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Evaluation of Emergency Rescue Efficiency in Coal Mines Based on Co-entropy

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Abstract: By decomposing the coal mine emergency rescue organization and coal mine emergency rescue work, the synergy entropy function is constructed by combining the synergy class with the entropy theory, and the synergy efficiency assessment model of coal mine emergency rescue is established. Analyze the synergistic relationship between departments in the rescue organization and between departments and functional units, construct the synergistic influence matrix, and obtain the synergistic status of the coal mine emergency rescue system by calculating the synergistic entropy, synergistic efficiency and synergistic degree. The quantitative analysis of the emergency rescue system in coal mines is achieved by analyzing the situation of the rescue work in coal mines and evaluating the rescue organizations at each tier based on the established evaluation model.

Keywords: Rescue Work; Emergency Relief; Entropy

0 Introduction

The coal mine emergency rescue system is a multi-level, multi-factor composite system^[1,2]. After a coal mine accident, emergency rescue work needs to be carried out quickly and efficiently, and because of the functional crossover between tiers in the coal mine emergency rescue system, the synergistic operation between the various tiers and component units within the system can effectively guarantee the smooth operation of the coal mine emergency rescue system. Improving the operational efficiency and synergy of the emergency rescue system can strengthen the communication between rescue organizations, increase the sharing of rescue information resources and improve the timeliness of rescue work, and maximize the function of the rescue system.

At present, researcher have conducted a series of studies on coal mine emergency rescue. Li^[3] established a coal mine emergency rescue material distribution model by studying the influencing factors of coal mine emergency rescue and using TOPSIS method to avoid the problem of unreasonable distribution of materials during rescue. Wang^[4] established the parameters of temperature and CO₂ and other stress factors during a coal mine disaster by simulating fire dynamics to cellular automata model for automatically selecting the shortest escape route. Wei^[5] combined 4R crisis management theory with coal mine emergency management to improve coal mine emergency management. Liang^[6] improved the coal mine rescue response system in three ways: optimizing resource allocation, improving emergency plans, and improving rescue technical support. Naim^[7] et al. found that by studying the relationship between leadership and government as well as organizational collaborative relationship, and found that improved information communication and efficient use of rescue materials can be used to improve the efficiency of emergency management. Yuan^[8] proposed the practicality of matrix organization structure applied to coal mine emergency rescue system. Wang^[9] established a coal mine accident emergency rescue command system based on Web GIS model to realize automatic processing function of coal mine

emergency management and improve the information sharing of emergency rescue. Zhang^[10] et al. proposed a design method for emergency rescue organizations in coal mines based on the characteristics of emergency rescue organizations in coal mines, and established a structure model for emergency rescue organizations in coal mines by decomposing rescue tasks and planning rescue materials.

So far, the research on coal mine emergency rescue mainly focuses on emergency rescue management mechanism^[11,12,13], emergency rescue technology^[14,15,16] and rescue information system^[17,18], but there is less research on the work effect and synergistic efficiency of coal mine emergency rescue organizations. In this paper, by analyzing the coal mine emergency rescue work and the organizations involved in coal mine emergency rescue, combining the functional units of coal mine emergency rescue with the organizations involved in rescue, using the theory of synergy and entropy, we establish a coal mine rescue synergy assessment model, analyze the synergy efficiency of coal mine emergency rescue work, and provide a reference for improving the efficiency of coal mine emergency rescue.

1 Analysis of emergency rescue in coal mines

1.1 Analysis of emergency rescue work in coal mines

Due to the complex environment of coal mines and the different causes of accidents, emergency rescue work in coal mines requires economic, medical and equipment support. In addition to searching for and rescuing people who have been killed underground, rescue work requires infrastructure repair, treatment of casualties and monitoring of the site environment. Because of the large number of fields and specialties involved in coal mine emergency rescue work, the support of specialized technical personnel is required. Successful emergency response in coal mines requires the integration of multiple departments in the first instance, the organization of rescue and medical personnel, and the rapid delivery of adequate rescue supplies and equipment to the accident site.

The specifics of the emergency rescue work in a coal mine are shown in Figure 1.

Figure 1. Coal mine emergency rescue work content

1.2 Analysis of emergency rescue organizations in coal mines

There are several organizations involved in the emergency rescue of coal mines, and each organization has different responsibilities in the rescue process. The organizations involved in coal mine emergency rescue work can be divided into two

categories: government organizations and social forces. Government organizations include: (1) the Ministry of Emergency Management, which is responsible for leading and coordinating the local emergency management authority for accident disposal, investigation and evaluation. (2) National Mine Rescue Command Center, responsible for organizing and coordinating the national mine emergency rescue work, mine rescue-related technology and equipment promotion, as well as mine emergency rescue education and training. (3) on-site command center, the main responsibility is to command the specific rescue work at the accident site, coordinate the various departments involved in rescue, command rescue teams, medical teams, professional and technical personnel to carry out work, leading expert groups to provide rescue support as well as to monitor the site environment. Social forces are mainly composed of enterprises and NGOs near the accident site. Compared to social forces, the professional rescue teams led by government organizations are the backbone of the emergency rescue work and are responsible for most of the emergency rescue work. The organizational structure of coal mine emergency rescue is shown in Figure 2.

Figure 2. Classification of emergency rescue organizations in coal mines

2 Coal mine emergency rescue collaboration assessment model

In a system, there are two states of order and disorder within the system, when the two states reach equilibrium will form the system order, known as the orderliness of the system. Haken, in the concordance, uses the change in order parameter to measure the transformation of order and disorder within the system, when the system is in a disordered chaotic state, the subsystems within the system are relatively independent, when the order parameter of the system is zero^[19]. When the system exchanges materials, information and energy with the outside world, the negative entropy increases continuously under the action of the subsystems within the system, and the orderliness within the system increases, and eventually the system reaches an equilibrium state and forms a new synergistic process.

Claude E. Shannon introduced the concept of information entropy in information theory^[20]. If there are multiple discrete events ($S = \{E_1, E_2, \dots, E_n\}$) inside some system S , the probability ($P = \{P_1, P_2, \dots, P_n\}$) of each discrete event occurring at random is called the information entropy.

$$H(s) = - \sum P_i \log P_i, \quad i = 1, 2, \dots, n \quad (\text{formula 1})$$

When functional units within the system perform actions, the information flow between each other forms the synergistic path, which reflects the state of the functional units involved in the synergy within the system. Because functional units cannot all participate in the action, so the synergistic paths are limited. The number of synergistic paths of functional units in a coal mine emergency rescue system is $f = \sum f_i, i = 1, 2, \dots, n$. According to the probability relationship, the synergistic probability of functional units is $P(f_i) = (f_i)/f$. According to the definition of entropy can derive the synergistic entropy of emergency rescue functional units as follows.

$$H = - \sum P(f_i) \log P(f_i), \quad i = 1, 2, \dots, n \quad (\text{formula 2})$$

In any system, the collaboration process between functional units shows a trend of decreasing collaboration efficiency and increasing confusion. For this situation, the synergy entropy is used to describe the collaboration between functional units, the larger the value of synergy entropy, the lower the efficiency of collaboration between functional units.

The key to evaluate the synergistic efficiency of coal mine emergency rescue system is to find out the system relationship between functional units at each tier, and use the cumulative iterative value of the synergistic relationship at each tier as the standard to judge the superiority of the system.

Starting from each functional unit of the coal mine emergency rescue system, the synergistic relationship between the functional units reflects the interaction influence between the functions. By analyzing and comparing the system relationship between the functional units, the emergency rescue unit collaboration matrix is obtained as $\varepsilon = [T_i, T_j]_{n \times n} = (\mu_{ij})_{n \times n}$.

$$\varepsilon = \begin{bmatrix} \mu_{11} & \mu_{12} & \dots & \mu_{1j} & \dots & \mu_{1n} \\ \mu_{21} & \mu_{22} & \dots & \mu_{2j} & \dots & \mu_{2n} \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ \mu_{i1} & \mu_{i2} & \dots & \mu_{ij} & \dots & \mu_{in} \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ \mu_{n1} & \mu_{n2} & \dots & \mu_{nj} & \dots & \mu_{nn} \end{bmatrix} \quad (\text{formula 3})$$

The same tier of rescue department emergency rescue functional units own information sharing is 1. Since multiple departments are involved under the coal mine emergency rescue organization, their own information sharing is determined by the degree of information communication between functional units. Therefore, the information sharing between rescue departments is 0.

$$\mu_{ij} = \begin{cases} 1 & \text{Rescue department information sharing} \\ 0 & \text{Other wise} \end{cases} \quad i \neq j \quad (\text{formula 4})$$

$$\mu_{ij} = \begin{cases} 1 & \text{Same level of rescue department} \\ 0 & \text{Other wise} \end{cases} \quad i = j \quad (\text{formula 5})$$

Y_{ijq} is the number of departments in the emergency response organization that are in a collaborative state, and Y_{ijf} is the number of departments in the organization that are not in a collaborative state. The number of departments in the emergency rescue organization is $Y_{ij} = Y_{ijq} + Y_{ijf}$. According to the relationship between probability and

information entropy, the synergistic entropy of the emergency rescue synergistic state is,

$$H_{ijq}(T_{ij}) = - \frac{Y_{ijq}}{Y_{ij}} \log \frac{Y_{ijq}}{Y_{ij}} \quad (\text{formula 6})$$

The synergistic entropy in the emergency rescue organization that is in a non-synergistic state is:

$$H_{ijf}(T_{ij}) = - \frac{Y_{ijf}}{Y_{ij}} \log \frac{Y_{ijf}}{Y_{ij}} \quad (\text{formula 7})$$

The total internal synergistic entropy of the emergency rescue department T_i in the emergency rescue organization of the coal mine is:

$$H_{niq}(T_i) = \sum_{j=1}^k H_{niq}(T_{ij}) = - \sum_{j=1}^k \frac{Y_{ijq}}{Y_{ij}} \log \frac{Y_{ijq}}{Y_{ij}} \quad (\text{formula 8})$$

$$H_{ijf}(T_i) = \sum_{j=1}^k H_{ijf}(T_{ij}) = - \sum_{j=1}^k \frac{Y_{ijf}}{Y_{ij}} \log \frac{Y_{ijf}}{Y_{ij}} \quad (\text{formula 9})$$

If the maximum synergistic entropy in the same tier in a coal emergency rescue organization is $H_{\max}$, C is the degree of synergy between emergency rescue departments, thus,

$$C = 1 - \frac{H_{ijq}}{H_{\max}} \quad (\text{formula 10})$$

Similarly, the synergy degree C of the coal mine emergency response department is:

$$C = 1 - \frac{H_{iq}(T_i)}{H_{\max}} \quad (\text{formula 11})$$

In an emergency response organization, the overall degree of synergy (B) at the same tier is,

$$B = \sum H_{ij} \quad (\text{formula 12})$$

The above equation shows that and denote the entropy values between departments at each tier in the synergistic and non-synergistic states, respectively, so that the synergistic efficiency (R) is,

$$R = 1 - \frac{H_{iq}}{H_{iq} + H_{if}} = 1 - \frac{Y_{iq}}{Y_i} \log \frac{Y_{iq}}{Y_i} / \frac{Y_{iq}}{Y_i} \log \frac{Y_{iq}}{Y_i} + \frac{Y_{if}}{Y_i} \log \frac{Y_{if}}{Y_i} \quad (\text{formula 13})$$

From the nature of logarithmic function, it is known that the more functional units in each tier of the system are in full synergistic state, the more it can reduce the degree of confusion and deviation of the system, and the higher the synergistic efficiency. When $Y_{if} = 0$, all the units in the hierarchy are in the synergistic state, and the synergistic efficiency is 1.

3 Case Analysis

In this paper, we analyze the synergistic efficiency of coal mine emergency rescue organizations with reference to the emergency rescue cases of coal mine accidents in China in recent years.

According to Figures 1 and 2 and the synergistic relationship between the functional units in the process of coal mine emergency rescue, a coal mine emergency

rescue system synergy matrix can be established. $\varepsilon_1 = [S_i, S_j]_{5 \times 5} = (\mu_{ij})_{5 \times 5}$ denotes the synergy matrix of government organizations and social forces in the coal mine emergency rescue organization; $\varepsilon_{13} = [S_{3i}, S_{3j}]_{5 \times 5} = (\mu_{ij})_{5 \times 5}$ denotes the synergy matrix of five rescue departments under the emergency rescue site command center; $\varepsilon_2 = [T_i, T_j]_{8 \times 8} = (\mu_{ij})_{8 \times 8}$ denotes the synergistic influence matrix between the eight functional units in the coal mine emergency rescue work.

Through the analysis of the organizations and functional units in the coal mine emergency rescue system, combined with the actual situation in the coal mine emergency rescue process, the synergistic influence matrix of the coal mine emergency rescue organization and the emergency rescue functional units is as follows.

$$\varepsilon_1 = \begin{bmatrix} 0 & 1 & 1 & 0 & 0 \\ 1 & 0 & 1 & 1 & 1 \\ 1 & 1 & 0 & 1 & 1 \\ 0 & 1 & 1 & 0 & 1 \\ 0 & 1 & 1 & 1 & 0 \end{bmatrix}, \quad \varepsilon_{13} = \begin{bmatrix} 1 & 1 & 1 & 1 & 1 \\ 1 & 1 & 0 & 0 & 0 \\ 1 & 0 & 1 & 0 & 1 \\ 1 & 0 & 0 & 1 & 1 \\ 1 & 0 & 1 & 1 & 1 \end{bmatrix}$$

$$\varepsilon_2 = \begin{bmatrix} 0 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\ 1 & 0 & 0 & 1 & 0 & 1 & 0 & 1 \\ 1 & 0 & 0 & 0 & 0 & 0 & 1 & 1 \\ 1 & 1 & 0 & 0 & 1 & 0 & 1 & 1 \\ 1 & 0 & 0 & 1 & 0 & 0 & 1 & 1 \\ 1 & 1 & 0 & 1 & 1 & 0 & 1 & 1 \\ 1 & 0 & 1 & 1 & 1 & 1 & 0 & 0 \\ 1 & 1 & 1 & 1 & 1 & 0 & 0 & 0 \end{bmatrix}$$

According to formulas (6) to (11), the calculation results are shown in Table 1 and Table 2.

Table 1. Coal mine emergency rescue organization synergy indicators

	Emergency relief organizations					B₁
	S₁	S₂	S₃	S₄	S₅	
Co-entropy (H_{ijq})	0.1592	0.0775	0.0775	0.1398	0.1398	0.5938
Co-entropy (H_{ijf})	0.1331	0.1398	0.1398	0.0775	0.0775	0.5677
Collaboration	0	0.5132	0.5132	0.1219	0.1219	0.2540
Synergy Efficiency	0.4554	0.6434	0.6434	0.3566	0.3566	0.4888
	Emergency relief organizations					B₂
	S₃₁	S₃₂	S₃₃	S₃₄	S₃₅	
Co-entropy (H_{ijq})	0	0.1592	0.1398	0.1398	0.0775	0.5163
Co-entropy (H_{ijf})	1	0.1331	0.0775	0.0775	0.1398	1.4279
Collaboration	1	0	0.1219	0.1219	0.5132	0.3514
Synergy Efficiency	1	0.4554	0.3566	0.3566	0.6434	0.9485

Table 2. Coal mine emergency rescue functional unit synergy indicators

	Emergency rescue functional unit for coal mines							B₃
	T₁	T₂	T₃	T₄	T₅	T₆	T₇	
Co-entropy (H_{ijq})	0.0507	0.1505	0.1597	0.1276	0.1505	0.0937	0.1276	0.9882
Co-entropy (H_{ijf})	0.1129	0.1505	0.1276	0.1597	0.1505	0.1505	0.1597	1.1711
Collaboration	0.6825	0.0576	0	0.2010	0.0576	0.4311	0.2010	0.2268
Synergy Efficiency	0.6901	0.5000	0.4441	0.5531	0.5000	0.6163	0.5531	0.5424

Code the participation of various departments in the coal mine emergency rescue organization in rescue work, and use 1 and 0 to indicate whether to participate in emergency rescue work. Through coding and combining the above mathematical models, a coordination matrix of coal mine emergency rescue organizations and functional units is established. Among them, the second-tier rescue organization coordination matrix is $\varepsilon_1 = (S_{ij}, T_i)_{5 \times 9}$, and the third-tier rescue organization coordination matrix is $\varepsilon_2 = (S_{ij}, T_i)_{7 \times 9}$. The coordination matrix is as follows:

$$\varepsilon_1 = \begin{bmatrix} 1 & 1 & 1 & 0 & 0 \\ 1 & 1 & 1 & 1 & 0 \\ 1 & 0 & 1 & 1 & 0 \\ 1 & 1 & 1 & 0 & 0 \\ 1 & 1 & 1 & 1 & 1 \\ 1 & 0 & 1 & 0 & 0 \\ 1 & 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 0 & 0 \end{bmatrix} \quad \varepsilon_2 = \begin{bmatrix} 1 & 1 & 0 & 0 & 1 & 1 & 1 \\ 1 & 1 & 0 & 0 & 0 & 1 & 1 \\ 1 & 0 & 1 & 0 & 1 & 0 & 0 \\ 1 & 1 & 1 & 0 & 1 & 0 & 1 \\ 1 & 1 & 1 & 1 & 0 & 0 & 0 \\ 1 & 0 & 1 & 1 & 0 & 0 & 0 \\ 1 & 1 & 1 & 1 & 0 & 1 & 0 \\ 1 & 1 & 0 & 0 & 0 & 1 & 1 \end{bmatrix}$$

According to formulas (6) ~ (13), the synergy indices between the emergency rescue functional units and emergency rescue organizations in coal mines are calculated as shown in Tables 3 and 4.

Table 3. First tier coal mine emergency rescue organization and emergency rescue functional unit synergy index

	Emergency rescue functional unit for coal mines								B ₄
	T ₁	T ₂	T ₃	T ₄	T ₅	T ₆	T ₇	T ₈	
Co-entropy (H_{ijq})	0.1331	0.0775	0.1331	0.1331	0	0.1592	0	0.1331	0.7691
Co-entropy (H_{ijf})	0.1592	0.1397	0.1592	0.1592	1	0.1331	1	0.1592	2.9096
Collaboration	0.1639	0.5132	0.1639	0.1639	1	0	1	0.1639	0.3961
Synergy Efficiency	0.5446	0.6432	0.5446	0.5446	1	0.4554	1	0.5446	0.7909

Table 4. Second tier coal mine emergency rescue organization and emergency rescue functional unit synergy index

	Emergency rescue functional unit for coal mines								B ₅
	T ₁	T ₂	T ₃	T ₄	T ₅	T ₆	T ₇	T ₈	
Co-entropy (H_{ijq})	0.1044	0.1389	0.1577	0.1044	0.1389	0.1577	0.1044	0.1389	1.0453
Co-entropy (H_{ijf})	0.1554	0.1577	0.1389	0.1554	0.1577	0.1389	0.1554	0.1577	1.2171
Collaboration	0.3380	0.1192	0	0.3380	0.1192	0	0.3380	0.1192	0.1715
Synergy Efficiency	0.5982	0.5317	0.4683	0.5982	0.5317	0.4683	0.5982	0.5317	0.5380

The collaborative efficiency of coal mine emergency rescue was evaluated by analyzing the collaborative relationship between the coordination process and the coordination efficiency of coal mine accident emergency rescue. From Figure 3 and Figure 4, it can be seen that: (1) the collaborative efficiency of the first tier of coal mine emergency rescue organizations is in the range of 0.4 to 0.6, and the difference between each department is not large, and it can be seen that the collaborative ability of the first tier of rescue organizations is approximately the same; (2) the difference between the second coal mine emergency rescue organization and the first tier is more obvious, with

the lowest being 0.3566 and the rescue team reaching 1; (3) the collaborative efficiency between emergency The synergistic efficiency between rescue functional units is higher, with a maximum of 0.6901 and a minimum of 0.4441, indicating that the basis of emergency rescue work in coal mines is accident analysis and investigation; (4) the maximum value of synergistic efficiency between rescue organizations and functional units in the first tier is 1 and the minimum value is 0.4554, and the maximum value of synergistic efficiency between rescue organizations and functional units in the second tier is 0.5982 and The minimum value is 0.4683, which is lower than the synergistic efficiency of the first tier of rescue organizations, indicating that the next tier is mainly concerned with the implementation of the work of the coal mine rescue team; (5) in a comprehensive view, the total synergistic efficiency of the coal mine emergency rescue organizations is high, all exceeding 0.5, with the highest synergistic efficiency between the first tier of rescue organizations and functional units being 0.7909, and the total synergistic efficiency between the second tier of rescue organizations and functional units efficiency is 0.5380.

Figure 3. Emergency rescue organization collaborative efficiency

Figure 4. Collaborative efficiency between emergency rescue organization and functional units

4 Conclusion

This paper analyzes the composition of coal mine emergency rescue organizations and the tasks of rescue work, analyzes the synergy of coal mine emergency rescue organizations, applies the theory of synergy and entropy to coal mine emergency rescue, and establishes a coal mine emergency rescue synergy efficiency assessment model. The synergistic relationship between coal mine emergency rescue organizations and between organizations and functional units is studied. The efficiency of the coal mine emergency rescue system is analyzed through the actual situation of the coal mine emergency rescue operation. Under the current emergency rescue organizational structure, the synergistic efficiency is high. In the post-accident rescue work, accident analysis and investigation are the core of the rescue work and are crucial to the rescue work. By studying the synergistic efficiency between functional units, it can provide a reference for the synergistic work between rescue organizations and the improvement of synergistic efficiency. At the same time, improving the efficiency of search and rescue and rescue material transportation can improve the synergistic efficiency of rescue organizations as a whole. Efficient collaborative rescue work can ensure that infrastructure repair work is carried out quickly and effectively, prevent secondary accidents, and guarantee the rapid resumption of production in coal mines.

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