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Research on the Safety Fault Diagnosis System of Mine Based on Information Fusion

Kedong LYU*, **Kun Li**
Department of Automation Engineering,
Tianjin Electronic Information Technician College,China

Email: *scut_08@sina.com

Abstract. The failure of any equipment in coal mine will directly affect the safety of coal mine staff and directly threaten the safe operation of the mine. When coal mine equipment is running in a complex and changeable environment, a single fault feature is difficult to accurately reflect the fault, which is easy to lead to misjudgment and missed judgment. Using a combination of AHP and evidence theory can improve the accuracy and reliability of the evaluation. This method determines the weight of each evaluation factor through AHP. In this process, D-S evidence theory is used to fuse and modify the expert scoring data. The synthesis rule of D-S evidence theory is used to determine the risk value of coal mine equipment. The experimental results show that: compared with the single signal fault diagnosis method, this method can diagnose the equipment fault more effectively, improve the accuracy of fault diagnosis, and be applied in the fields with higher requirements for fault identification accuracy. The method is applied to the safety risk assessment of the mine. The results show that the mine construction is at a good level, which is consistent with the mine construction and verifies the model's credibility.

Keywords: Information Fusion, Safety Fault Diagnosis, Diagnosis System

1. Introduction

With the rapid development of China's economy, the demand for coal is growing day by day, making coal mine production put forward higher requirements for power supply systems and underground dangerous environment monitoring of electrical equipment. Because of the coal mine equipment running in a complex and changeable environment, the possibility of failure is greatly improved. Suppose the fault can not be detected in time in the early stage of the fault. In that case, it will pose a great threat to the safety of the equipment and even the whole coal mine, so it is necessary to develop a high-reliability fault diagnosis method.

[1] from the perspective of management and maintenance, through the vibration signal of each running state of the gearbox, the fault diagnosis of the mine gearbox is carried out so that the coal mining workers can do a good job of maintenance and prevention in advance. In [2],

based on the action information of circuit breaker after fault occurrence, the Petri net model of fault area diagnosis was established. The fault area diagnosis method was studied and verified. [3] describes the key problems of abnormal signal identification of gas monitoring system of coal mine for fault diagnosis of the coal mine. [4] carried out a numerical analysis on the location and number of gas sensors in the mining face, and verified the location distance and gas sensors. In [5], FIR low-pass and band-stop digital filters are used to preprocess the collected signals. Then the "phase-sensitive protection" function of the three-phase short circuit and the fifth harmonic leakage protection function of zero-sequence voltage and current are used to effectively simplify the hardware circuit design and optimize the system's overall performance. [6] takes the gas monitoring system as the research object, uses the agent's autonomy to construct the fault diagnosis system based on multi diagnostic agent, and realizes the intelligent fault diagnosis of the complex gas monitoring system. The above literature is mainly based on a single fault feature, which can achieve a diagnosis.

However, the single signal acquisition is easy to be affected by a sensor failure. The uncertainty factors such as changeable environment will also cause measurement errors, leading to misjudgment and missed judgment. The method of fault diagnosis using information fusion technology has been paid attention to and developed to solve this problem, mainly divided into the fusion of the same information multi-sensor and the fusion of different information decision-making layers.

To achieve safe and reliable real-time monitoring, the existing environmental monitoring system in the mining area needs to collect gas content, humidity information, air pressure, and other key information of the underground environment in real-time. Then send information to the central processing system for analysis and processing, and give decision.

[7] analyzes the data and big data characteristics of gas geology information from gas geology, designs, and constructs a multi-source mine gas geology information fusion system using multi-source information fusion technology. In [8], information fusion technology, decision support system, and artificial intelligence technology are comprehensively used to implement a feasible implementation method for the intelligent decision support system of belt fault diagnosis. In [9], the prediction of water inrush from coal floor based on multi-source information fusion is used to mine the connotation and relevance of water inrush-related information fully. Conduct a comprehensive analysis and utilization to improve accuracy and effectiveness, and reliability of water inrush prediction. In [10], according to the risk prediction technology and early warning theory of coal and gas outbursts and gas explosion, the multi-sensor information fusion method is adopted. It fully excavates the regular knowledge in various sensing data, such as gas, wind speed, electromagnetic radiation, acoustic emission. It gives full play to the advantages of various sensors to build a gas safety monitoring and early warning system based on multi-sensor information fusion. In [11], the detection system of underground detection robots in the coal mine is studied. The navigation of robot in unknown complex environment underground is analyzed by using information fusion technology, focusing on the problem of autonomous obstacle avoidance of robot. In [12], a kind of wireless sensor network for environmental monitoring of coal mine roadway is proposed. The improved information fusion technology is applied to it. It can improve the early warning of a coal mine explosion as a good supplement to the wired monitoring system. In [13], MC9S12DG128B single-chip microcomputer is used as the control core to form an intelligent node to collect and fuse the information of several sensors with obvious characteristics, such as toxic and harmful gas, temperature, air volume. [13] simplify the system structure and

improve the reliability of the system. The above literature is mainly based on one aspect of the research characteristics. However, it can achieve the intended purpose, but the complex safety system of the coal mine is not ideal.

This paper will use the method of combining AHP and DS evidence theory to improve the accuracy and reliability of the evaluation. This method uses evidence theory to correct and fuse the human factor data in AHP. It then combines the weight of each evaluation factor with AHP to finally determine the risk value of coal mine. And according to the final results of the risk assessment of coal mine, the results of a single factor can also put forward relevant suggestions to improve the safety of coal mine.

2. Method

2.1. AHP

Analytic hierarchy process (AHP) decomposes complex problems into various factors and groups these factors according to the dominant relationship to form an orderly hierarchical structure. The relative importance of each factor in the hierarchy is determined by pairwise comparison. Then the relative importance of each factor in decision-making is sorted by synthesizing people's judgment.

The analytic hierarchy process can be divided into four steps,

1) In risk assessment, the whole assessment system is divided into target layer, criterion layer, and index layer;

2) A pairwise comparison judgment matrix is constructed for the elements of the same layer;

3) The relative weight of each element is calculated by the judgment matrix;

4) The combined weight of each layer element is calculated.

2.2. D-S Theory

Dempster's theory of evidence was improved and generalized by his student Shafer in 1967, so Dempster's theory of evidence is also known as D-S theory [15-16]. If there is some supporting evidence for the framework, then according to Dempster's theory of evidence, we can generate a reliability function on the framework. The core of the evidence fusion criterion in evidence theory is Dempster's two belief function composition theorem. According to Shafer, the mathematical model of evidence theory is as follows,

1) First, we establish the identification framework θ. Only by establishing the framework θ can we transform our research on propositions into research on sets;

2) According to the evidence, an initial allocation of new capital allocation is established; that is, the evidence processor analyzes the evidence and determines the support degree of the evidence for each set (proposition) itself (regardless of any true subset (cause and effect);

3) Analyze the cause and effect, calculate our reliability for all propositions.

Under the same identification framework θ, the trust allocation function from two evidence sources are $m_1(X)$, $m_2(Y)$, and the subset elements are X_1, X_2, ..., X_k and Y_1, Y_2, …, Y_k respectively. Thus, the probability allocation function from evidence source 1 can be represented by the interval on a line segment with a total length of 1.

Similarly, for the probability assignment function from evidence source 2, a segment of [0,1] in these two functions represents the trust on a subset determined by their respective basic probability assignment functions. It does not represent the whole recognition framework. The

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length of each segment represents the basic probability assignment value of the proposition to which it belongs.

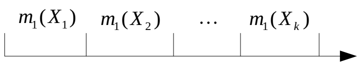

Figure 1. Trust allocation function of evidence source 1

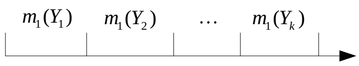

Figure 2. Trust allocation function of evidence source 2

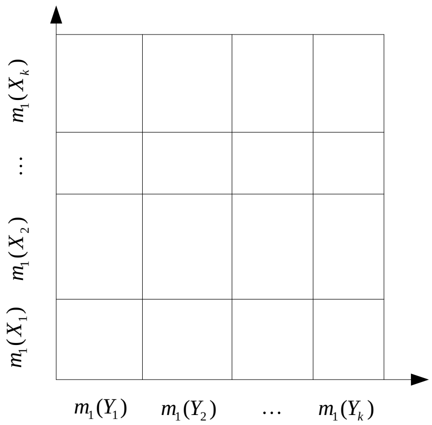

Figure 3. Intersection value of evidence source 1 and evidence source 2

Figure 3 represents how the basic trust allocation functions of these two different evidence sources complete the orthogonal composition. If the whole large rectangle is regarded as the total trust, then a bar represents the trust that $m_2(Y)$ is assigned to its subsets Y_1, Y_2, …, Y_k. Similarly, a bar represents the trust that $m_1(X)$ is assigned to subsets X_1, X_2, ..., X_k.

Given $X \subset \theta$, if $X_i \cap Y_j = C$ exists, so, $m_1(X_i)$ and $m_2(Y_j)$ are a part of the trust assigned to C exactly, and the total trust assigned to C exactly is:

$$\Sigma_{X \cap Y = C, \forall X, Y \subseteq \theta} m_i(X) \cdot m_j(Y)$$

However, $X_i \cap Y_j = \Phi$, There will be some trust $\Sigma_{X \cap Y = C, \forall X, Y \subseteq \theta}\, m_i(X) \cdot m_j(Y)$ is assigned to an empty set, that is, $m(\Phi) = \Sigma_{X \cap Y = C, \forall X, Y \subseteq \theta}\, m_i(X) \cdot m_j(Y) > 0$, which is obviously unreasonable and should be normalized.

Let:

$$K_{ij} = \Sigma_{X \cap Y = \Phi} m_i(X) \cdot m_j(Y)$$

is called conflict factor, then $[1 - \Sigma_{X \cap Y = \Phi}\, m_i(X) \cdot m_j(Y)]^{-1}$ is the normalization factor.

The Dempster composition rule can be summarized as the following theorem.

$$m(C) = m_i(X) \oplus m_j(Y)$$

$$= \begin{cases} 0, & X \cap Y = \Phi \\ \dfrac{\Sigma_{X \cap Y = C, \forall X, Y \subset \theta} m_i(X) \cdot m_j(Y)}{1 - \Sigma_{X \cap Y = C, \forall X, Y \subset \theta} m_i(X) \cdot m_j(Y)}, & X \cap Y = C \end{cases}$$

Where $i(j)$ denotes the $i(j)$-*th* evidence and $m_{i(j)}(X)$ is the trust assignment function of the $i(j)$-*th* evidence. $K_{ij} = \Sigma_{X \cap Y = \Phi}\, m_i(X) \cdot m_j(Y)$ is called the conflict factor of the *i* and *j* evidences, which indicates the conflict between the two evidences.

2.3. AHP & DSET Risk Assessment Model

The judgment matrix in AHP is the embodiment of experts' will, which inevitably has some subjectivity. The multi-expert evaluation method and the fusion technology of D-S evidence theory can greatly reduce the impact of personal subjective opinions on the full evaluation results and improve the credibility of the results.

The judgment matrix of AHP method is to compare index *i* and index *j* with each other, and define them according to their importance b_{ij} according to the nine-level scaling method, thus forming a positive mutual dissimilarity matrix: (θ_1, θ_2, θ_3, θ_4, θ_5, θ_6, θ_7, θ_8, θ_9, θ_{10}, θ_{11}, θ_{12}, θ_{13}, θ_{14}, θ_{15}, θ_{16}, θ_{17}).

Of which $\theta_1 = 9$, $\theta_{17} = 1/9$, θ_1 to θ_{17} is good to bad.

There are always some artificial differences in the experts' evaluation results of pairwise comparison between various factors in the sub-scaling method. According to the D-S synthesis rule, a new basic probability assignment function *m*(A) can be obtained for a single piece of data from different data sources.

D-S synthesis method was used, the formula is as follows:

$$Y_1 = \sum_{A_i \cap B_j = A} m_1(A_i) \cdot m_2(B_j)$$

$$Y_2 = 1 - \sum_{A_i \cap B_j = \Phi} m_1(A_i) \cdot m_2(B_j) = \sum_{A_i \cap B_j \neq \Phi} m_1(A_i) \cdot m_2(B_j)$$

$$m(\theta_1) = \frac{Y_1}{Y_2}$$

DSET is used to fuse the data, which can reduce the difference of opinion in different experts' scoring. The evaluation level with a high expert support rate has higher credibility. In contrast, experts generally believe that the credibility of the evaluation level with low credibility is lower after synthesis, which makes the fusion result appear polarization phenomenon. Uncertainty is also greatly reduced, making the results more accurate.

Combined with the combination rule of DSET and the weight coefficient assigned to each index by AHP, the weight vector $W = (w_1, w_2, \ldots, w_n)$ is set.

$$w_i \in [0,1] \;\; and \;\; \sum_{i=1}^{n} w_i = 1$$

Let $1\text{-}\partial_i = w_i / w_{\max}$, then ∂_i is the "discount rate" of w_i, and a new relative weight direction $W = (w_1, w_2, \ldots, w_n)/w_{\max}$ is obtained, the reliability function expression of evidence theory is modified as follows:

$$m(A) = (1 - \partial_i) m(A)$$

$$m(\theta) = (1 - \partial_i) m(\theta) + \partial_i$$

Then, the modified reliability function is introduced into the combination formula, and the combination rule of evidence theory is obtained.

Design identification framework θ. If there are several confidence functions on the matrix, the basic confidence function is m_i, A_i represents each focal element, and its weight is $W = (w_1, w_2, \ldots, w_n)$, then the discount rate is ∂_i, $1\text{-}\partial_i = w_i / w_{\max}$.

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$$m(A) = \sum_{\cap A_i = A} \prod_{i=1}^{n} (1-\partial_i) m_i(A_i)$$

$$m(\theta) = \sum_{\cap A_i = A} \prod_{i=1}^{n} [(1-\partial_i) m_i(A_i) + \partial_i] + \sum_{\cap A_i = A} \prod_{i=1}^{n} (1-\partial_i) m_i(A_i)$$

3. Risk Assessment of Proposed Coal Mine

In the specific coal mine risk assessment, the following steps can be implemented:

1) Establish a hierarchical structure;

2) For the criterion layer, the weight of each risk index in the index layer is determined by the modified pairwise comparison judgment matrix;

3) According to the above formula, the risk index of the same floor is synthesized, and the safety risk assessment value of the wharf is obtained from the last synthesis.

3.1. Proposed Coal Mine Project

Take Xima Coal Mine as an example to conduct risk assessment and analysis. Xima Coal Mine is the largest anthracite production mine in Northeast China. It is located in the south of Hongyang Coal Field. The geographical coordinates are 123°10'E and 41°21'N. There are Mafeng River, Shanggangzi River, and Yelaotan River in the minefield. The mine adopts the development method of a pair of shafts and one wind shaft(raise), and single-level up and down mining, with extractive ventilation method. The mine transportation method is the main shaft hoisting, mainly by belts and 3 tons of bottom-dump mine car, and auxiliary by 1 ton of mine car.

The mine adopts a comprehensive mechanized coal mining method. The immediate roof is interbedded with coal line and mudstone. The basic roof is layered medium and coarse sandstone with a thickness of 8.45m, and its coefficient of hardness f = 8~10. 12# coal has an outburst danger area, its gas content is 3.59~7.62 m^3/t, its coal dust explosion index is 8.75%, and 12# coal is a type II spontaneous pyrophoric coal seam. The hydrogeological conditions in the minefield are medium. The mining method of the working face is inclined backward mining. The goaf management method is paste filling. The roof fissure water does not affect the working face. The main source of water gushing in the working face is filling seepage water.

3.2. Evaluation Index System of Proposed Coal Mine

According to the analysis of AHP and evidence theory, to correctly reflect the influence of all factors and quantitatively evaluate the influence factors, the evaluation index system established in this paper is shown in Figure 4.

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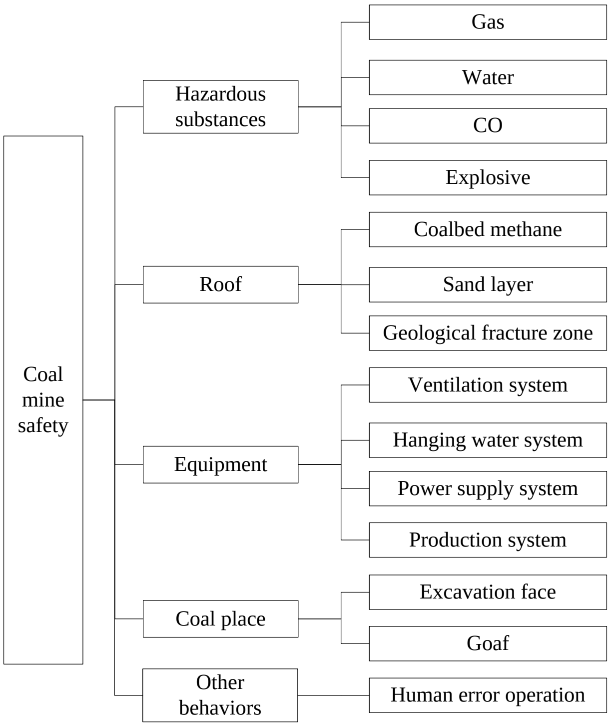

Figure 4. Safety evaluation index system of the proposed project

3.2.1. Basic Probability Distribution Function

An evaluation set is a set of possible evaluation results of evaluation objects, which can be expressed as $V = (v_1, v_2, \ldots, v_n)$. Among them, v_j ($j = 1, 2, \ldots, m$) is the evaluation result, and m is the number of grades or the number of comment files.

In this paper, the risk of coal mine construction evaluation is divided into five levels: low risk, medium low risk, medium risk, medium high risk and high risk.

V = {low risk, medium low risk, medium risk, medium high risk, high risk}

For the matrix composed of expert scoring, this paper only uses two expert scoring matrix, and the expert comments on various factors are shown in Table 1.

Table 1. Comments of mine site selection experts

Comment set	Expert 1	Expert 2
v_1	0.3	0.3
v_1	0.2	0.1
v_1	0.2	0.2
v_1	0.2	0.3
v_1	0	0
W	0.1	0.1

According to the combination formula, the data are fused to obtain the evidence fusion results of coal mine gas, as shown in Table 2.

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Table 2. The data are fused to obtain the evidence fusion results of coal mine gas

Comment set	Results of coal mine gas
v_1	0.375
v_1	0.125
v_1	0.2
v_1	0.275
v_1	0
W	0.025

According to the evidence theory, the evidence fusion results of other influencing factors are also calculated, as summarized in Table 3.

Table 3. The evidence fusion results of other influencing factors are also calculated

Comment set	**Results of coal mine information fusion**
Gas	(0.375, 0.125, 0.2, 0.275, 0, 0.025)
Water	(0, 0.26, 0.19, 0.26, 0.26, 0.03)
CO	(0.375, 0.21, 0.29, 0, 0.08, 0.045)
Explosive	(0, 0.26, 0.52, 0.18, 0, 0.04)
Coalbed methane	(0.43, 0.34, 0.19, 0, 0, 0.04)
Sand layer	(0, 0.3, 0.22, 0.22, 0.22, 0.04)
Geological fracture zone	(0, 0.15, 0.13, 0.38, 0.3, 0.04)
Ventilation system	(0.21, 0.28, 0.28, 0.21, 0, 0.02)
Hanging water system	(0.07, 0, 0.19, 0.26, 0.45, 0.03)
Power supply system	(0.2, 0.2, 0.375, 0.2, 0, 0.025)
Production system	(0.375, 0.2, 0.2, 0.2, 0, 0.025)
Excavation face	(0, 0.14, 0.21, 0.09, 0.49, 0.07)
Goaf	(0.2, 0.2, 0.375, 0.2, 0, 0.025)
Human error operation	(0.21, 0.29, 0.08, 0.375, 0, 0.045)

3.2.2. Determination of Weights at Each Level

On the basis of field research and expert data, the weight relations of each factor are calculated by using analytic hierarchy process (AHP) software, as follows:

Factor evaluation of hazardous substances

Weight value A_{11} = [0.2 0.3 0.2 0.3]

Factor evaluation of Roof

Weight value A_{12} = [0.3 0.3 0.4]

Factor evaluation of Equipment

Weight value A_{13} = [0.3 0.2 0.2 0.3]

Factor evaluation of Coal place

Weight value A_{14} = [0.5 0.5]

Factor evaluation of Other behaviors

Weight value A_{15} = [1]

The results of coal mine safety weight are as follows:

A = [0.4 0.2 0.2 0.1 0.1]

Because of the uncertainty of expert's opinion, we choose the right combination formula to synthesize the expert's opinion.

1) a comprehensive formula based on the classic Dempster combination rule:

$$m(\Phi) = 0$$

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$$m(A) = m_1(A) \oplus m_2(A) \oplus \ldots \oplus m_i(A) = \frac{\sum_{\cap B_j = A \le j \le i} \prod m_i(B_j)}{N}$$

Among them, m_1, m_2,..., m_i are the reliability functions of i expert evaluation. $\Pi m_i(B_j)$ reflects the degree of conflict between the i reliability functions.

(2) weighted average method is used to weight the reliability function of expert evaluation, and then Dempster's combination rule is used for iterative fusion.

3.2.3. Risk Synthesis Based on DSET

According to the DSET risk assessment model, the index layer is synthesized, and the comprehensive probability distribution function of the criterion layer is obtained, as shown in the table below.

Table 5. Comprehensive probability distribution function table of criterion layer.

	Criterion layer	Weight	Comments collection					Uncertainty
			Low risk	Medium low risk	Medium risk	Medium high risk	High risk	
Coal mine safety	Hazardous substances	0.4	0.15	0.22	0.25	0.2	0.18	0.033
	Roof	0.2	0.05	0.2	0.45	0.25	0.05	0.029
	Equipment	0.2	0.2	0.3	0.33	0.17	0	0.011
	Coal place	0.1	0.09	0.15	0.26	0.3	0.2	0.012
	Other behaviors	0.1	0.16	0.36	0.22	0.11	0.15	0.026

According to the DSET risk assessment model, the synthesis of criteria level factors is shown in the table below.

Table 6. Criteria level factor synthesis table

Result	Comments collection					Uncertainty
	Low risk	Medium low risk	Medium risk	Medium high risk	High risk	
Reliability	0.13	0.246	0.302	0.206	0.116	0.0285

3.3. Evaluation Conclusion of Proposed Coal Mine Project

Through the above analysis and calculation, it can be seen that the coal mine construction is at a good level in general, and hazardous substances and equipment are in a state of deviation in terms of single-factor analysis. Therefore, corresponding suggestions and maintenance measures can be put forward to improve the coal mine construction and operation environment.

4. Conclusion

1) This paper puts forward a new method to solve the problem of coal mine risk assessment, solves the shortcomings of AHP and D-S evidence theory, improves the credibility of expert comments, greatly reduces the uncertainty and makes the results more real and accurate.

2) In the follow-up work, we will study the AHP, D-S evidence theory parameter optimization to further improve the accuracy of risk assessment.

3) The calculation results can provide a theoretical basis for the competent authorities of coal mines to investigate the risks existing in coal mines, which is of great significance for reducing coal mine accidents and ensuring the safe production of coal mines.

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