Research Article

Risk Assessment of Rockburst with a LS-FAHP-CRITIC Method: A Case in Gaojiapu Coal Mine, North of China

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Rockburst is one of the main dynamic disasters in coal mines; it is of great significance to accurately evaluate the risk zoning of rockburst for mine safety construction and pressure relief design. Taking the Gaojiapu coal mine in the Bingchang mining area of Shaanxi Province as the study area, this paper quantifies the complex geological structure based on fractal theory and establishes the zoning evaluation model of rockburst risk index in the mining area by LS-FAHP-CRITIC method in combination with the distribution characteristics of field stress field, the distribution of geological structure, and the sedimentary environment of coal seam overburden. A new evaluation method of rockburst risk zoning in the coal mine is proposed, and the rockburst risk in the study area was evaluated. The results show that the dangerous areas in the study area are widely distributed, mainly in the area near the structure with high maximum horizontal principal stress. On the basis of the actual rockburst of the Gaojiapu coal mine, the areas where rockburst occurs are all located in dangerous area and high dangerous area, which verifies the accuracy and rationality of the zoning evaluation results of the new method. This method can be used to guide the safety production of similar mines or adjacent coalfaces.

1. Introduction

Coal is the main energy source in China [1–3]. With the gradual shift of the mining focus of China’s coal resources to the deep, the geological conditions and environment are becoming more and more complex, and dynamic disasters and accidents caused by coal resource exploitation are occurring frequently [4–6]. Rockburst is a typical coal mine dynamic disaster, which has the characteristics of sudden, fierce, and urgent [7]. Due to the intense damage of coal (rock) mass caused by the instantaneous release of elastic stress, it often causes serious damage to the shaft and roadway and heavy casualties and poses a great threat to the safe and efficient production of the mine [8, 9]. The prediction and early warning of rockburst is the basis of rockburst prevention and control. The prediction of rockburst plays an extremely important role and significance for the prevention and control of mine rockburst and safe and efficient production [10–12].

In recent years, many experts and scholars at home and abroad have done a lot of research on the risk prediction of rockburst. Dou and He [13] put forward the comprehensive index method of impact risk assessment based on mining and geological factors by analyzing the geological conditions and mining factors of rockburst. Zhang and Xia [14] analyzed the influencing factors of rockburst and established a variable weight identification model for comprehensive evaluation of rockburst risk based on attribute identification theory. Lei [15] put forward a rockburst risk assessment method based on quantitative theory according to the main factors affecting impact and quantitative theory. Liu et al. [16] used this method to evaluate the impact risk in the first mining area of Tangkou coal mine, which is used to guide the onsite mining and support
work of the coal mine. Peng et al. [17] briefly discussed the mechanism of coal seam rockburst and the influencing factors of coal seam rockburst risk and put forward a simple coal seam rockburst risk evaluation method. Dong et al. [18] selected the maximum tangential stress, elastic energy index, uniaxial compressive strength, and uniaxial tensile strength as the factors for judging the rockburst grade, combined them according to different combination forms, and determined the rockburst risk in combination with the method of random forest classification. Jiang et al. [19] proposed a dynamic assessment method for delimiting the rockburst risk area and risk degree by monitoring the dynamic information of vibration and stress during excavation by using microseismic ground sound and stress monitoring system. Zhang et al. [20] analyzed the active faults in the Laohutai mining area and put forward a geodynamic zoning method based on the form of fault structure and coal rock characteristics. Wang et al. [21] considered eight influencing factors including coal seam thickness, coal seam dip angle, mining depth, roof lithology, and structure, and used the local weighted learning random forest method to establish the prediction model of the rockburst risk level. Qi et al. [22] combed the basic concepts and functions of impact risk assessment, pointed out the shortcomings of current assessment methods, and defined the future development direction of rockburst risk assessment.

With the development of science and technology, experts and scholars have put forward a large number of impact risk assessment methods and selected many geological factors and indicators, but there is no impact risk assessment method from the perspective of geological sedimentary facies. This study takes the Gaojiapu coal mine in the Binchang mining area of Shaanxi Province as the research area. Based on the fractal theory, the complex geological structure was quantified. Combined with five influence indexes such as coal seam thickness and buried depth, distribution characteristics of initial in-situ stress field, geological structure distribution, and sedimentary environment of coal seam overburden, the zoning evaluation model of rockburst risk index in mining area was established, and a new zoning evaluation method of coal mine rockburst risk was proposed, and the risk of rockburst in the study area was evaluated. The impact appearance area of the Gaojiapu coal mine was selected as the verification area of the evaluation method to verify the accuracy and rationality of the zoning evaluation results of the new method. In addition, according to the results of the rockburst risk assessment, corresponding targeted suggestions are put forward. This method can provide a basic basis and guidance for coal mine safety production and anti-scour design.

2. Study Area

Gaojiapu coal mine is located in the northwest Binchang mining area and is under the jurisdiction of Changwuh County, Xianyang City, and Shaanxi Province (Figure 1(b)). On the whole, the Gaojiapu coal mine is located in the combination area of the northern Shaanxi loess plateau and eastern Gansu loess plateau. The terrain is high in the southwest and low in the northeast, and the geomorphic type is loess tableland and ridge gully area. The surface river water system in the study area is not developed, mainly including the Ching River and the Heihe River.

The main coal seam in the study area is the No.4 coal seam of the Jurassic Yan’an formation, the thickness range is 0.35 m-19.53 m, and the average coal seam thickness is 9.96 m. According to the exposure of nearby boreholes, the strata in the study area from old to new are the Middle Jurassic Yanan formation (J₂y), Zhihuo formation (J₁2z), Anding formation (J₁a), Lower Cretaceous Yijun formation (K₁y), Luohe formation (K₁l), Neogene (N), and Quaternary (Q).

Based on the borehole column and logging curve in the area, the sedimentary environment and microfacies of overburden in the mining area are analyzed. The strata of the Yanan formation are continental clastic rock deposits, mainly lacustrine deposits. The strata of the Zhihuo Formation and Anding formation are fluvial facies deposits. During the deposition period, the climate is dry and the sediment carrying capacity of the river is small. It is mainly braided channel sedimentary surfaces. The strata of the Yijun formation, Luohe formation, and Huachi formation are mainly alluvial fan sedimentary facies of dry land, river channel deposition, and overflow deposition of the river channel, and debris flow deposits with large sediment particle size are occasionally seen.

From 2017 to 2022, there have been many rockburst events in the Gaojiapu coal mine; resulting in large-scale roadway floor bulging, roof sinking, and two sides of roadway bulging in the study area, which has a significant impact on safety production. The area where rockburst occurs is mainly located in the main roadway corresponding to the 103 coalface and the crossheading of the 204 coalface. The distribution of the rockburst area is shown in Figure 1(c).

3. Methodology

3.1. Normalization of the Raw Data. Due to the different dimensions between the influencing factors inducing dynamic geological disasters, to eliminate the impact of different dimensions on the evaluation results, the data need to be normalized by the normalization method [23]. After data standardization, the original data has the same order of magnitude and can be used for comprehensive analysis and evaluation results. The data normalization is calculated according to the following:

$$x'_{ij} = \frac{x_{ij} - \min_{j}(x_{ij})}{\max_{j}(x_{ij}) - \min_{j}(x_{ij})},$$

where $x_{ij}$ is the original data of the $j$-th evaluation object in the $i$-th evaluation index; $\max_{j}(x_{ij})$ and $\min_{j}(x_{ij})$ are the maximum and minimum values of the $i$-th evaluation index, respectively; $x'_{ij}$ is the normalized data of the $j$-th evaluation object in the $i$-th evaluation index.

3.2. Fuzzy Analytic Hierarchy Process. Analytic Hierarchy Process (AHP) is a qualitative and quantitative multi-objective decision analysis method. Zhang proposed this multi-criteria
decision-making method to analyze complex decision-making problems [24]. Lu introduced the “membership degree” in fuzzy mathematics into the analytic hierarchy process model and used the membership function to deal with the fuzzy indexes [25]. To solve the problem that it is difficult to guarantee the consistency of the judgment matrix, Jesiya and Gopinath introduced the concept of the triangular fuzzy number of fuzzy set theory into the comparison matrix of the analytic hierarchy process and established Fuzzy Analytic Hierarchy Process (FAHP) [26]. When using this method to determine the index weight, the following steps are usually used:

According to the factor analysis, the fuzzy hierarchical structure model is constructed. Based on the 0.1-0.9 fuzzy scaling method, the influencing factors are compared in pairs according to expert experience, and the fuzzy complementary discrimination matrix is established, which is called matrix A.

$$A = (a_{ij})_{n \times n} = \begin{bmatrix} a_{11} & a_{12} & \cdots & a_{1n} \\ a_{21} & a_{22} & \cdots & a_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ a_{n1} & a_{n2} & \cdots & a_{nn} \end{bmatrix},$$

where $1 \geq a_{ij} \geq 0$, $a_{ii} = 0.5$, $a_{ij} + a_{ji} = 1$, and $i, j = 1, 2, \cdots, n$.

When the fuzzy complementary discriminant matrix satisfies $a_{ij} = a_{ik} - a_{jk} + 0.5$ and the fuzzy consistent discrimi-

nant matrix is satisfied, the fuzzy consistent matrix $R$ is

$$R = (r_{ij})_{n \times n} = \begin{bmatrix} r_{11} & r_{12} & \cdots & r_{1n} \\ r_{21} & r_{22} & \cdots & r_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ r_{n1} & r_{n2} & \cdots & r_{nn} \end{bmatrix},$$

$$r_{ij} = \frac{r_i - r_j}{2(n-1)} + 0.5,$$

$$r_i = \sum_{j=1}^{n} a_{ij}.$$

Assuming that $W = (w_1, w_2, \cdots, w_n)^T$ is the weight vector of fuzzy discriminant matrix $A$, then

$$W^* = (w_{ij})_{n \times n} = \begin{bmatrix} w_{11} & w_{12} & \cdots & w_{1n} \\ w_{21} & w_{22} & \cdots & w_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ w_{n1} & w_{n2} & \cdots & w_{nn} \end{bmatrix},$$

$$w_{ij} = \frac{w_i}{w_i + w_j},$$

$$w_i = \frac{\sum_{j=1}^{n} a_{ij} - 1 + (n/2)}{n(n-1)}.$$
In order to judge the consistency of the fuzzy complementary discrimination matrix, the compatibility index $I$ is used for inspection, and the compatibility index $I$ is calculated according to the following formula:

$$I(A, W^*) = \frac{\sum_{i=1}^{n} \sum_{j=1}^{n} |a_{ij} + W_{ij} - 1|}{n^2}. \quad (5)$$

According to the relevant definition of compatibility index, when the compatibility index $I(A, W^*) \leq 0.1$, it is considered that the fuzzy discrimination matrix meets the consistency requirements.

3.3. CRITIC Method. CRITIC method is an objective weighting method based on the comparative strength of evaluation indicators and the conflict between indicators to comprehensively measure the objective weight of indicators. Because it makes full use of the objective attributes of the data itself, it is better than the entropy weight method and standard deviation method [27]. The calculation steps of weighting through this method are as follows:

Construct the original evaluation matrix $X = (x_{ij})_{nm}$ as

$$X = \begin{bmatrix}
  x_{11} & x_{12} & \cdots & x_{1n} \\
  x_{21} & x_{22} & \cdots & x_{2n} \\
  \vdots & \vdots & \ddots & \vdots \\
  x_{m1} & x_{m2} & \cdots & x_{mn}
\end{bmatrix}. \quad (6)$$

Since the dimensions of each evaluation index are different, the standardization matrix $X'$ obtained by Equation (1) is:

$$X' = \begin{bmatrix}
  x_{11}' & x_{12}' & \cdots & x_{1n}' \\
  x_{21}' & x_{22}' & \cdots & x_{2n}' \\
  \vdots & \vdots & \ddots & \vdots \\
  x_{m1}' & x_{m2}' & \cdots & x_{mn}'
\end{bmatrix}. \quad (7)$$

The correlation coefficient and standard deviation between the indicators are

$$\rho_{xy} = \frac{\sum_{i=1}^{m} (x_{ij} - \bar{x}_j)(y_{ij} - \bar{y}_i)}{\sqrt{\sum_{i=1}^{m}(x_{ij} - \bar{x}_j)^2 \sum_{i=1}^{m}(y_{ij} - \bar{y}_i)^2}}, \quad \sigma_j = \sqrt{\frac{1}{n} \sum_{i=1}^{n} (x_{ij} - \bar{x}_j)^2}. \quad (8)$$

The quantitative result $\theta_i$ of the conflict between the $i$-th indicator and other indicators is

$$\theta_i = \sum_{i=1}^{n} (1 - \rho_{ij}). \quad (9)$$

The objective weight $\mu_i$ of the $i$-th evaluation index is as follows:

$$\mu_i = \frac{E_i}{\sum_{i=1}^{n} E_i}, \quad E_i = \sigma_i \theta_i. \quad (10)$$

3.4. LS-FAHP-CRITIC Method. In general, FAHP is a subjective decision analysis method, while CRITIC has obvious objectivity in calculating index weights. Therefore, it is one of the hot topics in academic circles to determine weights comprehensively by combining subjective and objective weighting methods. The least squares method is a mathematical optimization method that minimizes the sum of the squares of errors and searches for the best function matching the data and minimizes the sum of the squares of errors in the solution of the problem.

In this study, we use the least squares method to couple FAHP and CRITIC instead of the multiplicative synthesis normalization and linear weighting methods. The optimal models are as follows:

$$\min F(\zeta) = \sum_{j=1}^{n} \sum_{i=1}^{m} \left\{ \left[ (w_i - \zeta_i)X_i' \right]^2 + \left[ (\mu_i - \zeta_i)X_i' \right]^2 \right\}, \quad (11)$$

where $\sum_{i=1}^{m} \zeta_i = 1$, $\zeta_i \geq 0$, $i = 1, 2, ..., n$, $j = 1, 2, ..., m$, $\zeta_i$ is the weight calculated by the LS-FAHP-CRITIC method; and $X_i'$ is the normalized data matrix.

3.5. Risk Index Method. Based on the Vulnerability Index (VI) method, the vulnerability assessment model of rock burst in coal mining was established by adopting the topological reconstruction function in GIS software and combining the comprehensive weight determined by the LS-FAHP-CRITIC method. The Vulnerability Index reflects the possibility of rockburst occurring in an area of coal mining. VI is calculated as follows:

$$VI = \sum_{i=1}^{n} \zeta_i f_i(x, y), \quad (12)$$

where VI is the risk index of the rockburst, $\zeta_i$ is the weight of the evaluation index, and $f_i(x, y)$ is the normalized evaluation index for the $i$-th factor.

4. Zoning Evaluation Model of Rockburst Risk

4.1. Analysis of Influencing Factors. The basic geological factors of rockburst formation include mining depth, coal rock structure, geological structure, overburden spatial structure, and in-situ stress field distribution. A simplified engineering geological model of rockburst was established [28]. Five factors including the thickness of coal seam, burial depth of the coal seam, sedimentary microfacies, capacity dimension of the geological structure, and maximum horizontal principal stress were selected as the main influencing factors for risk
assessment of rockburst. The analysis of the selected factors is as follows:

(1) **Thickness of the coal seam (F1).** The mining thickness of the coal seam is one of the important parameters to evaluate the risk of rockburst. The thicker the coal seam, the greater the mining damage range of the coal seam and the greater the risk of rockburst. Since the prediction and evaluation work is generally done before the beginning of mining activities, the coal seam thickness exposed by geological drilling in the geological exploration stage is adopted as one of the evaluation indexes. The distribution of coal seam thickness in the study area is shown in Figure 2(a).

(2) **Burial depth of the coal seam (F2).** The burial depth of the coal seam is one of the important parameters to evaluate the stress level of the coal seam surrounding rock. With the different burial depths of coal seams, the overlying environment of coal has significant differences. Among them, the greater the burial depth of the coal seam, the stress levels of surrounding rock increase significantly and the higher the risk of rockburst. Therefore, the buried depth of the coal seam is selected as one of the evaluation indexes. The distribution of the burial depth of the coal seam in the study area is shown in Figure 2(b).

(3) **Sedimentary microfacies (F3).** Sedimentary facies refer to the complex lithologic characteristics and biological characteristics that can indicate the sedimentary environment and conditions of sediments. Sedimentary microfacies, as the most fundamental indicator of the overlying environment of geological bodies, play a key role in characterizing the characteristics of rock strata and the geological environment. The change of sedimentary environment means the change of geological historical environment, which can reflect the cementation degree, particle size, roundness, and other properties of the overburdened rock mass. Therefore, sedimentary microfacies are also one of the main factors affecting rockburst. The sedimentary microfacies of coal seam roof strata are also different due to different geological periods. For rockburst, the strata in the same period covered by coal seams are the main disaster-pregnant environment of rockburst. The main coal seam in the study area is the No.4 coal seam of the Jurassic Yan’an formation. Therefore, the sedimentary microfacies of the roof Yan’an formation are selected as one of the evaluation indexes. The distribution of the sedimentary microfacies of Yan’an formation in the roof of the study area is shown in Figure 2(c).

(4) **Geological structure (F4).** The geological structure is an important factor controlling the behavior of rockburst. Since the geological structure is a discrete and discontinuous factor, the method of structural capacity dimension can be used to quantitatively evaluate the structural complexity of the mining area [29]. Therefore, the complexity of fault or fold under the action of tectonic stress is expressed by calculating the capacity dimension of geological structure in the study area, to analyze, and study the influence of geological structure on dynamic pressure behavior. The distribution map of the geological structure capacity dimension in the study area is shown in Figure 2(d).

(5) **Maximum horizontal principal stress (F5).** In situ stress is the fundamental force that causes the deformation and failure of mining and other underground projects [11, 12]. Among them, the magnitude of the maximum horizontal principal stress has an obvious relationship with the behavior of the rockburst, and the higher maximum horizontal principal stress is the basis of the rockburst. Therefore, the maximum horizontal principal stress is selected as one of the evaluation indexes of rockburst in the evaluation model. The distribution of the maximum horizontal principal stress in the study area is shown in Figure 2(e).

4.2. Index Weight Calculation Based on LS-FAHP-CRITIC

4.2.1. Index Weight Calculation Based on FAHP. According to the selection and analysis of the above factors, the target layer of the impact risk assessment model is the rockburst risk index. The index layer includes five indexes, which are divided into coal seam thickness (F1), burial depth of the coal seam (F2), sedimentary microfacies (F3), geological structure capacity dimension (F4), and the maximum horizontal principal stress (F5).

The fuzzy complementary judgment matrix $A$ is obtained by comparing the factors of the index layer according to the establishment of the hierarchical model:

$$A = \begin{bmatrix} 0.5 & 0.6 & 0.4 & 0.3 & 0.3 \\ 0.4 & 0.5 & 0.4 & 0.3 & 0.4 \\ 0.6 & 0.6 & 0.5 & 0.4 & 0.5 \\ 0.7 & 0.7 & 0.6 & 0.5 & 0.6 \\ 0.7 & 0.6 & 0.5 & 0.4 & 0.5 \end{bmatrix}.$$ \hspace{1cm} (13)

Then, the characteristic matrix $W_A^*$ of fuzzy complementary judgment matrix $A$ is

$$W_A^* = \begin{bmatrix} 0.50 & 0.51 & 0.46 & 0.44 & 0.46 \\ 0.49 & 0.50 & 0.46 & 0.43 & 0.45 \\ 0.54 & 0.54 & 0.50 & 0.47 & 0.49 \\ 0.56 & 0.57 & 0.53 & 0.50 & 0.52 \\ 0.54 & 0.55 & 0.51 & 0.48 & 0.50 \end{bmatrix}.$$ \hspace{1cm} (14)
Figure 2: Continued.
Legend
- Lake beach deposition
- Lakeside mudflat deposition
- Lakeside swamp deposition

Figure 2: Continued.
The compatibility index is $I(A, W^*_A) = 0.1256 \geq 0.1$, which does not meet the consistency requirements.

The fuzzy consistent discrimination matrix $R$ is

$$R = \begin{bmatrix}
0.50 & 0.51 & 0.44 & 0.38 & 0.43 \\
0.49 & 0.50 & 0.43 & 0.36 & 0.41 \\
0.56 & 0.57 & 0.50 & 0.44 & 0.49 \\
0.62 & 0.64 & 0.56 & 0.50 & 0.55 \\
0.57 & 0.59 & 0.51 & 0.45 & 0.50 \\
\end{bmatrix}. \quad (15)$$

Then the characteristic matrix $W^*_R$ of fuzzy uniform discrimination matrix $R$ is:

$$W^*_R = \begin{bmatrix}
0.50 & 0.50 & 0.48 & 0.46 & 0.48 \\
0.50 & 0.50 & 0.48 & 0.46 & 0.47 \\
0.52 & 0.52 & 0.50 & 0.48 & 0.50 \\
0.54 & 0.54 & 0.52 & 0.50 & 0.51 \\
0.52 & 0.53 & 0.50 & 0.49 & 0.50 \\
\end{bmatrix}. \quad (16)$$

The compatibility index is $I(R, W^*_R) = 0.0734 < 0.1$, which meets the consistency requirements. Then calculate the weight of the corresponding indicators as shown in Table 1.

### 4.2.2. Index Weight Calculation Based on CRITIC Method

Based on the borehole exposure data and relevant geological data in the study area, the weight of each index was calculated by the CRITIC method, and the calculation results are shown in Table 2.

#### 4.2.3. Determination of Comprehensive Weights Based on LS-FAHP-CRITIC Method

Based on the least-squares method, the FAHP and the CRITIC method were coupled. Using Equation (11), it is calculated in Matlab to obtain the comprehensive weight of each factor calculated by the LS-FAHP-CRITIC, as shown in Table 3.

#### 4.3. Zoning Evaluation Model of Rockburst Risk Based on LS-FAHP-CRITIC Method

In this study, the comprehensive attribute data of the topological relationship between elements is compiled by using the topological reconstruction function in GIS software [30]. In addition, the complete map contains all information on all control factors. According to the weight of the evaluation index calculated by FAHP, the risk index model of rockburst in the study area is

$$VI = 0.2033 f_1(x, y) + 0.1681 f_2(x, y) + 0.2042 f_3(x, y) + 0.2257 f_4(x, y) + 0.1987 f_5(x, y), \quad (17)$$

where $VI$ is the risk index of rockburst and $f_i(x, y)$ is the normalized evaluation index of the $i$-th factor.

### 5. Results and Discussion

#### 5.1. Prediction Results

Since the natural breaks classification method is a statistical method that classifies and classifies...
Table 1: Calculate the weight result by FAHP method.

<table>
<thead>
<tr>
<th>Controlling factor</th>
<th>Thickness of the coal seam</th>
<th>Burial depth of the coal seam</th>
<th>Sedimentary microfacies</th>
<th>Geological structure</th>
<th>Maximum horizontal principal stress</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weights ($w_i$)</td>
<td>0.1875</td>
<td>0.1844</td>
<td>0.2031</td>
<td>0.2188</td>
<td>0.2063</td>
</tr>
</tbody>
</table>

Table 2: Calculate the weight result by CRITIC method.

<table>
<thead>
<tr>
<th>Controlling factor</th>
<th>Standard deviation</th>
<th>Index conflict</th>
<th>Index variability</th>
<th>Amount of information</th>
<th>Weights($\mu_i$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thickness of the coal seam</td>
<td>0.265</td>
<td>4.178</td>
<td>0.265</td>
<td>1.109</td>
<td>0.2187</td>
</tr>
<tr>
<td>Burial depth of the coal seam</td>
<td>0.264</td>
<td>2.897</td>
<td>0.264</td>
<td>0.765</td>
<td>0.1508</td>
</tr>
<tr>
<td>Sedimentary microfacies</td>
<td>0.248</td>
<td>4.207</td>
<td>0.248</td>
<td>1.045</td>
<td>0.2060</td>
</tr>
<tr>
<td>Geological structure</td>
<td>0.349</td>
<td>3.392</td>
<td>0.349</td>
<td>1.183</td>
<td>0.2333</td>
</tr>
<tr>
<td>Maximum horizontal principal stress</td>
<td>0.298</td>
<td>3.256</td>
<td>0.298</td>
<td>0.970</td>
<td>0.1913</td>
</tr>
</tbody>
</table>

Table 3: Calculate the weight result by LS-FAHP-CRITIC method.

<table>
<thead>
<tr>
<th>Controlling factor</th>
<th>Thickness of the coal seam</th>
<th>Burial depth of the coal seam</th>
<th>Sedimentary microfacies</th>
<th>Geological structure</th>
<th>Maximum horizontal principal stress</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weights ($\zeta_i$)</td>
<td>0.2033</td>
<td>0.1681</td>
<td>0.2042</td>
<td>0.2257</td>
<td>0.1987</td>
</tr>
</tbody>
</table>

According to the law of numerical statistical distribution, it can maximize the differences between classes. According to the risk index model, the risk assessment-zoning map of rockburst in the study area was drawn, and using the natural breaks classification method of GIS software (Figure 3), the area is divided into the safe area, relative safe area, relative dangerous area, dangerous area, and high dangerous area, as shown in Figure 4.

It can be seen from Figure 4 that there are high dangerous areas within the local scope of the mining area. When mining activities are carried out near these areas, corresponding pressure relief measures must be formulated and implemented in advance, and support work must be done well. Generally speaking, the dangerous areas in the study area are relatively widely distributed, mainly in the area near the structure with high maximum horizontal principal stress. The distribution range of safety zone and relative safety zone is relatively small, mainly concentrated in the northeast and west of the study area.

5.2. Model Verification. To verify the accuracy of the zoning results of this study, the area where the actual rockburst occurs in the Gaojiapu coal mine was selected as the validation area for the evaluation model of the research area. Based on the LS-FAHP-CRITIC method, evaluation results in this study are shown in Figure 4.

According to the results of risk zoning of rockburst, 103 coalface has a relatively high-risk index as a whole, both in dangerous and strong risk areas, especially near stopping lines, which indicates that 103 coalface has a relatively high risk of rockburst during the mining period. The risk index in the north of 204 coalface is relatively low, while the risk index in the south and the coalface are relatively large, which are in the high dangerous area.

On the basis of the actual mining situation of the Gaojiapu coal mine, rockburst occurs in the corresponding roadway area of 103 coalface during the mining period, especially when the 103 coalface is pushed to about 200 m away from the stopping line, and several strong shocks occurred near the roadway, which result in rockburst. The corresponding rockburst area near the roadway is located in the dangerous area.

In 204 coalface, although the risk index of the southern part of the coalface is relatively large, there is no rockburst at the coalface due to its small mining range. With the continuous advancement of 204 coalface, rockburst occurred in the crossheading area, and the occurrence area of rockburst along the crossheading is located in the high dangerous area. The evaluation results are consistent with the actual situation, which further verifies the validity and authenticity of the zoning results. Therefore, the zoning evaluation model of rockburst risk based on the LS-FAHP-CRITIC method is satisfactory and the predicted evaluation results are reasonable, which can be used to guide the safety production of similar mines or adjacent coalfaces.

5.3. Discussion. In order to further analyze the rationality of the selection of evaluation factors, based on the selected impact indicators, combined with the weight calculation results of the FAHP method, the rockburst risk zoning evaluation model was constructed, and the comparison of the two methods is carried out. The evaluation results of rockburst risk zoning of the FAHP method are shown in Figure 5.

The comparison between Figures 4 and 5 shows that, on the whole, the risk in the southeast region of the study area is relatively high due to the large structural distribution in this area and the large buried depth of the coal seam, and the local area is over 1000 m. In the northeast of the study area, the depositional environment is mainly composed of lakeside swamp deposits with small coal seam thickness, small burial depth, undeveloped structure, and low maximum horizontal principal stress, so it is relatively safe. Affected by the syncline structure in the middle of the study area, the axes of
The syncline structure has a large thickness of coal seam, largely buried depth, and relatively high maximum horizontal principal stress. Therefore, the traces of the syncline structure are mostly high-risk areas. The northwest part of the study area is a safe area. Although there are many synclinal structures developed in this area, the sedimentary environment is lakeside swamp deposits with a small thickness of coal seam and small maximum horizontal principal stress.
which makes the risk in this area relatively small. The evaluation results of the two methods are very close to the actual situation, which indicates that the selection of impact indicators in the rockburst risk zoning evaluation model is accurate and appropriate.

In Figure 4, the LS-FAHP-CRITIC model evaluates a locally high dangerous area on the north side of the stopping line at the 103 working face, whereas the FAHP evaluates the area as a hazardous area. Although this does not affect the final result, the risk assessment of rockburst is more...
reasonable than a conservative one before the face is recovered. The FAHP model is a subjective method, and the construction of a discriminant matrix often relies on a clear understanding of such engineering problems, otherwise, it will cause huge errors in the forecast results. Therefore, the LS-FAHP-CRITIC model as a whole is more detailed and accurate for the forecast results through subjective and objective comprehensive weights.

5.4. Future Study. In this study, taking the Gaojiapu coal mine in the Binchang mining area of Shaanxi Province as the research area, a new zoning evaluation method of coal mine rockburst risk was proposed and applied to Gaojiapu coal mine. By comparing the actual rockburst occurring area of Gaojiapu coal mine with the predicted result of this method, it shows that the predicted and evaluated result of this method is accurate and reasonable. This method cannot only provide guidance for the design of rockburst prevention and pressure relief in the research area but also provide references for other similar coal mines in the world.

Through working out different pressure relief measures for different areas with different impact risk levels in the study area, to achieve “grading” accurate pressure relief. In addition, real-time monitoring of areas with results in high dangerous areas and dangerous areas, the implementation of pressure relief measures, and reducing the mining speed can effectively reduce the occurrence of rockbursts, and prevent the occurrence of rockburst accidents.

However, there are still some deficiencies in the current research. As some mining areas may not perform in-situ stress field inversion, it is necessary to perform in-situ stress field inversion in advance when using this method. This may require a certain economic cost, which limits the application of our method. Therefore, the effect of mining intensity on rockburst risk is not considered in the method. So in future research, factors such as mining intensity should be taken into consideration, and the zoning evaluation of the rockburst risk index of mining areas under mining conditions should be further studied.

This study discusses the engineering geological model of rockburst evaluation in coal seam mining, and reasonably and accurately predicts the risk of mine rockburst behavior. The flow chart is shown in Figure 6.

6. Conclusions

Based on the five impact indicators of coal seam thickness, distribution characteristics of initial in-situ stress field, geological structure distribution, and sedimentary environment of coal seam overburden, this study puts forward a new coal mine rockburst risk zoning evaluation method. The following conclusions are drawn:

(1) Based on the engineering geological conditions of overburden in the study area, five indexes such as coal seam thickness, burial depth of the coal seam, sedimentary microfacies, geological structure capacity dimension, and the maximum horizontal principal stress are proposed as geological factors indexes for coal mine rockburst risk evaluation.

(2) Based on least square coupling FAHP and CRITIC comprehensive weighting method (LS-FAHP-CRITIC), the zoning evaluation model of coal mine rockburst risk was established, and the zoning evaluation of rockburst risk in the study area was carried out. According to the risk assessment results, the mine is divided into five areas by using the natural classification method of GIS software: safe area, relatively safe area, relative dangerous area, dangerous area, and high dangerous area. The prediction results are verified. This method can provide a basic basis and guidance for coal mine safety production and anti-scour design.

(3) Taking the rockburst appearance area in the study area as the model verification area, the accuracy of rockburst zoning evaluation results was verified. This method can provide a basic basis and guidance for coal mine safety production and anti-scour design.

(4) By comparing the FAHP method with the LS-FAHP-CRITIC method, the accuracy and rationality of the impact indicators selected by the evaluation model were verified. By analyzing the results of the two methods, it is determined that the LS-FAHP-CRITIC method is more detailed and accurate for the prediction results.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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