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Study on coal mine safety evaluation based on factor analysis

The safe production of coal mine is an important part of national safety production, which is related to the healthy and stable development of coal industry. It is very important to find a comprehensive and reasonable coal mine safety evaluation method for coal mine safety production. In this paper, a comprehensive evaluation index system of coal mine safety is systematically established, and a comprehensive evaluation model of coal mine safety based on factor analysis principle is proposed. Then, with three Shanxi coal mine enterprises as examples for case study, we use principal component analysis and SPSS software to analyse the main factors influencing coal mine safety and their mutual relations on the basis of the details of each factor. By calculating the scores of principal components and the comprehensive safety score, we undertake a comprehensive analysis and evaluation on coal mine safety.

Keywords: *Coal mine safety; factor analysis; index system; evaluation method.*

1. Introduction

Coal is a primary source of energy in China, and the safe production of coal has played an important role in China's economic development [1, 2]. In order to achieve sustainable development for coal mining enterprises, the primary task is to ensure work safety. In the coal mine production process, coal mine safety is a complex system problem [3]. Recent decades witnesses the occasional occurrence of coal mine safety accidents, causing vast loss on levels of nation, society, family and individual. Therefore, the national safety production sector has attached more and more importance to coal mine safety production. Many domestic and foreign scholars are also very concerned about coal mine safety management and evaluation theory [4-6].This paper is mainly about coal mine safe production evaluation based on factor analysis, in an attempt to minimize the damage and damage caused by accidents and disasters.

2. Related theories on factor analysis

2.1 Factor analysis model

In form, factor analysis model is similar to multiple regression model in that observed variables are represented by a linear combination of a set of factors [7-8]. Assuming that there are n observed variables. The observable random vector $X = (X_1, X_2, \ldots, X_n)$ is a normalized vector, i.e. the mean vector E(X) = 0 and the covariance matrix Cov(X) = Σ (Σ is equivalent to the correlation matrix R). The general expression is [9]:

$$X=AF+E \quad \ldots \quad (1)$$

i.e. x_i = a_i1f_i1 + a_i2 f_i2 + ... + a_imf_im + e_i (i = 1, 2 ...n) ... (2)

Among them,

(1) $F = (F_1, F_2, \ldots, F_m)$ ($m<n$) is an unobservable vector whose mean vector E(F) = 0 and the covariance matrix Cov(F) = I, meaning that all vector components are independent from each other. D(F) = I_m, which means that $F_1, F_2, \ldots, F_m$ are uncorrelated with each other and all of their variances are equal to 1;

(2) E(e_i) (i = 1, ..., n) is a random item that is independent of F with a zero mean. Its covariance matrix is diagonal, each component ei being independent of each other.

In the above model, F is called the common factor of X, and E(e_i) (i = 1, ..., n) is called the special factor of X, and matrix A (A = (a_ij)) is called factor loading matrix. A_{ij} is a factor loading whose value is the covariance or correlation coefficient of X_i and F_j. The larger the absolute value of a_{ij} is, the higher is degree X_i correlated with F_j, and the closer they are to each other.

The square sum of elements in the i-th row in the factor loading matrix A is called common variance [10]. The variance of the variable consists of two parts: one is determined by common factor, and the other by special factor. The common variance represents the variable variance that can be interpreted by the common factor, which is the contribution of all the common factors to the variance of X_i, reflecting the effect of all common factors on the variable X_i [11]. A common variance with large value indicates the high level of factor interpretation for the variable. The square sum of elements in the jth column (j = 1, 2,..., m) of the factor loading matrix A is called the contribution of the common factor F_j to the variance of X. The larger the variance contribution is, the greater the common factor F_j contributes to X, meaning the greater influence of F_j on X.

2.2 Steps of factor analysis

(1) Calculate the correlation matrix of the variables

The correlation matrix contains all the necessary data in

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factor analysis. After calculating the correlation matrix, we have to judge whether it is applicable to factor analysis [12]. The purpose of factor analysis is to simplify data. However, if there is no strong correlation between variables, there will be no way to share common factor. Therefore, it is necessary to verify the correlation matrix. If most of the correlation coefficients in the correlation matrix are smaller than 0.3, the factor analysis method cannot be used herein.

(2) Extract common factor

This paper mainly uses the principal component method to extract common factor. This method converts a set of correlated variables into another set of irrelevant variables by linear transformation, and these uncorrelated variables are arranged in descending order of variance [13-14]. The variable with the largest variance is the first principal component and is expressed as F1; the second largest variance is the second principal component and is represented by F2, which is uncorrelated with the first variable; similarly, we determine the principal components one after one. Our determination of the number of factors is based on eigenvalues. The principal components with eigenvalues greater than or equal to 1 can be regarded as common factors. Principal components with eigenvalues less than 1 are discarded.

(3) Factor rotation

After determining the common factor, if the representative variables of each common factor are not typical enough, it will be necessary to rotate factors such that simplifying factor structure and improve factor interpretability. The means of factor rotation includes orthogonal rotation and oblique rotation [15-16]. The former one is used in our study.

(4) Interpret factors and calculate their values

After finding out the solutions to factors, it is necessary to interpret factors by means of loading matrix. First, we find the variables with significant loadings on each factor and assign names to them according to their connotations; variables with higher loadings exert stronger influence on factor name [17]. Then, we measure the factors and calculate their scores for each sample by using the formula below:

$$f_{pi} = \sum_{j=1}^{k} w_{pj} x_{ji} \quad \text{... (3)}$$

where x_ji is the value of the jth variable on the ith sample, w_pj is the factor value coefficient between the pth variable and the jth variable.

With factor value, each sample case can be compared and analysed; according to the degree of interpretation of each factor on the sample, one can calculate the final comprehensive score such that finishes comprehensive sequencing and evaluation.

3. The application of coal mine safety factor analysis and evaluation methods

3.1 Collection and processing of raw data

In this paper, we evaluated and compared the work safety of three coal mines (named as C1, C2, and C3, respectively) in Shanxi province as the research object. By drawing reference from domestic and foreign literatures, we established the coal mine safety comprehensive evaluation index system, which includes four factor layers (human factor, machinery factor, environmental factor, and management factor) and 18 sub-layers, as listed in Table 1.

In the coal mine safety comprehensive evaluation index system, the data of eight indicators X_1-X_5, X_{12}, X_{14}, and X_{15} are obtainable according to quantitative indicator division criteria, and the data of the rest of the indicators can be obtained from expert score. In order to ensure the accuracy and objectivity of expert scoring, this paper evaluates the qualitative indicators of the index system by using the idea of fuzzy mathematics and set value statistics.

Assuming that there are n evaluation indexes in the coal mine safety evaluation index system, which constitute an index set $U=(u_{\_1}, u_{\_2}, ..., u_{\_n})$, and m experts, which constitute an expert set $p= (p_{\_1}, p_{\_2}, ..., p_{\_m})$. For a certain indicator ui, the interval of the set value of safety determined by expert can be expressed as: $[a_{\_1i}, b_{\_1i}]$, $[a_{\_2i}, b_{\_2i}]$, $[a_{\_3i}, b_{\_3i}]$, $[a_{\_mi}, b_{\_o}]$. For each indicator, such intervals form a statistic sequence of set values. If we overlap these sub-intervals, the overlapped area will distribute across the safety value axis, which is expressed as:

$$\overline{A}(u_j) = \frac{1}{n}\sum_{i=1}^{n} A(a_{ij}, b_{ij}) \quad \text{...} \quad (4)$$

where $i = 1, ..., m$, $j = 1, ..., n$. Through analysis, we have:

$$A(a_{ij}, b_{ij}) = \begin{cases} 1 & a_{ij} \le u_{ij} \le b_{ij} \\ 0 & \text{the rest} \end{cases} \quad \text{...} \quad (5)$$

Table 1: Indicator system of coal mine safety synthetic evaluation

Target layer	Factors layer	Sub factors layer
Comprehensive evaluation system	Human factor	Technical quality of staff (X_1) Employee safety awareness (X_2) Employee physiology (X_3) Employee safety operation (X_4)
	Machinery factor	Mechanical safety factors for mining (X_5) Transportation safety factor (X_6) Material safety factor (X_7) Protective equipment safety factor (X_8) Monitoring equipment safety factors (X_9) Electrical equipment safety factor (X_{10})
	Environmental factors	The gas condition (X_{11}) Roof safety factor (X_{12}) Safety factors of coal dust (X_{13}) Hydrogeologic safety factors (X_{14}) Work space security factor (X_{15})
	Management factors	Improve the safety management system (X_{16}) Safety management performance (X_{17}) Coordination of safety management organizations (X_{18})

The distribution diagram is shown in Fig.1.

The safety value of the evaluation index u_j is:

$$\bar{u}_J = \frac{\int_{u_{j\,min}}^{u_{j\,max}} u_j \bar{A}(u_j)du}{\int_{u_{j\,min}}^{u_{j\,max}} \bar{A}(u_j)du} \quad \text{... (6)}$$

in which $u_{j\,min} = \min(a_{1j}, a_{2j}, ..., a_{mj})$, $u_{j\,max} = \max(b_{1j}, b_{2j}, ..., b_{mj})$, the above equation can be simplified as:

$$\bar{u}_J = \frac{\frac{1}{2}\sum_{i=1}^{m}\left|b_{ij}^2 - a_{ij}^2\right|}{\sum_{i=1}^{m}\left|b_{ij} - a_{ij}\right|} \quad \text{... (7)}$$

For the weights obtained from the set-valued statistics, the reliability should also be analyzed. In this paper, we use the interval variance F_j to express its reliability, and the formula is:

$$F_j = \frac{\sum_{i=1}^{m}\left[\left(b_{ij} - \overline{u_j}\right)^3 - \left(a_{ij} - \overline{u_j}\right)^3\right]}{3\sum_{i=1}^{m}\left[\left(b_{ij} - a_{ij}\right)\right]} \quad \text{... (8)}$$

The larger the F_j value is, the greater difference it generates in evaluating the indicator u_j. Experts are required to re-offer comments until the value of F_j is reduced to a certain threshold to gain a certain level of expert evaluation reliability. The smaller the F_j value is, the more reliable the expert comments become. This article uses g_j *to* represent the reliability of expert evaluation on an indicator u_j, whose formula is:

$$g_j = \frac{100}{100 + F_j} \quad \text{... (9)}$$

In this paper, 5 experts are selected to grade some of the safety indexes of the three companies' comprehensive evaluation index systems. The evaluation range of most of the index factors are [0,100]. Through data compilation, we have Table 2, Table 3 and Table 4.

With this as an example, we calculate the comprehensive evaluation value of the index X_6 of the C1 coal mine by using formula (7):

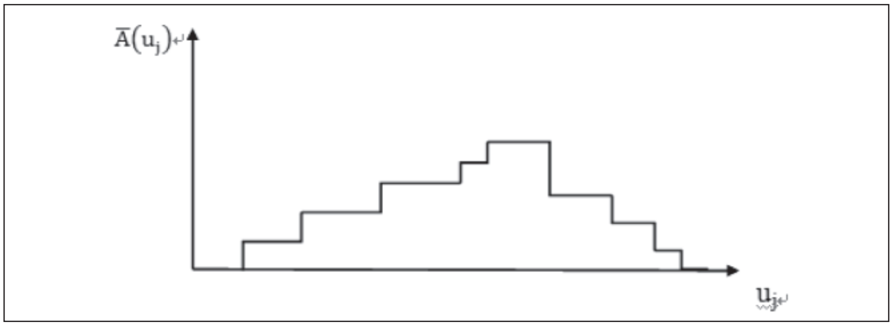

Fig.1 Shade distribution graph of performing monitoring security value degree

TABLE 2: EACH SECURITY TARGET APPRAISAL TABLE OF C1 COAL MINE

	Professor 1	Professor 2	Professor 3	Professor 4	Professor 5
X_6	[75,85]	[80,85]	[85,95]	[85,95]	[80,90]
X_7	[85,90]	[75,90]	[85,95]	[83,90]	[80,95]
X_8	[80,90]	[85,95]	[75,85]	[85,95]	[90,100]
X_9	[90,100]	[85,90]	[80,85]	[90,95]	[80,90]
X_{10}	[85,95]	[90,95]	[80,85]	[75,90]	[90,100]
X_{11}	[75,85]	[85,95]	[90,95]	[85,90]	[80,90]
X_{13}	[18,24]	[16,20]	[18,22]	[16,18]	[18,24]
X_{16}	[85,95]	[85,90]	[75,85]	[80,85]	[75,90]
X_{17}	[75,80]	[75,85]	[70,80]	[80,85]	[85,90]
X_{18}	[85,95]	[85,90]	[90,95]	[90,100]	[90,95]

TABLE 3: EACH SECURITY TARGET APPRAISAL TABLE OF C2 COAL MINE

	Professor 1	Professor 2	Professor 3	Professor 4	Professor 5
X_6	[80,90]	[88,94]	[83,90]	[85,95]	[85,95]
X_7	[85,95]	[80,89]	[84,92]	[85,95]	[80,90]
X_8	[85,95]	[80,90]	[75,85]	[90,95]	[90,95]
X_9	[90,95]	[75,80]	[80,95]	[90,100]	[85,90]
X_{10}	[89,94]	[92,98]	[80,95]	[92,96]	[85,95]
X_{11}	[64,70]	[62,70]	[60,65]	[60,70]	[64,72]
X_{13}	[10,15]	[14,18]	[12,16]	[14,18]	[12,15]
X_{16}	[75,80]	[77,82]	[78,84]	[80,85]	[82,87]
X_{17}	[78,84]	[77,82]	[75,80]	[76,80]	[75,80]
X_{18}	[92,96]	[95,100]	[86,94]	[90,15]	[95,98]

$$\overline{u_6} = \frac{\frac{1}{2}\sum_{i=1}^{5}\left|b_{i6}^2 - a_{i6}^2\right|}{\sum_{i=1}^{5}\left|b_{i6} - a_{i6}\right|} =$$

$$\frac{1}{2} \times \frac{\left(85^2 - 75^2\right) + \left(85^2 - 80^2\right) + \left(95^2 - 85^2\right) + \left(95^2 - 85^2\right) + \left(90^2 - 80^2\right)}{(85-75) + (85-80) + (95-85) + (95-85) + (90-80)} = 85$$

Through formulas (8) and (9), we conducted a reliability test:

$$F_j = \frac{\sum_{i=1}^{5}\left[\left(b_{i6} - \overline{u_6}\right)^3 - \left(a_{i6} - \overline{u_6}\right)^3\right]}{3\sum_{i=1}^{5}\left[\left(b_{i6} - a_{i6}\right)\right]} =$$

$$\frac{1}{3} \times \frac{\left[(85-85)^3 - (75-85)^3\right] + \left[(85-85)^3 - (80-85)^3\right] + \left[(95-85)^3 - (85-85)^3\right] + \left[(95-85)^3 - (85-85)^3\right] + \left[(90-85)^3 - (80-85)^3\right]}{(85-75) + (85-80) + (95-85) + (95-85) + (90-80)} = 208$$

TABLE 4: EACH SECURITY TARGET APPRAISAL TABLE OF C3 COAL MINE

	Professor 1	Professor 2	Professor 3	Professor 4	Professor 5
X_6	[80,86]	[84,92]	[82,90]	[80,90]	[85,95]
X_7	[80,90]	[75,85]	[77,84]	[78,85]	[80,85]
X_8	[70,80]	[75,85]	[77,82]	[80,85]	[75,90]
X_9	[80,90]	[80,95]	[84,92]	[78,84]	[82,88]
X_{10}	[70,78]	[68,74]	[66,70]	[65,70]	[66,76]
X_{11}	[78,84]	[80,85]	[77,83]	[76,80]	[80,90]
X_{13}	[12,16]	[15,20]	[14,18]	[16,18]	[15,19]
X_{16}	[88,94]	[85,90]	[86,90]	[87,82]	[90,95]
X_{17}	[78,84]	[75,80]	[77,82]	[80,85]	[70,80]
X_{18}	[65,70]	[68,76]	[70,80]	[69,77]	[70,80]

TABLE 5: SYNTHETIC EVALUATION VALUE OF EACH COAL MINE SECURITY TARGET APPRAISAL

	C_1	C_2	C_3
X_6	85.00	88.02	77.90
X_7	84.04	86.27	76.69
X_8	87.68	85.00	82.68
X_9	88.72	86.02	79.90
X_{10}	91.06	90.22	84.35
X_{11}	85.44	86.32	88.09
X_{13}	14.28	13.63	18.06
X_{16}	86.68	90.08	84.32
X_{17}	80.28	75.00	77.32
X_{18}	86.32	87.09	76.32

$$g_j = \frac{100}{100+F_j} = \frac{100}{100+20.8} = 0.828$$

The same method can be used to calculate the comprehensive evaluation value and reliability of each qualitative index of the three coal mines. The reliability of all the indexes verified is larger than 0.75. The comprehensive evaluation value of each coal mine safety index is shown in Table 5.

The data of the 8 indicators X_1-X_5, X_{12}, X_{14}, and X_{15} can be obtained through quantitative indicator division standards, as shown in Table 6.

The data in Tables 5 and 6 are standardized and the formula is:

$$Z_i = \frac{x_i - \bar{x}}{s} \quad \text{... (10)}$$

where x is the average of the samples, s is the sample corrected variance, and the standardized data are shown in Table 7.

3.2 EXTRACT THE SAFETY EVALUATION FACTOR OF SHANXI COAL MINES

SPSS 17.3 is used for factor analysis of the data, such that selecting the common factors that affect coal mine safety.

According to the criterion that the eigenvalue is greater than 1, three common factors are selected, as shown in Table 8. The variance contribution rate of the three common factors is 57.49336%, 22.16947% and 15.33628%, respectively. The cumulative variance contribution rate is 94.99911%, which is much higher than 85%. This phenomenon shows that the factor analysis method produces positive outcomes.

TABLE 6: SYNTHETIC EVALUATION DATA OF COAL MINE SECURITY

	C_1	C_2	C_3
X_1	9	8.5	8.1
X_2	11	10.3	13.8
X_3	17.6	15.8	14.9
X_4	34.8	38.2	36.9
X_5	0.47	0.39	0.58
X_{12}	25.02	22.18	20.96
X_{14}	14.31	13.86	13.52
X_{15}	5	4.8	4.6

3.3 FACTOR CALCULATION OF COAL MINE SAFETY

After determining the three common factors, their respective score coefficient matrices are calculated by SPSS 17.3, as shown in Table 9.

With formula (3), we can calculate the scores of the three common factors:

$$\begin{cases} F_1 = 0.134928x_1 - 0.144627x_2 + ... + 0.015923x_{18} \\ F_2 = -0.060834x_1 + 0.043368x_2 + ... + 0.122763x_{18} \\ F_3 = 0.090346x_1 - 0.062996x_2 + ... - 0.072398x_{18} \end{cases}$$

Through the above calculation, we can determine the comprehensive score of the three coal mines' safety factor, as is shown in Table 10.

TABLE 7: STANDARDIZED DATA

	X_1	X_2	X_3	X_4	X_5	X_6	X_7	X_8	X_9
C_1	1.2012	-0.4492	1.4689	-1.2314	-0.1092	0.7783	0.8569	1.4258	1.2983
C_2	0.7462	-0.9365	-1.2853	-0.4892	0.7846	1.3395	-0.4594	0.6582	-0.1963
C_3	-1.2863	1.2018	0.2854	1.3768	-1.0962	-1.1524	-1.1985	-0.8762	-0.6972

	X_{10}	X_{11}	X_{12}	X_{13}	X_{14}	X_{15}	X_{16}	X_{17}	X_{18}
C_1	-1.4032	-0.5983	1.5069	-1.4123	0.5003	1.3092	0.9006	1.3341	1.0048
C_2	1.2098	1.4572	-1.4209	0.8096	-1.5782	0.06892	-0.7963	-0.9982	0.8868
C_3	0.6793	-0.0469	-0.1542	0.7768	-1.2794	-0.7783	-0.2269	-0.8763	-1.3386

TABLE 8: TOTAL VARIANCE EXPLAINED

Common factor	The eigenvalue	Contribution (%)	The cumulative contribution rate (%)
F_1	10.96732	57.49336	57.49336
F_2	5.697431	22.16947	79.66283
F_3	3.996822	15.33628	94.99911

TABLE 9: COMPONENT SCORE COEFFICIENT MATRIX

Indicators	Factor score coefficient		
	F_1	F_2	F_3
X_1	0.134928	–0.060834	0.090346
X_2	–0.144627	0.043368	0.062996
X_3	0.006224	–0.044728	0.265438
X_4	–0.009003	–0.081136	–0.036328
X_5	0.158326	–0.098723	–0.083327
X_6	0.052238	0.080672	–0.074113
X_7	0.050032	0.080973	–0.017024
X_8	0.050982	0.062351	0.044763
X_9	0.068334	0.045032	0.028871
X_{10}	0.130142	–0.019231	–0.023761
X_{11}	0.090125	0.024438	–0.043692
X_{12}	–0.040134	0.066341	–0.250085
X_{13}	0.066328	–0.180069	0.094382
X_{14}	–0.073289	0.122389	0.138762
X_{15}	0.066734	–0.034826	–0.243613
X_{16}	–0.105387	0.174628	–0.055283
X_{17}	0.086932	0.014238	0.050013
X_{18}	0.015923	0.122763	–0.072398

TABLE 10: TOTAL COMPONENT SCORE COEFFICIENT MATRIX OF COAL MINE

Coal mine	Common factor score		
	F_1	F_2	F_3
C_1	0.60438	0.84689	1.45632
C_2	0.58863	0.98537	–1.38869
C_3	–0.97751	–1.49938	–0.06632

3.4 ANALYSIS AND EVALUATION OF SAFETY FACTORS IN THE THREE SHANXI COAL MINES

According to the common factor scores calculated in Table 10, the safety common factor scores of the three coal mines are plotted in a scatter diagram in the three-dimensional coordinate space, as shown in Fig.2. Among them, the three coordinate axes represent the common factors F_1, F_2 and F_3, respectively. The location of the points in the figure shows the projection of the safety value of these three coal mines in the three public factors.

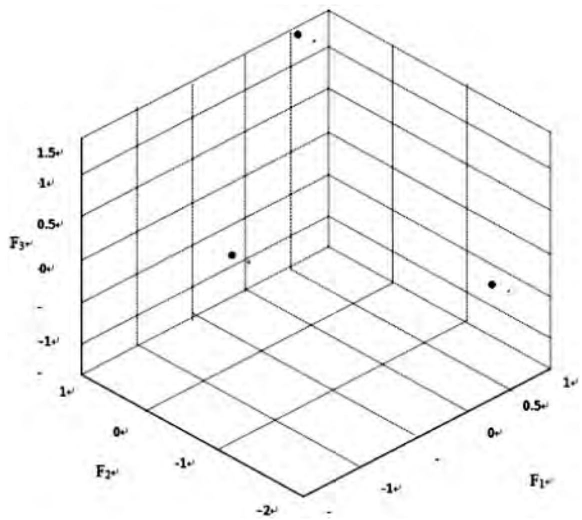

Fig.2 Score scatter distribution figure of five coal mines principal factor

TABLE 12: STANDARD OF DEVIATION CLASSIFICATION METHOD

Level	Factor score F_i
Excellent	$F_i > \bar{x}+1.28s$
Good	$\bar{x}+0.67s < F_i < \bar{x}+1.28s$
Medium	$\bar{x}-0.67s < F_i < \bar{x}+0.67s$
Poor	$\bar{x}-1.28s < F_i < \bar{x}-0.67s$
Worse	$F_i < \bar{x}-1.28s$

According to the variance contribution value of the influence degree of common factors on coal mine safety and their scores, the formula of coal mine safety is established:

$$SL_{ij} = k_{ij} f_{ij} \quad \text{... (11)}$$

where SL_ij denotes the total score of coal mine safety evaluation, k_ij denotes the contribution rate of the *j*th factor to the safety evaluation of the *i*-th coal mine, f_ij denotes the score of the *j*th factor in the *i*-th coal mine, $i = 1, 2, 3$; $j = 1, 2, 3$. The safety evaluation factor scores of the three coal mines and their ranking are shown in Table 11.

According to the deviation method, the coal mine safety level is divided into five levels (Table 12).

In Table 12, x is the average of the factor scores, and s is

TABLE 11: SCORE AND SORT OF COAL SECURITY EVALUATION FACTOR

Coal mine	F1		F2		F3		Total score	Total rank
	Score	Rank	Score	Rank	Score	Rank		
C_1	0.60302	2	0.83041	1	1.4582	1	0.765321	1
C_2	-0.58492	3	-0.11263	3	0.69247	2	-0.226934	3
C_3	0.92086	1	0.68392	2	0.43829	3	0.268343	2

the standard deviation of the total score. Combined with the safety evaluation factor scores of the three coal mines in Table 11, the critical values can be calculated as 0.799634, 0.388926, -0.206983 and -0.632964, respectively. Therefore, we can conclude that the safety status of the three coal mines in Shanxi (C_1, C_2, and C_3) are good, poor and intermediate, respectively. The three coal mining enterprises should attach great importance to the safety of coal production problems, especially for those whose work safety is not that satisfactory.

4. Conclusions

(1) Through an overview of Chinese literatures on coal mine work safety, the paper analyzes the relevant factors that affect the safety of coal mines and accordingly establishes the coal mine safety evaluation index system, which includes four factor layers (human factor, machinery factor, environmental factor, and management factor) and 18 sub-layers.

(2) The factor analysis method is applied to the comprehensive evaluation of coal mine safety, and the influencing factors and their relationship of coal mine safety are studied in depth. Through case study analysis of three Shanxi coal mines, we verify the practicability of factor analysis in evaluating coal mine safety. By means of factor analysis and SPSS software, we finally determine the exact safety status of the three coal mines in Shanxi (C_1, C_2, and C_3), which are good, poor and intermediate, respectively.

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