustion marker gas concentration and temperature growth rate of some gas drainage boreholes in the mine are high.

3) When predicting the spontaneous combustion risk of Pingdingshan No. 10 coal mine by using the combined weighting SPA coupling goaf spontaneous combustion risk evaluation model, the calculation results clearly and effectively reflect the level of each evaluation index, and the risk level is sorted according to the connection degree parameters of each index. Thus, the evaluation results have high accuracy, which provides the foundation for the reasonable prevention and control of spontaneous combustion in goafs.

In summary, the goaf spontaneous combustion risk evaluation model proposed in this study can effectively reduce the impact of subjective and objective factors, ensure the accuracy of the evaluation results, and provide a theoretical basis for the evaluation of similar problems. However, because the parameters of spontaneous combustion risks in goafs need to be actually measured and the accuracy of the measurement results varies greatly due to different measurement techniques and levels, in future research, the model will be improved by changing the acquisition method of measured data or by introducing a correction coefficient in order to improve the accuracy and scope of application of the model and provide great help to the prediction of spontaneous combustion risks in goafs.

Acknowledgments
The study was supported by the Doctoral Research Startup Project of Shanxi Datong University (2020-B-18,2020-B-08) and key special-funded projects of the State key R & D program (2018YFC0807900)

References

1.Qi, Y., Qi, Q. J,Wang, W., Zhou, X. H., "Prediction model of spontaneous combustion risk in goaf based on set valued statistics-entropy and its application". *Journal of Safety and Environment*, 19(5), 2019, pp.1526-1531

2.Wang, J, B., Hou, J. L., Zhang, L., Shu, L. Y.,"Entropy weight extension method for spontaneous combustion risk assessment of residual coal in gob" . *Mining Safety & Environmental Protection*, 42(2), 2015, pp.43-48.

3.Qiu, X., Cao, Q., Wang, Y., Liu, Q., "Risk assessment method of coal spontaneous combustion based on catastrophe theory". In: *Earth and Environmental Science*, Shanghai, China: IOP Conference Series, 2020,pp.12017.

4.Wang, Y., Dong, X. M.,Wu, J. B., Wu, M. M., Guo, R. Z.,"Study on hazard zone of coal spontaneous combustion in adjacent goaf along working face". *Safety in Coal Mines*, 53(3), 2022, pp.193-199.

5.Qi, Y., Wang, W., Qi, Q. J., Ning, Z. X., Yao, Y. L., "Distribution of spontaneous combustion three zones and optimization of nitrogen injection location in the goaf of a fully mechanized top coal caving face" . *PLoS One*, 16(9),2021,pp:e0256911.

6.Wang, W., Qi, Y., Jia, B. S., Yao, Y. L., "Dynamic prediction model of spontaneous combustion risk in goaf based on improved CRITIC-G2-TOPSIS method and its application". *PLoS One*, 16(10), 2021,pp: e0257499.

7.Zhang, Q., Wang, X. F., Huang, G., Wang, Y. S., "Study on goaf gas drainage technology and float coal spontaneous combustion coupling control" .*Coal Science and Technology*,45(10),2017, pp.111-116.

8.Zhang, J. F., Shi, S. L., Lu, Y., You, B., "Symbiotic disasters of mine gas and coal spontaneous combustion:coupling relationship,disaster mechanism, prevention and control technology". *China Safety Science Journal*, 30(10), 2020, pp.149-155.

9.Wang, M. C., Liu, Z. G., Zhang, X. J., Xia, T. F., Lv, K. K., "Research of risk assessment on spontaneous combustion of goaf coal based on Analytic Hierarchy Process and extended set pair theory". *Journal of Safety Science and Technology*, 10(8), 2014, pp.182-188.

10.Luo, D. Y., "Cause analysis of spontaneous combustion of coal in gob" . *Mining Safety & Environment Protection*, 44(5), 2017, pp.107-110.

11.Sun, Z., Wen, C. P., Bai, Y. Y., Chen, Z. H., Chen, Y. Q.,"Evaluation of goaf coal spontaneous combustion based on attribute mathematical theory". *Journal of PLA University of Science and Technology*, (4), 2017, pp.1-5.

12.Kursunoglu, N., Gogebakan, M., "Prediction of spontaneous coal combustion tendency using the Multinomial Logistic Regression". *International Journal of Occupational Safety and Ergonomics*,7(26), 2021, pp:1-10.

13.Brodny, J., Tutak, M., "The use of the open innovation concept to develop a method to improve safety during the mining production process: A case Study of the integration of university and industry" . *Journal of Open Innovation:Technology,Market,and Complexity*, 8(2),2022, pp.1-21.

14.Sun, L. L., Wang, H. S., Zhang, C., Zhang, S. H., Liu, N., He, Z. L., "Evolution of methane ad-/desorption and diffusion in coal under in the presence of oxygen and nitrogen after heat treatment". *Journal of Natural Gas Science and Engineering*, 95(11), 2021, pp.104196

15.Li, Z. X., Hu, D. J., Liu, Y.,Zhang, M. Q.,"On the spontaneous combustion risk in the goaf based on the closed oxygen consumption experiment". *Journal of Safety and Environment*, 21(5), 2021, pp.2030-2036.

16.Cao, W. H., Wang, F., "Study on the identification of spontaneous combustion hazard area in goaf based on optical fiber temperature measurement technology". *Mining Safety & Environmental Protection*, 47(6), 2020, pp.75-79,84.

17.Luo, Z., Qin, B., Shi, Q., Hu, H., Sheng, P., Tian, S., "Compound effects of water immersion and pyritic sulfur on the microstructure and spontaneous combustion of non-caking coal" . *Fuel*, 2022, doi: 10.1016/j.fuel.2021.121999.

18.Sahu, H. B., Padhee, S., Mahapatra, S. S., "Prediction of spontaneous heating susceptibility of indian coals using fuzzy logic and artificial neural network models". *Expert Systems with Applications*, 38(3), 2011, pp.2271-2282.

19.Prabhakaran, S. S., Swaminathan, G., Joshi, V. V., "Combustion and pyrolysis kinetics of Australian lignite coal and validation by artificial neural networks". *Energy*, 242, 2022, pp.21-18.

20.Zhao, L. L., Wen, G. F., Shao, L. S., "PCA-AdaBoost model for predicting coal spontaneous combustion in caving zone with imbalanced data". *China Safety Science Journal*, 28(3), 2018, pp.74-78.

21.Xiao, H. F., Liu, L. M., Wang H. Q., "The application of modified BP neural network to predict mine coal layer spontaneous combustion". *Journal of China Coal Society*, 26(6), 2001, pp.649-653.

22.Wang, W., Jia, B. S., Qi, Y., "Prediction model of spontaneous combustion risk of extraction drilling based on improved CRITIC modified G2-TOPSIS method and its application". *China Safety Science Journal*, 29(11), 2019, pp.26-31.

23.Chen, J. Q., Wang, J. R., Yue, L. Z., "Evaluation model on possibility of coal spontaneous combustion in goaf based on partially ordered set". *Journal of Safety Science and Technology*, 15(2), 2019, pp.89-93.

24.Li T. S., He, Q. L., "Application of set pair analysis in the risk evaluation of coal spontaneous combustion". *Journal of Safety Science and Technology*, 9(8), 2013, pp.54-58.

25.Yue, N. F., Jin, Y., Chen, G. L.,Sun, M. F, Ran, X. C."Research on the division method of the dangerous ara of coal spontaneous combustion in goaf based on multi-parameter". *Mining Safety & Environmental Protection*, 48(4), 2021, pp.1-5+11.

26.Lin H. F., Gao F.,Yan, M., "Study on PSO-BP neural network prediction method of coal seam gas content and its application" . *China Safety Science Journal*, 30(9), 2020, pp.80-87.

27.Chen, L. Y., Li X. J., Bi, J., Hua, Y. J, Wei, Z. Y. "Prediction of coal-gas outburst induced by rock-burst tendency based on AHP-TOPSIS" , *China Safety Science Journal*, 30(4), 2020, pp.47-52.

28.Lin, Y. L., Zhao, L., "Monitoring and analysis for goaf spontaneous combustion during gas extraction". *Safety in Coal Mines*, 15(4), 2019, pp.1239-1245.