Analysis of Mine Safety Performance Evaluation Law Based on Matter-Element Analysis and Rough Set of Concept Lattice Reduction

JIANHONG CHEN, XUDONG ZHONG, ZITONG XU, SHAN YANG, AND YING SHI

School of Resources and Safety Engineering, Central South University, Changsha 410083, China

Corresponding authors: Shan Yang (yangshan@csu.edu.cn) and Ying Shi (shiyingfriend@csu.edu.cn)

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ABSTRACT
The mine safety performance evaluation and its law were taken as research objects; the human factor, mechanical equipment, management system, environment and technology were taken as mine safety state indexes; accident loss and disabling incident frequency rate as mine safety performance evaluation indexes. The classification standard of safety performance was determined according to the range of influence index and evaluation index, and then the influence index value of safety performance was discretized. According to the classification standard, the classical domain and node domain of safety performance evaluation index classification were determined. Combined with the weight of each safety performance evaluation index, the correlation degree of each mine safety performance evaluation was calculated, and then the safety performance was evaluated, and the mine safety performance evaluation decision system was constructed. Based on the dominance-based rough set, the evaluation law of mine safety performance evaluation decision system was analyzed. To generate more reliable laws, an efficient concept lattice reduction method was introduced to reduce the attributes of decision system. The example shows that when the concept lattice is used for reduction, there are 84 concepts in the Hasse diagram, and 24 of them can be identified. The decision system has 8 conditional attributes. And 255 power sets can be obtained under 8 conditional attributes. After eliminating the defect attribute, there are 148 reducible sets, among which there are 4 optimal reducible sets with two conditional attributes. The results show that the proposed method can be used to analyze the law of mine safety performance, so as to improve mine safety work.

INDEX TERMS Mine, safety performance, matter-element analysis, concept lattice.

I. INTRODUCTION
Mine safety evaluation is to evaluate the safety of each link or the whole in the mine production and management operation, which provides reference and support for mine safety decision-making. The rapid and accurate mine safety evaluation can effectively prevent the occurrence of mine safety disasters, which is of great significance to mine production. Mine safety evaluation mainly includes two aspects: influence factor evaluation and influence result evaluation. Influence factor evaluation, also known as safety state evaluation, is the evaluation of various inputs or influence factors for mine safety; influence result evaluation, also known as safety performance evaluation, is the evaluation of the results embodied in mine safety. In the past, the mine safety evaluation has been performed in the unilateral evaluation of mine safety state or mine safety performance, and the relationship between mine safety state and mine safety performance has been rarely analyzed, and the causal relationship of mine safety was not revealed. If the causal relationship between mine safety state and safety performance can be analyzed and obtained, the mine safety production and management can be guided, then the high-efficiency mine safety production can be ensured.

At present, most of mine safety evaluation is carried out by means of mathematical analysis, among which fuzzy mathematics, analytic hierarchy process and grey theory are the most commonly used mathematical methods.
Zheng-wen and Fan-yu used the fuzzy comprehensive evaluation method based on entropy technology to evaluate mine safety performance [3]. Sen and Jian-hong evaluated mine safety performance by grey interval correlation analysis [4]. James O., Jr. used the audit procedure to evaluate the safety performance [5]. The safety performance was effectively evaluated in the above studies. However, the single evaluation on the safety state and safety performance of mines was conducted by mathematical methods in these studies, while the internal relationship between the safety state and safety performance cannot be analyzed and revealed, leading to the insufficiency of the support information for mine safety production. As a result, the support and help provided for mine safety are limited [6].

Mine safety performance evaluation based on matter-element analysis is the evaluation and analysis of mine safety performance using mathematical methods. Based on the classification standard of each safety performance index, the matter-element analysis method determines the classical domain and node domain of each safety performance index, and carries out weighted calculation according to the weight of each index factor, so as to obtain the correlation degree of mine safety performance at all grades. Through the correlation degree of each grade, the mine safety performance grade is determined according to the maximum membership principle. For the causality analysis of mine safety evaluation and safety performance evaluation, the dominance-based rough set theory can be used. The dominance-based rough set theory [7]–[9] is based on the traditional rough set theory, and the dominance relation is used to replace the indiscernibility relation-based rough set theory [10], [11]. In the dominance-based rough set theory, the state index of mine safety evaluation and the preference information in the state index are both comprehensively considered. Attribute reduction is the core problem of law analysis in the rough set, which is directly related to the accuracy, scientificity and complexity of rough set analysis. However, the efficiency of traditional discernibility matrices in searching for reduction is not high. The concept lattice is used to replace the discernibility matrices of the traditional rough set to reduce attributes, and the preference decision table is transformed into the formal background, and the Hasse diagram corresponding to the concept lattice is generated. As a result, the redundant connotation is removed from equivalent connotation of concept lattice, and reduction concept lattice is formed, which improves the reduction efficiency and deepens the reduction connotation [12], [13]. Therefore, the theoretical basis of mine safety performance grade evaluation based on matter-element analysis method is relatively perfect, and the analysis process is scientific, simple and easy; the analysis of safety evaluation law based on dominance-based rough set theory has sufficient information mining and comprehensive analysis system, which provides comprehensive and diverse information for mine safety production decision-making [14]; in addition, the application of concept lattice reduction method greatly improves the reduction efficiency, thus reducing the difficulty and complexity of the analysis. Therefore, the matter-element analysis and dominance-based rough set of concept lattice reduction can carry out systematic, scientific, effective and simple safety evaluation and connotation law analysis for mine production, which is helpful to optimize and improve the grade of mine safety production management [15]–[18].

II. SYSTEM MODELING
A. SYSTEM INDEX CONSTRUCTION
The mine safety evaluation index system mainly includes two aspects: the mine safety state index system representing influence factors of mine safety, and the mine safety performance index system representing the mine safety results [18].

1) SAFETY STFETY INDEX SYSTEM
According to relevant theories, safety production factors can be classified according to personnel, machinery, materials, methods and environment. Based on this, the mine safety state indexes can be summarized as five first-class indexes: human factor C1, equipment factor C2, management system factor C3, environmental factor C4 and technical factor C5. Specifically, human factor C1 can be concretely divided into safety skills c1 and safety awareness c2; equipment factor C2 can be embodied as equipment safety performance c3 and protective equipment c4; management system factor C3 can be embodied as safety production organization c5, safety production system c6 and safety production rate c7 (Note: safety production rate is the percentage of safety investment and total project cost); environmental factor C4 can be embodied as potential hazard risk c8 and possible accident severity c9; and technical factor C5 can be embodied as process safety c10 and technical safety measures c11. Among the above secondary indexes, some are qualitative analysis indexes, and some are quantifiable analysis indexes. To improve the accuracy of mine safety evaluation and law analysis, the qualitative indexes were scored by experts and the quantitative indexes were used for unified quantitative analysis. Figure 1 shows the state indexes of mine safety.

There are many secondary indexes in the mine safety state index system. In the actual analysis, the above secondary indexes can be increased, reduced, merged and refined according to the number of samples and the actual situation of mine analysis, then secondary indexes which are close to the reality and convenient for analysis can be formed.

2) SAFETY PERFORMANCE INDEX SYSTEM
The safety performance index is the quantity representing safety performance, and its essence is the result of safety state index after time and space transition. According to the definition and description of relevant literature, safety performance indexes can be divided into accident loss D1 and disabling incident frequency rate D2. The accident loss D1 can be subdivided into economic loss d1 and man-hour
loss $d_2$, and the disabling incident frequency rate $D_2$ can be subdivided into minor injury accident rate $d_3$, serious injury accident rate $d_4$ and death rate per 10,000 people $d_5$. The secondary indexes of safety performance are quantitative indexes, and the mine safety performance index system is shown in Figure 2.

B. MINE SAFETY PERFORMANCE EVALUATION

1) CLASSIFICATION STANDARD OF MINE SAFETY GRADE

In the final result of mine safety performance evaluation, there must be preference attributes that can be used to classify the mine safety state indexes. Generally speaking, mine safety performance evaluation can be divided into 3 - 5 categories according to preference attributes. The more categories are, the finer the classification granularity is, and the more analysis samples are required. The three categories can be subdivided into {excellent, medium and poor}, and the five categories can be subdivided into {excellent, good, medium, general and poor}. Mine safety state indexes can be classified according to each performance grade.

2) MINE SAFETY PERFORMANCE EVALUATION BASED ON MATTER-ELEMENT ANALYSIS

According to the mine safety performance index value to be evaluated, the matter-element matrix $R_0$ of the safety
performance index of this mine is established

\[
R_0 = \begin{bmatrix}
R_1 \\
R_2 \\
\vdots \\
R_n
\end{bmatrix} = \begin{bmatrix}
P_0 & D_1 & X_1 \\
D_2 & X_2 \\
\vdots & \vdots & \vdots \\
D_n & X_n
\end{bmatrix}
\]

(1)

where \(P_0\) is the mine to be evaluated, \(D_i\) is the \(i\)-th safety performance evaluation index, \(X_i\) is the specific value of the \(i\)-th safety performance index, \(i = 1, 2, \ldots, n, n = 5\).

The classical region \(R_0\) of mine safety performance evaluation classification can be expressed as:

\[
R_0(N_j, C, X_j) = \begin{bmatrix}
N_j & D_1 & X_{j1} \\
D_2 & X_{j2} \\
\vdots & \vdots & \vdots \\
D_n & X_{jn}
\end{bmatrix}
\]

(2)

where \(N_j\) is the \(j\)-th evaluation grade, \(D_i\) is the \(i\)-th safety performance evaluation index, \(X_{ji} = [a_{ji}, b_{ji}]\) is the range of \(N_j\) values about \(D_i\), where \(j = 1, 2, \ldots, m\). And \(m\) is the classification number of mine safety performance evaluation, and \(m\) ranges from 3 - 5.

The node domain matter-element \(R_p\) is as follows:

\[
R_p(N_p, C, X_p) = \begin{bmatrix}
N_p & D_1 & X_{p1} \\
D_2 & X_{p2} \\
\vdots & \vdots & \vdots \\
D_n & X_{pn}
\end{bmatrix}
\]

(3)

where \(N_p\) is the set of all grades of mine safety evaluation, \(D_i\) is the \(i\)-th influence index, \(X_{pi} = [a_{pi}, b_{pi}]\) is the value range of \(N_p\) about index \(D_i\), where \(j = 1, 2, \ldots, m\).

Obviously, for index \(D_i\), there is always \(X_{ji} \subset X_{pi}\), and \(i = 1, 2, \ldots, n, n = 5\).

The weight set \(W\) of each performance index in the comprehensive evaluation of mine safety performance is determined by experience judgment or mathematical calculation.

\[
W = [w_1, w_2, \ldots, w_a]
\]

(4)

According to the classical domain and the weight of each performance index, the correlation degree of each grade of mine safety performance evaluation is calculated, and the correlation degree represents the degree that the matter-element meets the required value range. The distance from a point \(x_i\) to the classical domain interval \(X_{ji}\) is

\[
\rho(x_i, X_{ji}) = \begin{cases}
x_i - 0.5(a_{ji} + b_{ji}) & x_i \geq 0.5(a_{ji} + b_{ji}) \\
0.5(b_{ji} - a_{ji}) & x_i < 0.5(a_{ji} + b_{ji})
\end{cases}
\]

(5)

The distance \(\rho(x_i, X_{pi})\) from the point \(x_i\) to the node region \(X_{pi}\) is:

\[
\rho(x_i, X_{pi}) = \begin{cases}
x_i - 0.5(a_{pi} + b_{pi}) & x_i \geq 0.5(a_{pi} + b_{pi}) \\
0.5(b_{pi} - a_{pi}) & x_i < 0.5(a_{pi} + b_{pi})
\end{cases}
\]

(6)

The calculation formula of the correlation function \(K_j(x_i)\) of point \(x_i\) about the mine safety performance evaluation grade \(j\) is as follows:

\[
K_j(x_i) = \begin{cases}
-\frac{\rho(x_i, X_{ji})}{|X_{ji}|} & x \in X_{ji} \\
\frac{\rho(x_i, X_{ji}) - \rho(x_i, X_{ji})}{|X_{ji}|} & x \notin X_{ji}
\end{cases}
\]

(7)

and \(|X_{ji}| = |a_{ji} - b_{ji}|\).

According to the correlation function and \(i\) index factor weight \(w_i\), the comprehensive correlation degree \(K_j(P_0)\) of mine safety performance belonging to grade \(j\) is obtained as follows:

\[
K_j(P_0) = \sum_{i=1}^{n} w_i K_j(x_i)
\]

(8)

Mine safety performance evaluation criteria are as follows:

\[
K_j = \max(K_j(P_0))
\]

(9)

**C. ANALYSIS OF Mine Safety PERFORMANCE RULE**

1) ESTABLISHMENT OF EVALUATION DECISION TABLE

In this study, the results of mine safety performance evaluation are taken as decision attributes, and the mine safety state indexes as condition attributes; then the decision table of rough set analysis for mine safety performance evaluation is established.

2) DATA DISCRETIZATION

According to the classification standard of each mine safety state index in the rough set analysis decision table of mine safety performance evaluation, the data of each mine safety state index are classified and discretized. Because the classification attribute of mine safety state index has the bias tendency to mine safety performance, the preference decision table of mine safety performance evaluation rough set analysis is generated.
3) REDUCTION SEARCH BASED ON CONCEPT LATTICE
In concept lattice theory, if two object concepts \((A_1, B_1), (A_2, B_2)\) share a common parent concept \((A, B)\), and the connotation of the parent concept \((A, B)\) does not contain decision attributes and \(V_D \cap B_1 \neq \emptyset \lor V_D \cap B_2 \neq \emptyset\), then the common parent concept \((A, B)\) is called the compatible and distinguishable concept of concepts \((A_1, B_1), (A_2, B_2)\), where \(V_D\) is the decision attribute set.

For concepts \((A, B)\), if the condition attribute \(C_i\) in the original decision table satisfies \(V_{C_i} \cap B_2 = \emptyset\), then the set of all condition attributes \(C_i\) satisfying this condition is called the deficiency attribute of concepts \((A, B)\) relative to the initial decision table.

From the preference decision table of mine safety performance evaluation, the power set of conditional attributes is removed from the set containing deficient attributes, that is, the reducible attribute set is finally obtained [16]-[18]. The reducible attributes are removed from the conditional attributes of the preference decision table of mine safety performance evaluation, and the conditional attribute reduction after concept lattice reduction is obtained.

4) GENERATION OF PREFERENCE RULES
As before, mine safety performance grades can be generally divided into three or five categories. The mine safety performance grade of three categories \{excellent, medium and poor\} is taken as an example, then the generation process of preference rules is explained. The condition attribute and decision attribute in the preference decision table of mine safety performance evaluation have preference information for mine safety performance. Therefore, the comprehensive evaluation category can be divided into three preference order categories: \(Cl_1 = \{\text{poor}\}, Cl_2 = \{\text{general}\}, Cl_3 = \{\text{excellent}\}\) according to the decision attribute of mine safety performance. In line with the preference decision class, the domain is divided, and the union of decision classes is obtained as follows:

\[
Cl_i^{\geq} = Cl_i \text{ indicates that the mine safety performance is poor;}
\]

\[
Cl_i^{\leq} = Cl_i \cup Cl_2 \text{ indicates that the mine safety performance is general or poor;}
\]

\[
Cl_i^{=} = Cl_2 \cup Cl_3 \text{ indicates that the mine safety performance is excellent or general;}
\]

\[
Cl_t^{=} = Cl_3 \text{ indicates that the mine safety performance is excellent.}
\]

According to the selected reduction attributes, the least preference decision rule sets \(D_{\geq}\) and \(D_{\leq}\) are generated.

The at-least decision rule \(D_{\geq}\) is as follows:

\[
if f(x, q_1) \geq r_{q_1} \land f(x, q_2) \geq r_{q_2} \cdots \land f(x, q_p) \geq r_{q_p} \quad \text{then } x \in Cl_i^{\geq}
\]

The at-most decision rule \(D_{\leq}\) is as follows:

\[
if f(x, q_1) \leq r_{q_1} \land f(x, q_2) \leq r_{q_2} \cdots \land f(x, q_p) \leq r_{q_p} \quad \text{then } x \in Cl_i^{\leq}
\]

where, \(\{q_1, q_2, \cdots, q_p\} \subseteq C, (r_{q_1}, r_{q_2}, \cdots, r_{q_p}) \in V_{q_1} \times V_{q_2} \times \cdots \times V_{q_p}\) and \(t\) is the number of preference order classes. According to the generated preference rules, the mine safety performance can be evaluated by using the index attributes of the mine safety state contained in the optimal reduction.

The system modeling flow chart is shown in Figure 3.

FIGURE 3. System analysis flowchart.

III. CASE ANALYSIS
A. ENGINEERING BACKGROUND
A metallogenic belt is located at the junction of Yunnan and Guizhou. There are dozens of medium and small-scale mines in the metallogenic belt. For a long time, due to the constraints of capital, technology, personnel structure and staff quality of mining enterprises, the mine safety performance has not been high. Although mining enterprises have invested a lot of manpower, material resources, financial resources and energy to carry out safety work, safety accidents still occur frequently, resulting in huge casualties and property losses. To improve the mine safety work and improve the mine safety benefits in this area, the mine authorities plan to conduct scientific analysis on the mine safety investment and performance, and improve the relevant constraints. In this paper, a group of mining enterprises with different representativeness in this region was selected, and statistics on the average annual safety state index (representing safety input) and safety performance index of mining enterprises in the past 15 years were statistically analyzed. According to the actual situation of mine safety work in this region, the relevant
TABLE 1. State indexes of mine safety.

| Evaluation objects | Safety state indexes |
|--------------------|---------------------|
|                    | Safety awareness $c_1$ | Safety skills $c_2$ | Equipment safety $c_3$ | Safety organization system $c_4$ | Safety production rate $c_5$ | Environmental risk $c_6$ | Process safety $c_7$ | Safety technical measures $c_8$ |
| 1°Mine              | 65                  | 67                   | 71                     | 88                     | 1.5%                  | 55                    | 72                    | 87                    |
| 2°Mine              | 52                  | 87                   | 74                     | 88                     | 3.7%                  | 76                    | 64                    | 90                    |
| 3°Mine              | 60                  | 87                   | 81                     | 90                     | 2.9%                  | 67                    | 84                    | 82                    |
| 4°Mine              | 70                  | 82                   | 82                     | 81                     | 3.2%                  | 79                    | 82                    | 65                    |
| 5°Mine              | 66                  | 81                   | 63                     | 82                     | 2.9%                  | 64                    | 69                    | 80                    |
| 6°Mine              | 68                  | 61                   | 62                     | 82                     | 1.9%                  | 58                    | 63                    | 62                    |
| 7°Mine              | 84                  | 92                   | 87                     | 83                     | 3.6%                  | 71                    | 87                    | 69                    |
| 8°Mine              | 55                  | 67                   | 73                     | 85                     | 1.8%                  | 59                    | 66                    | 82                    |
| 9°Mine              | 76                  | 82                   | 81                     | 93                     | 2.6%                  | 63                    | 90                    | 74                    |
| 10°Mine             | 62                  | 83                   | 71                     | 91                     | 2.7%                  | 74                    | 72                    | 91                    |
| 11°Mine             | 73                  | 64                   | 70                     | 91                     | 1.2%                  | 49                    | 72                    | 80                    |
| 12°Mine             | 59                  | 82                   | 70                     | 84                     | 4.7%                  | 69                    | 76                    | 83                    |
| 13°Mine             | 81                  | 82                   | 88                     | 89                     | 3.6%                  | 85                    | 93                    | 84                    |
| 14°Mine             | 62                  | 52                   | 61                     | 83                     | 1.3%                  | 55                    | 69                    | 83                    |
| 15°Mine             | 52                  | 90                   | 65                     | 86                     | 3.2%                  | 71                    | 77                    | 84                    |
| 16°Mine             | 85                  | 72                   | 64                     | 88                     | 1.8%                  | 59                    | 78                    | 74                    |
| 17°Mine             | 62                  | 87                   | 91                     | 82                     | 4.6%                  | 83                    | 83                    | 92                    |
| 18°Mine             | 69                  | 82                   | 70                     | 84                     | 4.2%                  | 69                    | 76                    | 83                    |
| 19°Mine             | 77                  | 65                   | 69                     | 81                     | 1.5%                  | 47                    | 63                    | 54                    |
| 20°Mine             | 68                  | 86                   | 72                     | 91                     | 3.4%                  | 76                    | 68                    | 89                    |

Note: the score of the qualitative index is 100 points.

indexes of mine safety are optimized and merged. The safety awareness $c_1$, safety skills $c_2$, mechanical equipment safety $c_3$, safety organization system $c_4$, safety production rate $c_5$, environmental risk $c_6$, process safety $c_7$, safety technical measures $c_8$ were selected as mine safety state indexes; economic loss $d_1$, working hour loss $d_2$, the minor injury accident rate $d_3$, the serious injury accident rate $d_4$, and the death rate per 10,000 people $d_5$ were taken as the mine safety performance indexes. The safety production rate $c_5$, economic loss $d_1$, man-hour loss $d_2$, minor injury accident rate $d_3$, serious injury accident rate $d_4$ and death rate of ten thousand people $d_5$ were quantitative indexes, which can be directly quantified, and the other indexes are qualitative indexes. To facilitate the quantitative analysis of the indexes and increase the scientificity of the analysis process, the positive score of qualitative indexes was changed into quantitative indexes, so that the quantitative analysis can be carried out. The higher the score, the better the mine safety performance.

Table 1 shows the statistical results of mine safety state indexes.

Table 2 shows mine safety performance indexes.

B. MINE SAFETY PERFORMANCE EVALUATION

1) GRADING STANDARD OF SAFETY PERFORMANCE INDEX

According to the statistics, the range of safety performance indexes of the mines to be analyzed is as follows: economic loss is 136,000 - 7,843,000 yuan; working hours loss is 25 - 622 workday; minor injury accident rate is 9 - 69 times; serious injury accident rate is 5 - 33 times; death rate of the ten thousand people is 0 - 11.7. Considering the serious influence degree of safety performance index, unequal interval classification is adopted for safety performance index value, and the proposed classification standard is shown in Table 3.

2) WEIGHT CALCULATION OF INFLUENCE FACTORS

In the evaluation of the matter-element analysis method, the mine safety performance needs to be based on the weight of each performance index. According to the characteristics of the mine safety performance index, the weight is calculated by the relative importance correlation grade calculation method. According to the experience of relevant experts, the correlation grade of the relative importance degree of each index weight is assigned. The relative importance correlation grade of each index of mine safety performance is obtained, as shown in Table 4.

According to Table 4, the weight of mine safety performance index is calculated as follows: 

$$
\{\text{economic loss}, \text{man-hour loss, minor injury accident rate, serious injury accident rate, death rate per 10,000 people}\} = (w_1, w_2, w_3, w_4, w_5) = (0.09, 0.05, 0.15, 0.27, 0.44).$$

Through the consistency test of index weight matrices, the consistency index $CI = 0.0107$, the number of indexes
TABLE 2. Mine safety performance state indexes.

| Evaluation objects | Safety performance indexes |
|--------------------|---------------------------|
|                    | Economic loss $d_1$ (ten thousand yuan) | Man hour loss $d_2$ (workday) | Minor injury accident rate $d_3$ (number) | Serious injury accident rate $d_4$ (number) | Death rate per 10,000 people $d_5$ (number) |
| 1# Mine            | 584.3                      | 366                           | 62                                           | 37                                           | 14.2                                           |
| 2# Mine            | 124.7                      | 228                           | 22                                           | 7                                            | 3.9                                            |
| 3# Mine            | 13.6                       | 32                             | 27                                           | 9                                            | 3.2                                            |
| 4# Mine            | 53.6                       | 44                             | 9                                            | 5                                            | 0                                              |
| 5# Mine            | 328.5                      | 43                             | 51                                           | 11                                           | 6.2                                            |
| 6# Mine            | 384.3                      | 508                            | 63                                           | 46                                           | 13.1                                           |
| 7# Mine            | 23.9                       | 41                             | 38                                           | 11                                           | 3.4                                            |
| 8# Mine            | 784.3                      | 622                            | 61                                           | 35                                           | 12.6                                           |
| 9# Mine            | 44.9                       | 39                             | 22                                           | 5                                            | 0                                              |
| 10# Mine           | 328.5                      | 43                             | 51                                           | 11                                           | 6.2                                            |
| 11# Mine           | 312.8                      | 112                            | 59                                           | 37                                           | 14.6                                           |
| 12# Mine           | 319.4                      | 72                             | 23                                           | 7                                            | 11.7                                           |
| 13# Mine           | 34.6                       | 25                             | 12                                           | 8                                            | 2.2                                            |
| 14# Mine           | 666.9                      | 374                            | 62                                           | 39                                           | 18.2                                           |
| 15# Mine           | 132.5                      | 31                             | 17                                           | 7                                            | 6.9                                            |
| 16# Mine           | 412.4                      | 223                            | 69                                           | 37                                           | 14.1                                           |
| 17# Mine           | 59.4                       | 45                             | 24                                           | 5                                            | 1.9                                            |
| 18# Mine           | 32.5                       | 131                            | 23                                           | 13                                           | 8.9                                            |
| 19# Mine           | 212.4                      | 418                            | 72                                           | 43                                           | 17.9                                           |
| 20# Mine           | 77.8                       | 131                            | 23                                           | 17                                           | 6.1                                            |

Note: minor injury accident rate and serious injury accident rate refer to the number of accidents, not the ratio. The death rate of ten thousand people refers to the number of deaths in ten thousand people.

TABLE 3. Classification of mine safety performance.

| Indexes                             | Excellent | General | Poor      |
|-------------------------------------|-----------|---------|-----------|
| Economic loss (ten thousand yuan)   | [0,50)    | [50,500) | [500,1000)|
| Man hour loss (workday)             | [0,50)    | [50,500) | [500,1000)|
| Minor injury accident rate (number) | (0,10)    | (10,100) | (100,200)|
| Serious injury accident rate (number)| (0,5)    | (5,50)   | (50,100)|
| Death rate per 10,000 people (number) | (0,5)    | (5,10)   | (10,20)|

$n = 5$, $RI = 1.12$, and the consistency ratio $CR = CI/RI = 0.0096<0.1$ are calculated. Therefore, the weight distribution of each index of mine safety performance is reasonable.

3) CALCULATION OF CORRELATION DEGREE

The classical domains of mine safety performance evaluation are as follows:

$R_a = \begin{bmatrix}
\text{Excellent Economic loss} & [0, 50)
\text{Manhour loss} & [0, 50)
\text{Minor injury accident rate} & [0, 10)
\text{Serious injury accident rate} & [0, 5)
\text{Death rate per 10,000 people} & [0, 5)
\end{bmatrix}$

$R_b = \begin{bmatrix}
\text{Medium Economic loss} & [50, 500)
\text{Manhour loss} & [50, 500)
\text{Minor injury accident rate} & [10, 100)
\text{Serious injury accident rate} & [5, 50)
\text{Death rate per 10,000 people} & [5, 10)
\end{bmatrix}$

$R_c = \begin{bmatrix}
\text{Poor Economic loss} & [500, 1000)
\text{Manhour loss} & [500, 1000)
\text{Minor injury accident rate} & [100, 200)
\text{Serious injury accident rate} & [50, 100)
\text{Death rate per 10,000 people} & [10, 20)
\end{bmatrix}$

The node domain of mine safety performance evaluation are as follows:

$R_a = \begin{bmatrix}
\text{Excellent Economic loss} & [0, 50)
\text{Manhour loss} & [0, 50)
\text{Minor injury accident rate} & [0, 10)
\text{Serious injury accident rate} & [0, 5)
\text{Death rate per 10,000 people} & [0, 5)
\end{bmatrix}$

Taking the safety performance evaluation of the 1# mine as an example, the process of evaluating mine safety performance by matter-element analysis method is illustrated.
TABLE 4. Relative importance correlation grade calculation method.

| Indices                  | Economic loss | Man hour loss | Minor injury accident rate | Serious injury accident rate | Death rate per 10,000 people |
|--------------------------|---------------|---------------|---------------------------|-----------------------------|-----------------------------|
| Economic loss            | 1             | 2             | 1/2                       | 1/3                         | 1/5                         |
| Man hour loss            | 1/2           | 1             | 1/3                       | 1/5                         | 1/6                         |
| Minor injury accident rate| 2             | 3             | 1                         | 1/2                         | 1/3                         |
| Serious injury accident rate| 3             | 5             | 2                         | 1                           | 1/2                         |
| Death rate per 10,000 people| 5             | 6             | 3                         | 2                           | 1                           |

The matter-element \( R_c \) of 1\# mine safety performance index to be evaluated is

\[
R_c = \begin{bmatrix}
1\# Mine & Economic loss & 584.3 \\
& Man hour loss & 366 \\
& Minor injury accident rate & 62 \\
& Serious injury accident rate & 37 \\
& Death rate per 10,000 people & 14.2 
\end{bmatrix}
\]

According to Equations (5) (6) (7), the correlation degree of 1\# mine safety performance corresponding to each grade is shown in Table 5.

According to the weights of influence factors and Equation (8), the comprehensive correlation degrees of 1\# mine safety performance belonging to excellent, general and poor are \(-0.5373\), \(-0.0438\) and \(0.0594\) respectively. The safety performance grade of the maximum correlation degree belongs to general, that is to say, the safety performance of 1\# mine is poor.

The above safety performance judgment process for other mines is repeated, and the safety performance grade judgment results of all mines are shown in Table 6.

As shown in Table 6, among the 20 mines, only 6 mines have good safety performance evaluation results, less than 1/3 of the total number of sample mines. It indicates that the safety performance of mines in this region is not optimistic.

TABLE 5. Correlation degree of 1\# mine safety performance grade.

| Influence factors                  | Mine safety performance | Excellent | General | Poor |
|------------------------------------|-------------------------|-----------|---------|------|
| Economic loss                      | -0.5624                 | -0.1686   | 0.1686  |
| Man hour loss                      | -0.6633                 | 0.2978    | -0.2680 |
| Minor injury accident rate         | -0.4561                 | 0.4222    | -0.3800 |
| Serious injury accident rate       | -0.4638                 | 0.2889    | -0.2600 |
| Death rate per 10,000 people       | -0.6133                 | -0.4200   | 0.4200  |

TABLE 6. Judgment result Table of mine safety.

| Evaluation objects | Correlation degree of safety performance grades | Maximu m correlation degree | Judgment result |
|-------------------|-----------------------------------------------|-----------------------------|-----------------|
| 1\# Mine          | -0.5373                                       | -0.0438                     | -0.0594         | Poor            |
| 2\# Mine          | -0.0718                                       | -0.0301                     | -0.7124         | -0.0301         | General         |
| 3\# Mine          | 0.0598                                        | -0.1896                     | -0.7645         | 0.0598          | Excellent       |
| 4\# Mine          | 0.0153                                        | -0.4603                     | -0.9455         | 0.0153          | Excellent       |
| 5\# Mine          | -0.2678                                       | 0.2372                      | -0.5279         | 0.2372          | General         |
| 6\# Mine          | -0.4994                                       | -0.0284                     | 0.0393          | 0.0393          | Poor            |
| 7\# Mine          | 0.0339                                        | -0.1141                     | -0.7256         | 0.0339          | Excellent       |
| 8\# Mine          | -0.5155                                       | -0.0228                     | 0.0259          | 0.0259          | Poor            |
| 9\# Mine          | -0.0328                                       | -0.4402                     | -0.9280         | -0.0328         | Excellent       |
| 10\# Mine         | -0.2678                                       | 0.2372                      | -0.5279         | 0.2372          | General         |
| 11\# Mine         | -0.5338                                       | -0.0117                     | -0.0018         | -0.0018         | Poor            |
| 12\# Mine         | -0.3636                                       | -0.0026                     | -0.3482         | -0.0026         | General         |
| 13\# Mine         | 0.1513                                        | -0.2778                     | -0.8333         | 0.1513          | Excellent       |
| 14\# Mine         | -0.6630                                       | -0.2475                     | -0.0198         | -0.0198         | Poor            |
| 15\# Mine         | -0.2143                                       | 0.1884                      | 0.6062          | 0.1884          | General         |
| 16\# Mine         | -0.5252                                       | -0.0140                     | 0.0202          | 0.0202          | Poor            |
| 17\# Mine         | 0.1046                                        | -0.2526                     | -0.8382         | 0.1046          | Excellent       |
| 18\# Mine         | -0.2787                                       | 0.1440                      | -0.4848         | 0.1440          | General         |
| 19\# Mine         | -0.6369                                       | -0.2173                     | -0.0474         | -0.0474         | Poor            |
| 20\# Mine         | -0.2759                                       | 0.2050                      | -0.5782         | 0.2050          | General         |

C. ANALYSIS OF MINE SAFETY PERFORMANCE EVALUATION LAW

1) ESTABLISHMENT OF THE DECISION-MAKING KNOWLEDGE SYSTEM

In this study, mine safety state index is taken as condition attribute \( C \), and the mine safety performance judgment result is taken as decision attribute \( D \), the decision-making knowledge system of mine safety performance evaluation law analysis is established.

2) DATA DISCRETIZATION

According to the range of safety state index values of each mine in Table 1, equal interval discretization is taken as the basic principle. Except for the percentage of safety production rate, other indexes of mine safety state are quantified by 100-point positive scoring system. The safety state index of safety production rate was discretized by \([0,2\%)\) as low, \([2\%,4\%)\) as medium and \([4\%,6\%)\) as high, the other state indexes of mine safety are discretized by \([40,60)\) as low, \([60,80)\) as medium and \([80,100)\) as high. The mine safety performance judgment results obtained in Table 6 are directly taken as the decision attributes, and the mine safety performance evaluation decision table is constructed based on this, as shown in Table 7.
TABLE 7. Evaluation decision table of mine safety.

| Evaluation object set U | Condition attribute C | Decision attribute D |
|-------------------------|-----------------------|---------------------|
|                         | Safety awareness $c_1$ | Safety skills $c_2$ | Equipment safety $c_3$ | Safety organization system $c_4$ | Safety production rate $c_5$ | Environmental risk $c_6$ | Process safety $c_7$ | Safety technical measures $c_8$ | Mine safety performance $d$ |
| $n_1$                   | Medium                | Medium              | Medium                | High                        | Low                         | Low                         | Medium                 | High                         | Poor                        |
| $n_2$                   | Low                   | High                | Medium                | High                        | Medium                      | Medium                      | Medium                 | Medium                      | General                     |
| $n_3$                   | Medium                | High                | High                  | High                        | Medium                      | Medium                      | Medium                 | High                         | Excellent                   |
| $n_4$                   | Medium                | High                | High                  | Medium                      | Medium                      | Medium                      | Medium                 | High                         | General                     |
| $n_5$                   | Medium                | High                | Medium                | High                        | Medium                      | Low                         | Medium                 | Medium                      | Poor                        |
| $n_6$                   | Medium                | High                | High                  | Low                         | Medium                      | Low                         | Medium                 | Medium                      | Excellent                   |
| $n_7$                   | High                  | High                | High                  | Medium                      | Medium                      | High                         | Medium                 | Excellent                   | Poor                        |
| $n_8$                   | Low                   | Medium              | Medium                | High                        | Low                         | Low                         | Medium                 | High                         | Poor                        |
| $n_9$                   | Medium                | High                | High                  | High                        | Medium                      | High                         | Medium                 | General                     | Excellent                   |
| $n_{10}$                | Medium                | High                | High                  | Medium                      | Medium                      | Low                         | Medium                 | Medium                      | Poor                        |
| $n_{11}$                | Medium                | High                | Medium                | Medium                      | Low                         | Medium                      | Medium                 | High                         | General                     |
| $n_{12}$                | Low                   | High                | High                  | Low                         | Medium                      | Medium                      | Medium                 | High                         | Poor                        |
| $n_{13}$                | High                  | High                | High                  | High                        | High                         | High                         | High                   | High                         | Excellent                   |
| $n_{14}$                | Medium                | Low                  | Medium                | Low                         | Low                         | Medium                      | Medium                 | High                         | Poor                        |
| $n_{15}$                | Low                   | High                | Medium                | Medium                      | Medium                      | Medium                      | Medium                 | High                         | General                     |
| $n_{16}$                | High                  | Medium              | Medium                | High                        | Low                         | Low                         | Medium                 | Medium                      | Poor                        |
| $n_{17}$                | Medium                | High                | High                  | High                        | High                         | High                         | High                   | High                         | Excellent                   |
| $n_{18}$                | Medium                | High                | Medium                | High                        | Medium                      | Medium                      | Medium                 | High                         | General                     |
| $n_{19}$                | Medium                | Medium              | High                  | Low                         | Medium                      | Low                         | Medium                 | Low                         | Poor                        |
| $n_{20}$                | Medium                | High                | Medium                | Medium                      | Medium                      | Medium                      | Medium                 | High                         | General                     |

Note: $n_1$-$n_{20}$ corresponds to $1^\text{st}$-$20^\text{th}$ mines.

3) ATTRIBUTE REDUCTION

Reduction is the most important part of the rough set analysis, which is directly related to the complexity and accuracy of law analysis and the law support number (law reliability). Compared with the traditional indiscernibility relation reduction analysis, the concept gehastu model, which is more scientific and richer in connotation, is adopted for attribute reduction. The formal background of mine safety evaluation decision-making established by the concept gehastu model is shown in Table 8.

After the formal background is established, the Hasse diagram of the concept lattice corresponding to the formal background is generated by using lattice miner 1.4 software, as shown in Figure 4. There are 84 nodes in the Hasse diagram, that is, 84 concepts can be found in the concept lattice corresponding to the formal background in Table 8, among which 24 are compatible and distinguishable.

From the Hasse diagram, the relationship between the parent concept and the child concept can be clearly seen. According to the definition of the defect attribute, the defect attribute of the decision table of mine safety performance evaluation is \{c3, c7, c2, c5, c6, c1, c2, c5\}. As there are up to 8 conditional attributes in this decision table, namely \{c1, c2, c3, c4, c5, c6, c7, c8\}, the power set is up to 255. After eliminating the set containing deficient attributes from the power set, 148 reducible attribute sets can be obtained. Among them, there are 4 6-conditional attribute sets, 22 5-conditional attribute sets, 40 4-conditional attribute sets, 47 3-conditional attribute sets, 27 2-conditional attribute sets, and 8 1-conditional attribute sets in the reducible attribute set. After eliminating any of the above reducible attribute sets, the reduced attribute of mine safety performance evaluation knowledge system can be obtained. According to the definition of optimal reduction: the minimum reduction of conditional attributes is the optimal reduction, that is, the optimal reduction can be obtained by eliminating the most reducible attributes. In the reducible attribute set, there are at most six reducible attributes, namely \{c1, c4, c5, c6, c7, c8\}, \{c1, c3, c4, c5, c6, c8\}, \{c1, c2, c4, c6, c7, c8\}, \{c1, c2, c3, c4, c6, c8\}, and the optimal reduction is \{c2, c3\}, \{c2, c7\}, \{c3, c5\}, \{c5, c7\}.

4) RULE EXTRACTION

For the mine safety performance, the condition attributes and decision attributes in Table 7 contain preference information. For each condition attribute, the attributes representing the safety performance from good to bad are: high > medium > low.

According to the decision attribute of mine safety performance evaluation decision, mine safety performance
TABLE 8. Formal context of decision table.

|       | c₁₁ | c₁₂ | c₁₃ | c₂₁ | c₂₂ | c₂₃ | ... | ... | ... | cₙ₁ | cₙ₂ | cₙ₃ | d₁ | d₂ | d₃ |
|-------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|----|----|----|
| n₁    | X   | X   |     |     |     |     |     |     |     | X   |     |     | X  |    |    |
| n₂    |     | X   | X   |     |     |     |     |     |     |     | X   |     |     | X  |    |    |
| n₃    | X   |     | X   |     |     |     |     |     |     |     |     | X   |     | X  |    |    |
| n₄    |     | X   |     |     |     |     |     |     |     |     |     |     | X  |    |    |    |
| n₅    |     |     | X   |     |     |     |     |     |     |     |     |     |     | X  |    |    |
| n₆    | X   |     |     |     |     |     |     |     |     |     |     |     |     |     | X  |    |
| n₇    |     | X   |     |     |     |     |     |     |     |     |     |     |     |     |     | X  |
| n₈    |     |     |     |     |     |     |     |     |     |     |     |     |     |     |     |     |
| n₉    | X   |     |     |     |     |     |     |     |     |     |     |     |     |     |     |     |
| n₁₀   |     |     |     |     |     |     |     |     |     |     |     |     |     |     |     |     |
| n₁₁   | X   |     |     |     |     |     |     |     |     |     |     |     |     |     |     |     |
| n₁₂   |     | X   |     |     |     |     |     |     |     |     |     |     |     |     |     |     |
| n₁₃   |     |     | X   |     |     |     |     |     |     |     |     |     |     |     |     |     |
| n₁₄   |     |     |     |     |     |     |     |     |     |     |     |     |     |     |     |     |
| n₁₅   |     |     |     | X   |     |     |     |     |     |     |     |     |     |     |     |     |
| n₁₆   | X   |     |     |     |     |     |     |     |     |     |     |     |     |     |     |     |
| n₁₇   |     |     |     |     |     |     |     |     |     |     |     |     |     |     |     |     |
| n₁₈   |     |     |     |     | X   |     |     |     |     |     |     |     |     |     |     |     |
| n₁₉   |     |     |     |     |     |     |     |     |     |     |     |     |     |     |     |     |
| n₂₀   |     |     |     |     |     |     |     |     |     |     |     |     |     |     |     |     |

Note: In the table, c₁₁, c₁₂, and c₁₃ represent three types of attributes of high, medium, and low safety awareness, and the other conditional attributes are expressed similarly; d₁, d₂, and d₃ represent three types of excellent, general, and poor safety performance respectively. "x" indicates that the object contains this connotation.

can be divided into three preference order categories: $C_{\text{I}} = \{\text{excellent}\}$, $C_{\text{II}} = \{\text{general}\}$, $C_{\text{III}} = \{\text{poor}\}$. In line with the preference decision class, the domain is divided, and the union of decision classes is obtained as follows:
- $C_{\text{I}} = C_{\text{I}}$, the mine safety performance is excellent;
- $C_{\text{II}} = C_{\text{I}} \cup C_{\text{II}}$, the mine safety performance is general at least;
- $C_{\text{III}} = C_{\text{II}} \cup C_{\text{III}}$, the mine safety performance is general at most;
- $C_{\text{III}} = C_{\text{III}}$, the mine safety performance is poor.

According to the optimal reduction, preference rules can be generated. There are two kinds of preference rules: the upward coverage is at-least rule sets and the downward coverage is at-most rule sets. Taking the optimal reduction
TABLE 9. $D_\geq$ preference decision rule set.

| Preference rule set                                                                 | Support number |
|-----------------------------------------------------------------------------------|----------------|
| If Safety skills $\geq$ High and Equipment safety $\geq$ High, then mine safety performance = excellent | 6              |
| If Safety skills $\geq$ High and Equipment safety $\geq$ Medium, then mine safety performance $\geq$ General | 7              |
| If Safety skills $\geq$ Medium and Equipment safety $\geq$ Medium, then mine safety performance $\geq$ Good | 6              |
| If Safety skills $\leq$ Low and Equipment safety $\leq$ Medium, then mine safety performance $\leq$ Poor | 1              |

TABLE 10. $D_\leq$ preference decision rule set.

| Preference rule set                                                                 | Support number |
|-----------------------------------------------------------------------------------|----------------|
| If Safety skills $\geq$ High and Equipment safety $\geq$ High, then mine safety performance = excellent | 6              |
| If Safety skills $\geq$ High and Equipment safety $\leq$ Medium, then mine safety performance $\geq$ General | 7              |
| If Safety skills $\leq$ Medium and Equipment safety $\leq$ Medium, then mine safety performance $\leq$ Poor | 7              |

$\{C_2, C_3\}$ ($\{\text{safety skills, equipment safety}\}$) as an example, the preference rule set is generated.

The generated at-least preference rule set $D_\geq$ is shown in Table 9.

The generated at-most preference rule set $D_\leq$ is shown in Table 10.

It can be seen from Table 9 and Table 10 that the coverage rate of rules generated by at-least decision rule set $D_\geq$ and at-most decision rule set $D_\leq$ is 100%, and there is no ambiguity between rules; all the classifications are correct, and the classification quality is very high. Moreover, most of the rules have more than 5 support numbers and high credibility, which can be used as rules.

5) RULE APPLICATION

According to the preference rule set, the mine safety work can be guided. When the requirements for safety work are high, safety work is adjusted according to the rules. The rule of at-least rule set $D_\geq$ “if safety skills $\geq$ high and mechanical equipment safety $\geq$ high then mine safety performance = excellent” and “if safety skills $\geq$ high and mechanical equipment safety $\geq$ medium”. When the safety skills of mine personnel are high, only the safety of mechanical equipment is adjusted to high, then the safety performance of mine can be guaranteed to be excellent. According to the rule of in the at-most preference rule set $D_\leq$ “if safety skills $\leq$ high and mechanical equipment safety $\leq$ medium, then mine safety performance $\leq$ general” and “if safety skills $\leq$ medium and mechanical equipment safety $\leq$ medium, then mine safety performance $\leq$ poor”, the safety performance of all mining enterprises is adjusted to a high grade, then safety performance can be guaranteed to be general. The above two adjustment measures are examples of using the information provided by the preference rule set to improve the mine safety performance at a relatively small cost. Finally, the mine safety production is facilitated.

IV. CONCLUSION

1) In this study, the matter-element analysis method is used to evaluate mine safety performance, and then the dominance-based rough set theory is used to analyze the law of mine safety performance. Considering the connotation and science of reduction, concept lattice is employed as a tool to reduce the condition attributes, and the upward and downward coverage are generated. Examples show that the proposed model can evaluate the mine safety performance and analyze the law of mine safety performance, so as to guide the mine safety work scientifically.

2) In the calculation method of matter-element analysis model, the multiple attributes of the evaluation index value are considered, and the contribution difference of each index to the mine performance is weighted; the comprehensive correlation degree of mine safety performance belonging to all grades of attributes is obtained, and the mine safety performance is judged according to the principle of maximum membership degree. The evaluation method of mine safety performance based on the matter-element analysis model considers the multiple attributes of evaluation indexes, comprehensive, logical and reasonable. Therefore, this calculation process is scientific. In the study, the safety performance of 20 mines is comprehensively evaluated by the matter-element analysis model.

3) In the analysis of mine safety performance law based on the dominance-based rough set, the concept lattice with good knowledge discovery ability is used as attribute reduction tool, and Hasse graph is used as a concept identification tool; then the deficient attribute of mine safety performance evaluation decision is obtained. The reducible attribute can be obtained by removing the deficient attribute from the power set of conditional attributes. The reduction with the least number of conditional attributes is the optimal reduction. In the example, four optimal reductions are obtained by using concept lattice.

4) Based on the theory of dominance-based rough set, the preference rule at-least or at-most sets of the mine safety performance evaluation are generated. According to the preference rule sets, mine safety work can be improved to improve quality and efficiency. In the example, all the preference rule sets of dominance-based rough set production are classified correctly, with high support number and high reliability, and the information of preference rule set is used to improve mine safety production. Compared with the decision law set generated by the traditional indiscernibility relation-based rough set, the preference rule generated by the dominance-based rough set has the advantages of large support number, high classification quality, high reliability and accuracy.

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JIANHONG CHEN received the Ph.D. degree in mining engineering from Central South University, in 2002. He is currently the Vice Dean of the School of Resources and Safety Engineering, Central South University, and also a Professor, a Doctoral Tutor, a Hunan Fulong Scholar Program Distinguished Professor, and a Visiting Scholar with the University of Missouri. He is the Hunan Province Teaching Master and a Special Government allowance experts, and he is mainly engaged in mining engineering, resource economy, digital mining, and the teaching and scientific research work in mine safety. He has undertaken over 50 scientific research projects. He holds two national invention patents and two software copyright patents, published over 210 articles to compile the publication of mining economics, mineral resources economics, digital mining technology, and modern emergency management theory and technology, and other works teaching materials. He received nine Provincial and Ministerial Science and Technology Progress awards and the National Excellent Doctorate Thesis Award.

SHAN YANG was born in Jianli, Hubei, China, in 1983. He received the Ph.D. degree in mining engineering from the School of Resources and Safety Engineering, Central South University, Changsha, China, in 2012. He is currently an Associate Professor with the School of Resources and Safety Engineering, Central South University. His research interests include mining system engineering, resources, and environmental economics.

XUDONG ZHONG was born in Mianyang, Sichuan, China, in 1986. He received the master’s degree in mining engineering from the School of Resources and Safety Engineering, Central South University, Changsha, China, in 2014, where he is currently pursuing the Ph.D. degree in mineral engineering. His research interests include mining system engineering, resources, and environmental economics.

YING SHI received the Ph.D. degree in chemical engineering from The University of Queensland, Brisbane, Australia, in 2014. She is currently an Associate Professor with the School of Resources and Safety Engineering, Central South University, Changsha, China. Her research interests include mining system engineering, wastewater and solid waste treatment, and recycling.