Comprehensive Evaluation Model of Coal Safety Risk based on Entropy Weight Theory

Shuxi Yan*, Xin Du

School of Mathematics and Statistics, Yulin University, Yulin 719000, China

Abstract

Coal is an important basic energy in China, and has an important strategic position in the national economy. Under the guidance of system theory, together with the comprehensive using of the principle and method of system engineering, this paper systematically analyzes the structural characteristics, influence factors, mechanism of the safety risk system of coal enterprise. At the same time, this paper establishes a comprehensive evaluation index system of coal mine safety and risk, and constructs comprehensive evaluation model of coal mine risk based on safety and risk index, as well as comprehensive evaluation model of coal mine safety based on entropy weight method and grey relational analysis; Besides, the practical research has performed on four coal mines in Su county Mine Area, Huabei Mining Group. The research results are of great theoretical and practical significance for the scientific countermeasures to improve the safety production of coal enterprises and to promote the fundamental improvement of the coal industry safety production situation.

Keywords: Coal safety risk, Entropy weight theory, Comprehensive evaluation, Risk analysis.

1. INTRODUCTION

Coal is an important basic energy and raw material in our country, and has an important strategic position in the national economy. In terms of energy production and energy consumption, China has formed a highly energy structure dependent on coal resources (Tsiridis et al., 2012). Before the 1960s, the proportion of coal in China's energy production and consumption structure remained above 90%. In the 20th century, 70 to 80 years, the proportion of coal in China's energy production and consumption structure decreased gradually to below 80%, among which in 1976 had dropped to 70%. 80 to 90 years of the 20th century (Callénet et al., 1998; Orsulak et al., 2010), its proportion in China's energy production and consumption structure remained above 75%. As one of China's basic industries, coal industry has an important position and role in the national economy, and the dominant position of coal in primary energy will last for a longer period.

With the continuous and stable development of the coal industry, the safety problem has always been plaguing the coal enterprises. Due to the restriction of many factors such as production environment, technical equipment, management level and so on, resulting in the phenomenon of many accidents, heavy casualties, large economic losses in China's coal industry, meanwhile heavy casualties have happened occasionally, to bring life and significant property damage to the country and the people. However, the aspects that coal mine safety involved are too many and too broad, as shown in Figure 1, from the equipment design, manufacture, maintenance, inspection and operation, as well as underground management, enterprise management, and even operating environment, social environment, economic factors and political environment, are all closely related to the occurrence of coal mine accidents. Not only the above-mentioned content, there are...
many man-made reasons which affect the management of coal enterprises, for example, the quality of staff, education, training, corporate culture and so on. Only with in-depth understanding of influence factor of coal mine safety, can achieve preventive function at all levels, further to reduce the occurrence of coal mine accidents.

**Figure 1.** Flow chart of coal mine accident and the relationship between safety factors

As shown in Figure 1, coal mine safety has a lot of influencing factors, such as design, manufacturing, maintenance, equipment inspection and operation, underground management, enterprise management, working environment, as well as social, economic and political factors. All of these factors have an impact on the occurrence of coal mine accidents. Similarly, the management of coal enterprises is also affected by multiple elements, most of them are human factors. There are staff quality, education, training, organizational culture and so on (Nian et al., 2012; Chen et al., 1939; Li and Xu, 2011). Without in-depth understanding of the aforementioned factors, it is impossible to implement preventive measures effectively at all levels, not to mention reducing the number of coal mine accidents.

**2. ANALYSIS OF WORK SAFETY PRINCIPLES**

According to the accident-proneness theory, the likelihood of accident is partially determined by human factors because the people involved have predisposition to suffer accidents. Heinrich’s “Domino Theory” thought out that the genetic environment leading to human defects; so that the human would have unsafe behaviors and objects (mechanical equipment or environment) would exist unsafe condition, which is prove to causing accident, finally resulting in heavy casualties and property losses. Bode modernizes Heinrich’s theory by proposing a causal chain of accidents. The new theory believes that the unsafe behavior of people and unsafe situation of object are harbingers of accidents; However, these factors are superficial reasons, and the real cause of accidents lies in management errors (Hanak et al., 2015). Another model of accident causal chain is established by Zabetakis (Figure 2). The theory of accidental release of energy holds that accident prevention relies on good energy management, and the most effective way of energy control is shielding, i.e. separating the people from the object, and separating the people/object from energy source. Developed from the causal chain theory, modern accident-causing theory provides the theoretical basis to investigation of accident causes and evaluation of system safety at home and abroad. It is also one of the theoretical bases of this paper. As shown in Figure 3, trajectory intersection model stresses on the direct causes of accident: unsafe behavior of people, unsafe condition of
object, along with the root cause: management defect (Ličina et al., 2013; Bagherpour et al., 2015; Niczyporuk, 1996). The model further divides the object factor into cause object and harmed object, and the human factor into actor and victim. During coal mine risk evaluation, the analysis of the object mainly focuses on harm, while the analysis of the human factor mainly focuses on actor (Wang et al., 2015; Perrone and Amelio, 2016).

---

**Figure 2.** Causation chain model from the perspective of energy

**Figure 3.** The trajectory intersection model

### 3. Construction of Comprehensive Evaluation Index System for Coal Mine Safety Risk

#### 3.1 Design process of the index system

The coal mine risk evaluation index system is mainly designed in the following four steps (the process of the evaluation index system is shown in figure 4):

1. **Risk factor analysis**

   The purpose of the analysis is to confirm the risk range of the system. The risk factors are listed one by one, serving as the research objects of the safety risk evaluation system. Risk factors are the sources and basis of evaluation indices. On the basis of
those risk factors which directly affect enterprise safety, the author creates the evaluation indices through decomposition, refinement, consolidation and integration.

(2) Theoretical verification

The preliminary index system is not scientific. To improve the scientific basis, the author carries out a scientific argument to improve the system.

(3) Confirmation

The author refines the index system to make it more scientific and reasonable. After soliciting the opinions of site personnel, managers and experts, the author deletes the indices difficult to operate and measure, decomposes the indices overlapping each other, and integrates indices reflecting the same problem from different dimensions.

(4) Revision

There are two ways to further improve the rationality of the indices. 1) Revise before use in consultation with the experts: submit the confirmed indices to a leader, an academic authority or an export for review. Revise, supplement and improve the index system in light of their opinions. 2) Revise after use: After applying the index system, make revisions in view of the effect so that the indices are more ideal and effective.

---

**Figure 4.** Design process of coal mine safety risk index system
3.2 Structure of the comprehensive evaluation index system

After analyzing the risk factors that affect coal mine safety and enterprise operation, this paper subdivides the index system into seven parts (the specific content as shown in figure 5), respectively dealing with coal mine inherent risk, personnel safety risk, equipment safety risk, environment safety risk, management safety risk technical equipment support safety risk and accident & occupational hazard. The subdivision follows the steps of forming the coal mine safety risk index system, and abides by the principles of building an advanced, scientific, systematic, correlative, comprehensive and operable index system (Xue et al., 2013; Falcke et al., 2011; Korban, 2015). The accident & occupational hazard is taken as an index of coal mine safety risk because the previous accidents and occupational hazards tell about the deep-seated safety risks and demonstrate the safety degree of the enterprise in the past (Ghosh, 2010; Jiao et al., 2013).

Figure 5. The index system of coal mine safety risk evaluation

4. COMPREHENSIVE EVALUATION MODEL FOR COAL MINE SAFETY RISK
4.1 Construction of comprehensive evaluation model of coal mine safety risk based on safety risk index

As the evaluation problem involves multiple attributes, the author assumes that it fits a multi-attribute scheme \( S=\{S_1,S_2,\ldots,S_m\} \), where the indices (attributes) are expressed as \( P=\{P_1,P_2,\ldots,P_n\} \). Let the observation value of index \( S_i \) of \( P_i \) be \( x_{ij}(i=1,2,\ldots,m, \ j=1,2,\ldots,n) \). The author constructs an index to evaluate the multi-attribute scheme:

\[
y_j = f(w,x_j)
\]

Quantified by the index method, the index mitigates difficulties in determining probability of occurrence of risk and the seriousness of the consequences. It is also capable of disclosing the nature of risk, making it easier to compare the risk levels in different regions (Bukowski, 2011).

In this paper, the coal mine safety risk index is selected by a risk evaluation system centering on index construction. The process puts emphasis on the selection and optimization of risk index and finally forms coal mine safety risk index.

The comprehensive evaluation model for coal mine safety risk index is constructed as:

\[
R = \sum_{i=1}^{n} F_i \cdot W_i
\]

Where \( R \) is coal mine comprehensive safety risk index; \( F_i \) is the standard value of the first index of the mine, i.e. the index value after non-dimensional treatment; \( W_i \) is the weight of the first index.

4.2 Construction of comprehensive evaluation model of coal mine safety based on entropy weight method and grey relation theory

Once a concept in thermodynamics, entropy has been widely applied in engineering technology, management science and social economy since it was introduced by Shannon into communication engineering. It measures the degree of disorderliness of the system and the amount of effective information provided by data (Mukherjee et al., 2005; Wang et al., 2009; Cioca and Moraru, 2012). Hence, entropy can be applied to weight determination. Suppose a system may be in \( n \) different states, and the probability of occurrence of each state is \( P_i(i=1,2,\ldots,n) \). Then, the entropy of this system can be defined as:

\[
E = -\sum_{i=1}^{n} P_i \cdot \ln P_i
\]

\[
0 \leq P_i \leq 1, \quad \sum_{i=1}^{n} P_i = 1
\]

Entropy is about extreme values. When \( P_i=x/n(i=1,2,\ldots,n) \), the probability of occurrence of each state is equal, and the maximum value obtained by entropy weighting is:

\[
E_{\text{max}} = \ln n
\]
Normalize the original data matrix within the regional system with m evaluation indices and n evaluation objects. According to the principle of combination of qualitative and quantitative, the evaluation matrix R can be formed by the index values of the n evaluation objects corresponding to the m evaluation indices.

\[
G = R \cdot W = \begin{bmatrix}
    r_{11} & r_{12} & \cdots & r_{1n} \\
    r_{21} & r_{22} & \cdots & r_{2n} \\
    \vdots & \vdots & & \vdots \\
    r_{m1} & r_{m2} & \cdots & r_{mn}
\end{bmatrix}
\begin{bmatrix}
    W_1 \\
    W_2 \\
    \vdots \\
    W_n
\end{bmatrix}
\]

(6)

Normalize the evaluation matrix R to get matrix R’:

\[
R' = \left( r'_{ij} \right)_{m \times n}
\]

(7)

Where, the maximal value is obtained by the principle “the bigger, the better.”

\[
r_{ij} = \left( \frac{r_{ij} - \min_{j} r_{ij}}{\max_{i} r_{ij} - \min_{j} r_{ij}} \right)
\]

(8)

The minimal value is obtained by the principle “the smaller, the better.”

\[
r_{ij} = \left( \frac{\max_{i} r_{ij} - r_{ij}}{\max_{i} r_{ij} - \min_{j} r_{ij}} \right)
\]

(9)

(2) Definition of the entropy of evaluation index

In the regional system with m evaluation indexes and n evaluation objects, define the entropy value of the j-th evaluation index as:

\[
H_j = -K \sum_{i=1}^{n} f_{ij} \ln f_{ij}, (j = 1, 2, \ldots, n)
\]

(10)

(3) Define the entropy weight \( W_j \) of the j-th index as:

\[
W_j = \frac{1 - H_j}{m - \sum_{j=1}^{n} H_j}
\]

(11)

The entropy of weight has special significance. When the values of evaluation object differ greatly on one index, the entropy value is small. It indicating the amount of effective information that the index provides is large, accordingly the weight of the index should be relatively large. On the contrary, when the values of evaluation object differ slightly on one index, the entropy value is big. It indicating the amount of effective information that the index provides is small, the weight of the index should also be relatively small. When the values of evaluation object are exactly the same on one index, the entropy weight reaches the maximum, putting the entropy weight at 0. In this case, the index does not provide any useful information to the decision-maker and should be removed.
5. EMPIRICAL ANALYSIS OF COMPREHENSIVE EVALUATION THEORY OF COAL MINE SAFETY RISK

5.1 Original value of evaluation index system of coal mine safety risk

In this paper, the collection and selection of original data of coal mine safety risk evaluation index follows a uniformed standard. Since some of the data can be directly queried and obtained from the production capacity report of the mines, thus there is no need to analyzing or processing them. Such data include utilization index of coal mine production capacity, dip angle of coal seam, complexity degree of geological structure, average gas emission, normal water inflow of mine, spontaneous combustion period of coal seam and coal dust explosion index. While, in terms of the following data: staff cultural quality, certificate holding rate, training rate, qualified rate, law-abiding index, equipment readiness rate, equipment reliability rate, equipment renewal rate, implementation rate of safety management system, equipment rate of safety supervision personnel (Singh et al., 2011), safety investment index, completeness degree of technical measure, death rate per million tons, economic loss, incidence of occupational disease and so on, they can first be accessed through the various departments and then after analyzing and calculating, we can obtain them (Cheng et al., 2011).

5.1 Comparison and analysis

The factors of accident and occupational hazards include equivalent of death B61, equivalent of injured B62, equivalent of economic loss B63 and equivalent of occupational disease B64. Since accident and occupational hazards may result in personal injury, financial damage and other accidents, the value of the factors is expected to be as small as possible, where the ideal object is e6*=(0,0,0,0).

Similarly, the equilibrium degree of each evaluation object and the ideal object is obtained by the grey entropy-based comprehensive evaluation of fixed risk factors in coal mine: \( \omega_1=0.7345, \omega_2=0.3999, \omega_3=0.7709, \omega_4=0.8635 \). By judgment principle, it can be inferred that \( e_1>e_3>e_4>e_2 \).

Then, the author sums up the equilibrium degree of proximity matrix \( W_2' \) based on the grey entropy evaluation results of elements like coal mine inherent risk, personnel safety risk, environment safety risk, management safety risk, technology and equipment support security risk and accident & occupational hazard analysis. As shown in Table 3, the weight matrix \( A=(0.3450, 0.0924, 0.0924, 0.0578, 0.2331, 0.1503, 0.0290) \), consisting of the said elements, can be obtained by the AHP.

The comprehensive evaluation of the second layer is carried out by the following formula:

\[
W_2 = A W_2',
\]

\[
= (0.325,0.236,0.065,0.0514,0.214,0.125,0.036)
\]

Through the comprehensive evaluation of safety risk index, it is concluded that Luling mine has the biggest risk, its safety risk index is the highest, followed by Taoyuan mine.
and Qinan mine, and Zhuxianzhuang mine has the smallest safety risk. Through entropy weighting and comprehensive evaluation of grey relational analysis, the author finds that Zhuxianzhuang mine is the safest one, followed by Qinan mine and Taoyuan mine, leaving Luling mine as the least safe one. The results obtained by both methods are consistent with each other.

4. CONCLUSION

The research results are as follows:

1. According to the concepts and connotations of safety, risk, system, safety status, degree of safety and so on, the concept of safety and risk system is put forward, and the research scope of safety and risk system is defined. It is pointed out that the enterprise safety and risk system is a typical complex system, due to the constraints of inherent risk factors of system, human, machine, environment, management and other factors and affect and interference of many complex factors.

2. Based on the theory of accident causation and the basic principle of risk evaluation, the paper analyzes the factors of coal mine safety and risk, determines the main influencing factors of coal mine safety and risk, meanwhile analyzes the interaction between the factors, at final constructs the coal mine safety risk evaluation index system. Select coal mine inherent safety risk index and so on seven major index system to evaluate the overall coal mine safety risk level.

3. By using of the coal mine safety risk index comprehensive evaluation method, the entropy weight method and the gray relational analysis combined comprehensive evaluation method. The practical applications have performed on Zhuxianzhuang, Luling, Taoyuan and Qinan total 4 mines of HuaiBei Mining Group in Su County, and then have ranked the mine safety risk level. Through comparative analysis of the evaluation results of two methods, it was found that the results of the two methods are almost the same, except for the slight deviation of the individual points, and the evaluation results well reflect the safety status of the mine. Among the safety level of the four Mine, the safety and risk of Luling Mine is the highest, followed by Taoyuan Mine, Qinan Mine, Zhuxianzhuang Mine has the smallest safety and risk.

5. ACKNOWLEDGMENTS

This research is made possible by the support from the industry-university-research cooperation of Yulin Science and Technology Bureau.

6. REFERENCES


