# Health Status Assessment of a Scraper Conveyor Mechanical System

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**Abstract.** A method leveraging cooperative game theory is proposed to determine the combined weights of the mechanical system of a scraper conveyor, with a particular mining face serving as the research object. Additionally, the immune principle is introduced to estimate the health status of the mechanical system. First, a hierarchical analysis model and an immune hierarchical analysis model are established for the mechanical system of the scraper conveyor. The analytic hierarchy process, fuzzy statistics method, and entropy weight method are employed to determine the individual weights of each component in the mechanical system. Subsequently, the combined weights of various components in the mechanical system of the scraper conveyor are calculated using the cooperative game method. Second, the health values and health status of each component are calculated based on the sequence vector of component states output by the immune principle and the comprehensive weight vector. Finally, the weight vector of the mechanical system of the scraper conveyor is obtained based on the analytic hierarchy process. The health status of the entire mechanical system is then evaluated using the health status data of each component as the initial data for the system layer. The research results demonstrate that the presented method effectively obtains the health status of the mechanical system of the scraper conveyor by considering the physical characteristics of each component. Moreover, it facilitates the effective formulation of maintenance and repair plans for various components of the system.

**Keywords:** Line pan, Health status assessment, Cooperative game method, Principles of immunity.

## 1. Introduction

Intelligent coal mining represents an effective strategy for the transformation, upgrading, and high-quality development of the coal industry [1-3]. However, China's intelligent coal mining technology remains at an initial stage, with deficiencies in intelligent perception, decision-making, and control technology systems. Achieving disruptive innovation in intelligent control technologies, such as comprehensive multidimensional perception; multi-system integration, analysis, and prediction; independent decision-making; and collaborative control, is urgently needed [4]. The scraper conveyor, as a vital component of fully mechanized mining equipment in coal mines, operates continuously in harsh, high-load environments. Its optimization is crucial for realizing the intelligence of coal mines [5].

Currently, health status assessment methods have been extensively studied across various fields. In the transportation sector, Wang Qi et al. [6] proposed the utilization of the analytic hierarchy process and fuzzy statistics to determine the weight of the subway traction power supply system. By establishing a multi-layer immune model for the subway traction power supply system to evaluate its health status, this method combines subjectivity and objectivity, resulting in relatively accurate analysis results. Zhao Feng et al. [7] proposed a health evaluation method for the traction power supply system of multiple units based on a combination weighting method and fuzzy gray clustering. By utilizing the component clustering coefficients of the component layer as initial data for evaluating the health status of the preceding layer system, the state evaluation of the traction power supply system of multiple units was effectively achieved. Zhao Feng et al. [8] proposed a cooperative game method that integrates the entropy weight method, analytic hierarchy process, and gray correlation degree method to evaluate the health status of an auxiliary power supply system of high-speed trains, resulting in more accurate weight calculation results. In the field of water conservancy and hydropower, Zhang Longsheng et al. [9] utilized a specific type of hydroelectric generator to construct a combination of qualitative and quantitative indicator systems. By employing cloud model theory, the health status of hydroelectric generator equipment was effectively evaluated. Meanwhile, Cao Wei et al. [10] proposed the utilization of the fuzzy comprehensive evaluation method to comprehensively assess the health status of hydroelectric generators. This addressed challenges such as excessive real-time monitoring data, difficulty in evaluating equipment health status, and complexity in assessing overall equipment operation status. The evaluation results aligned well with the actual equipment status. In the mining field, Zhang Yukun et al. [11] applied a genetic algorithm back propagation (GA-BP) neural network prediction model to predict the health level of a disc cutter excavation cutting system during excavation operations. Through experimental verification, the prediction results proved accurate and effective. Yan Xiangtong et al. [12] proposed an intelligent evaluation method for the health status of coal mining machines based on optimized back propagation (BP) neural networks, resulting in more accurate analysis results. Cao Xiangang et al. [13-15] proposed a health status evaluation method for coal mining machines based on a convolutional neural network (CNN) and extreme gradient boosting algorithm (XGBoost), effectively addressing the challenges of imbalanced data collection and coal mining machine status evaluation.

Currently, there is relatively limited research on the health status evaluation of scraper conveyors in the coal mine working face, with the primary evaluation indicators mainly focusing on electrical system parameters. Zheng Yunlong et al. [16] employed a (BP) neural network approach and identified five key parameters as evaluation metrics for the real-time assessment of a scraper conveyor's health status: chain speed, head motor current, tail motor current, head motor torque, and tail motor torque. Notably, the health evaluation outcomes were susceptible to influences from various factors, including coal quantity fluctuations, raw coal quality variability, and changes in the particle size of the scraper conveyor. The mechanical system of the scraper conveyor constitutes approximately 70% of the total cost of the scraper conveyor, and its health status plays a crucial role in determining the efficient and stable operation of the scraper conveyor, warranting increased attention.

The line pan, rack bar, flight bar, and sprocket are the primary components of a scraper conveyor's mechanical system. This study selects the key parameters of these components as evaluation metrics to develop a hierarchical analysis model and a multi-layer immune monitoring model for the mechanical system of a scraper conveyor. This study employs a multimethod approach, combining the analytic hierarchy process (AHP) based on subjective judgment, fuzzy statistics grounded in objective analysis, and the entropy weight method to calculate the individual weight vectors for each component. The cooperative game method, which integrates these three approaches, is utilized to determine the combined weight vectors for each component. The weight information is then quantified based on the immune principle to obtain the health values of each component. The AHP is subsequently applied to determine the weight vector of the mechanical system of the scraper conveyor, with the health value data of each component serving as the initial data for the system layer. This enables the completion of a comprehensive health status evaluation of the entire mechanical system, yielding more accurate analysis results. (Figure 1)

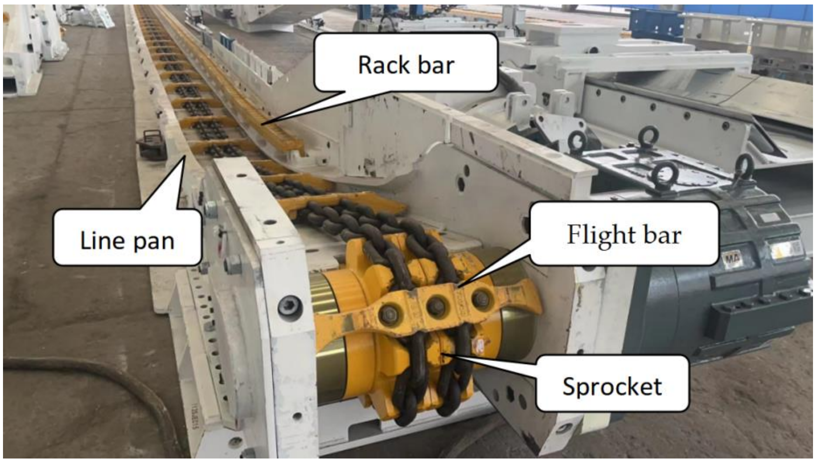



**Figure 1.** Mechanical system of a scraper conveyor

## 2. Weight Calculation Method

This article employs a multi-method approach, combining the AHP grounded in subjective judgment, the fuzzy statistics method based on objective analysis, and the entropy weight method to calculate the individual weight vectors for each component at the component layer, denoted by $\boldsymbol{W}_{\mathrm{i}}^{(l)}$ $(i = 1,2,3,4;\ l = 1,2,3)$. Notably, i denotes the i-th component at the component layer, whereas l represents the l-th method employed to determine the weights of each component. By applying cooperative game theory, the comprehensive weight vector of each component of the scraper conveyor mechanical system is denoted as $\boldsymbol{W}_i$ $(i = 1,2,3,4)$, and the weight vector of the scraper conveyor mechanical system is determined using the AHP, denoted as W.

### 2.1. AHP

The AHP is a subjective weight calculation method. Initially, the mechanical system of the scraper conveyor is decomposed into a hierarchical structure comprising the system layer, component layer, and indicator layer. Next, using the results of pairwise comparisons of the TL Saaty 1–9 proportional scale method (Table 1) to establish the judgement matrix $\boldsymbol{A} = (a_{jt})_{n\times n}$, the formula is $a_{jt} > 0$, $a_{jt} = \frac{1}{a_{jt}}$, $a_{jt} = 1$, where j denotes the j-th indicator of the component, while n denotes the total number of indicators. Third, employing formulas $CI = \frac{\lambda_{max}-n}{n-1}$ and $CR = \frac{CI}{RI}$ for assessing the construct validity of matrix A, under the conditions where n ≥ 3 and 0 < CR < 0.1, we find that each indicator is capable of being attributed with sensible weight values. Ultimately, the weight is derived through the formula $\boldsymbol{A} \cdot \boldsymbol{W}_i^{(l)} = \lambda_{max} \cdot \boldsymbol{W}_i^{(l)}$, in which $\lambda_{max}$ represents the maximum eigenvalue corresponding to matrix A. The weight vector of component i within the system, derived from the AHP, is denoted as $\boldsymbol{W}_i^{(l)} = [w_1^{(l)}, w_2^{(l)}, \dots, w_n^{(l)}]$.

**Table 1.** TL Saaty 1-9 proportional scale method

| Scale Value | Meaning |
|---|---|
| 1 | Both indexes are equally important |
| 3 | One index is slightly important than another |
| 5 | One index is important than another |
| 7 | One index is very important compared to another |
| 9 | One index is extremely important compared to another |
| 2, 4, 6, 8 | Take the middle value |

## 2.2. Fuzzy Statistical Method

Fuzzy statistics serve as an objective method for calculating weights. Initially, the health status of the system or component is divided into five levels, and the evaluation set is defined as $T_s = \{T_1, T_2, T_3, T_4, T_5\}$, where $T_1$ represents health, $T_2$ represents sub health, $T_3$ represents mild pathology, $T_4$ represents moderate morbidity, and $T_5$ represents severe morbidity. Based on their actual significance, the indexes are categorized into cost-type and benefit-type indexes. The value interval of the fuzzy distribution for each index is determined, and an index evaluation matrix is constructed using the calculation formula $\boldsymbol{D}_j = [\lambda_j^{(1)}, \lambda_j^{(2)}, \lambda_j^{(3)}, \lambda_j^{(4)}, \lambda_j^{(5)}]$. The calculation formulas for the two types of indexes are as follows.

### 2.2.1. Benefit Type

$$\lambda_i^{(1)} = \begin{cases} 1 & z \geq b \\ (z - c_4)/d & c_4 \leq z < b \\ 0 & z < c_4 \end{cases} \tag{1}$$

$$\lambda_i^{(s)} = \begin{cases} 0 & z \geq c_{5-s+2} \\ (c_{5-s+2} - z)/d & c_{5-s+1} \leq z < c_{5-s+2} \\ (z - c_{5-s})/d & c_{5-s} \leq z < c_{5-s+1} \\ 0 & z \leq c_{5-s} \end{cases} \tag{2}$$

$$\lambda_i^{(5)} = \begin{cases} 0 & z \geq c_2 \\ (c_2 - z)/d & a \leq z < c_2 \\ 1 & z < a \end{cases} \tag{3}$$

Formula: a represents the worst-case critical value, while b denotes the optimal critical value, $c_1 = a$, $c_5 = b$, $d = (b - a)/4$, $s = 2,3,4$.

### 2.2.2. Cost Type

$$\lambda_i^{(1)} = \begin{cases} 1 & z < a \\ (c_2 - z)/d & a \leq z < c_2 \\ 0 & z \geq c_2 \end{cases} \tag{4}$$

$$\lambda_i^{(s)} = \begin{cases} 0 & z < c_{s-1} \\ (z - c_{s-1})/d & c_{s-1} \leq z < c_s \\ (c_{s+1} - z)/d & c_s \leq z < c_{s+1} \\ 0 & z \geq c_{s+1} \end{cases} \tag{5}$$

$$\lambda_i^{(5)} = \begin{cases} 0 & z < c_4 \\ (c_5 - z)/d & c_4 \leq z < b \\ 1 & z \geq b \end{cases} \tag{6}$$

Formula: b represents the worst-case critical value, while a denotes the optimal critical value.

Subsequently, objective correction coefficients for each indicator are derived using formulas $e_j = max\{\lambda_j^{(s)}\}$ and $\alpha_j = (1/e_j)/(\sum 1/e_j)$, leading to the acquisition of comprehensive weights for each indicator within the indicator layer, denoted as:

$$w_j^{(2)} = \frac{\alpha_j w_j^{(1)}}{\sum \alpha_j w_j^{(1)}} \tag{7}$$

Finally, the weight vector of component i in the system based on the fuzzy statistical method is calculated as: $\boldsymbol{W}_i^{(2)} = [w_1^{(2)}, w_2^{(2)}, \dots, w_n^{(2)}]$.

### 2.3. Entropy Weight Method

The entropy weight method is also an objective method of weight determination. Initially, normalization is applied to the raw data. Herein, there are n assessment indexes for the components, with each index comprising q groups of data. These tiers of data collectively form a raw data matrix, denoted as $x_{\mathrm{jk}}{}'$. Subsequently, this matrix $x_{\mathrm{jk}}{}'$ undergoes a normalization process in accordance with the given formula:

$$x_{\mathrm{jk}} = \frac{x_a - x_{\mathrm{jk}}{}'}{x_a - x_b},\ (j = 1,2,\ldots,n;\ k = 1,2,\ldots,q) \tag{8}$$

The following formula is then used to calculate the information entropy of the j-th indicator in the system:

$$E_j = -\alpha \sum_{q=1}^{q} (p_{\mathrm{jk}} \ln p_{\mathrm{jk}}) \tag{9}$$

Formula: $p_{\mathrm{jk}} = \frac{x_{\mathrm{jk}}}{\sum_{q=1}^{q} x_{\mathrm{jk}}}$, $a = \frac{1}{\ln q}$.

Calculate the weight of the j-th indicator as:

$$w_j^{(3)} = \frac{1-E_j}{n-\sum_{n=1}^{n} E_j} \tag{10}$$

Finally, calculate the weight vector of a component i in the system based on the entropy weight method as: $\boldsymbol{W}_i^{(3)} = [w_1^{(3)}, w_2^{(3)}, \ldots, w_n^{(3)}]$.

### 2.4. Cooperative Game Method

To obtain combination weights with both subjective and objective significance, an effective amalgamation of the AHP, fuzzy statistical method, and entropy weight method is employed, resulting in combination weights of higher precision. Initially, the consistency correlation coefficient $L_j^{(l)}$ between $w_j^{(l)}$ and $w_j^{(3\_l)}$ is calculated.

$$L_j^{(l)} = \frac{\sum_{l=1}^{3}[w_j^{(l)} - \overline{w_j^{(l)}}][w_j^{(3\_l)} - \overline{w_j^{(3-l)}}]}{\{\sum_{l=1}^{3}[w_j^{(l)} - \overline{w_j^{(l)}}]^2\}^{1/2}\{\sum_{l=1}^{3}[w_j^{(3\_l)} - \overline{w_j^{(3\_l)}}]^2\}^{1/2}} \tag{11}$$

The formula for $w_j^{(3\_l)}$ is:

$$\left.\begin{aligned} w_j^{(3\_1)} &= \frac{w_j^{(2)}+w_j^{(3)}}{2}, l = 1 \\ w_j^{(3\_2)} &= \frac{w_j^{(1)}+w_j^{(3)}}{2}, l = 2 \\ w_j^{(3\_3)} &= \frac{w_j^{(1)}+w_j^{(2)}}{2}, l = 3 \end{aligned}\right\} \tag{12}$$

Subsequently, the formula for calculating the combined weight of the j-th index, denoted as $w_j'$, is as follows:

$$w_j{}' = \sum_{l=1}^{3} w_j^{(1)} L_j^{(l)} \tag{13}$$

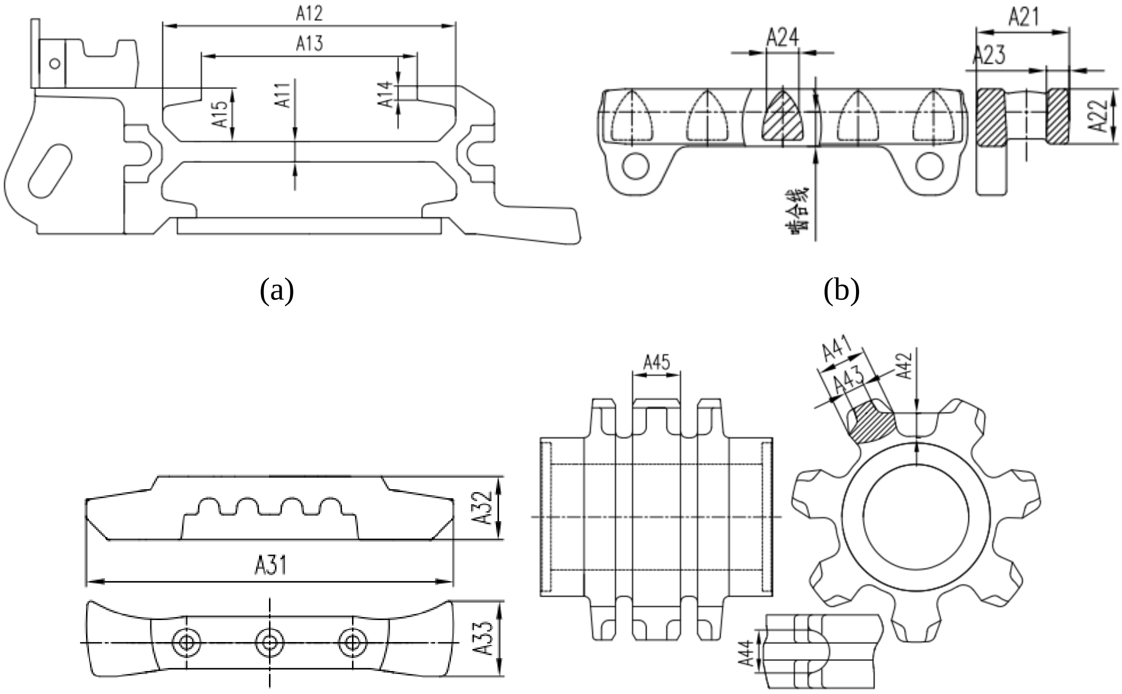
Normalize $w_j'$:

$$w_j = \frac{w_j{}'}{\sum_{n=1}^{n} w_j{}'} \tag{14}$$

Finally, calculate the combined weight vector of component i in the system based on cooperative game theory as: $\boldsymbol{W}_i = [w_1, w_2, \ldots, w_n]$.

## 3. Scraper Conveyor Mechanical System Health Status Assessment Model

The line pan, rack bar, flight bar, and sprocket are the primary components of the scraper conveyor's mechanical system. The functional condition of these components significantly impacts the scraper conveyor's overall service life. The selection of essential parameters from the line pan, rack bar, flight bar, and sprocket as evaluative benchmarks is depicted in Figure 2.




(a) (b)

(c) (d)

**Figure 2.** Parameters of the (a) line pan, (b) rack bar, (c) flight bar, and (d) sprocket

### 3.1. Hierarchical Analysis Model of the Scraper Conveyor Mechanical System

The scraper conveyor's mechanical system is categorized into a three-tiered hierarchical structure: system level, component level, and indicator level (Figure 3).

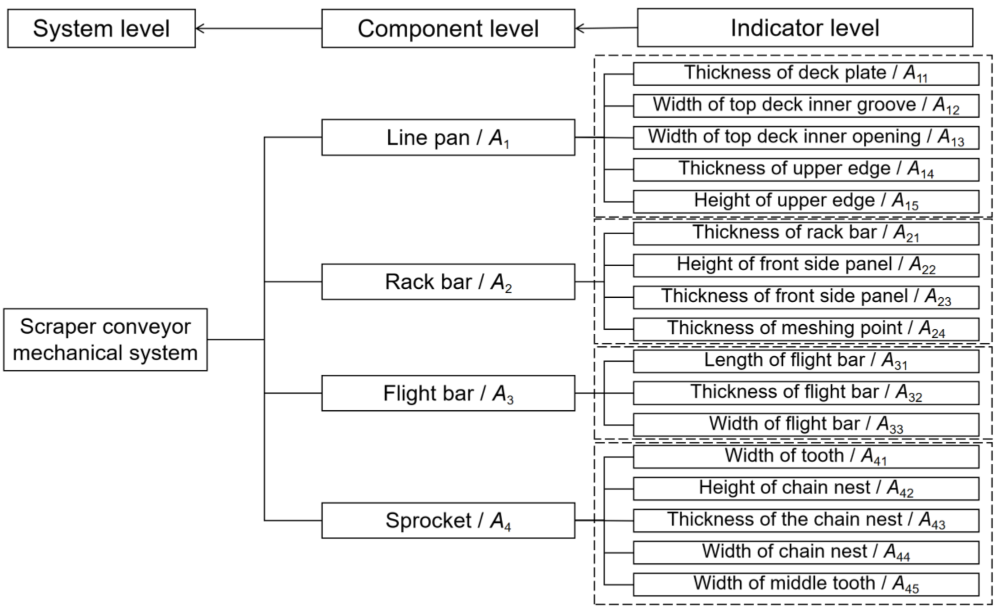



**Figure 3.** The hierarchical analysis model for the mechanical system of a scraper conveyor

The uppermost tier, the system level, serves to ascertain the overall health status of the scraper conveyor's mechanical framework. The intermediate tier, known as the component level, is utilized to evaluate the health status of individual conveyor components. Meanwhile, the foundational tier, or indicator level, furnishes the essential data for the health assessment of the mechanical system. Health status evaluations are conducted progressively, beginning from the indicator level and culminating at the system level, to ultimately achieve a comprehensive health status assessment of the scraper conveyor's mechanical system.

### 3.2. Multi-layer Immune Monitoring Model of a Scraper Conveyor Mechanical System

The principle of immunity, originating from biological immune mechanisms in the field of biomedicine, is an intelligent algorithm designed to solve various complex problems. The construction of a multi-level immune monitoring system for the scraper conveyor mechanical framework is depicted in Figure 4.

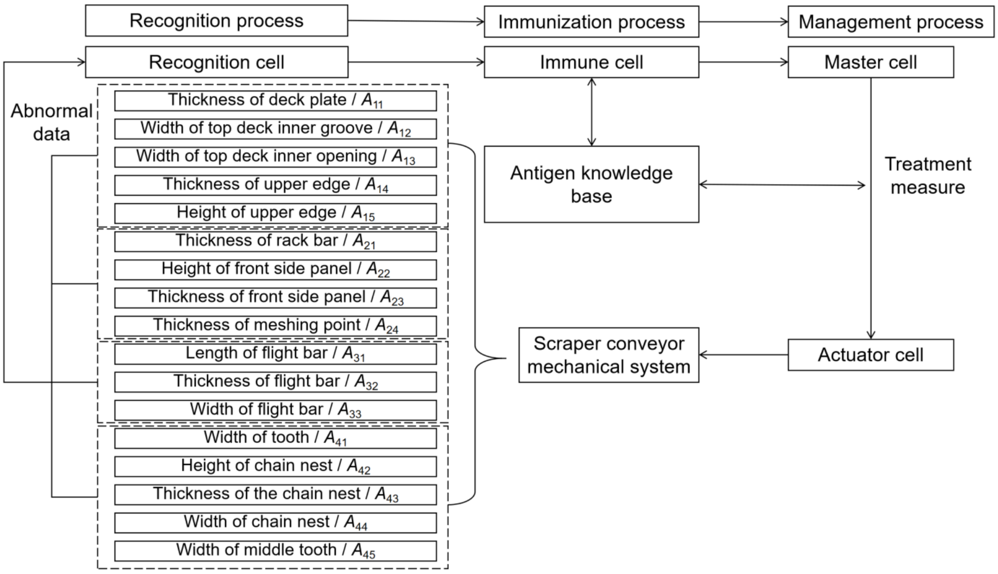



**Figure 4.** Multilayer immune monitoring model of a scraper conveyor mechanical system

The principal components of this immune monitoring system include recognition cells, immune cells, master cells, and actuator cells. Recognition cells are placed at the indicator level to gather the information required for assessing the health status of components (such as the line pan). This information is acquired either through structurally integrated online monitoring devices or through regularly scheduled manual inspections. The recognition cells upload any abnormalities detected to the immune cells, which then process the aberrant data and generate a health status sequence conveyed to the master cells. By identifying the status sequence, the master cells coordinate the formation of corresponding antibodies to the diverse failure states of each component, determining relevant control schemes and passing them to the actuator cells. In this process, the abnormal information and corresponding control measures are stored in an antigen knowledge database. With the accumulation of data in the antigen knowledge database, the decision-making level of the immune system is continually enhanced. Sitting at the end of the multi-level immune monitoring system, the actuator cells are embodied in the form of relevant maintenance plans, methods, tools, or personnel, which are utilized to improve the health status of the scraper conveyor mechanical system. Situated at the final stage of the multilevel immune monitoring system, the actuator cells are manifested through targeted maintenance protocols, strategies, instruments, or staff dedicated to improving the scrap conveyor's mechanical system's health state.

### 3.3. Calculate the Health Value

Following the membership calculation method in the fuzzy statistics approach, the status detection information corresponding to each indicator of the component can be obtained. When $e_j = \lambda_j^{(4)}$ or $e_j = \lambda_j^{(5)}$, an abnormal status for the said indicator is present, thus outputting status information $K_j$ as 1. On the other hand, when $e_j = \lambda_j^{(1)}$, $e_j = \lambda_j^{(2)}$ or $e_j = \lambda_j^{(3)}$, the indicator is identified as being in a normal state, which in turn outputs the status information $K_j$ as 0. The output vector for the component's status sequence is identified as $\boldsymbol{K}_i = [K_1, K_2, \ldots, K_n]$.

The impact factor of the indicator layer on the component layer is:

$$\gamma_{\mathrm{Ei}} = \boldsymbol{K}_i \cdot \boldsymbol{W}_i^T \tag{15}$$

The impact factor of the component layer on the system layer is:

$$\gamma_U = \boldsymbol{\gamma}_E \cdot \boldsymbol{W}^T \tag{16}$$

Formula: $\boldsymbol{\gamma}_{\mathrm{Ei}} = [\gamma_{\mathrm{E1}}, \gamma_{\mathrm{E2}}, \gamma_{\mathrm{E3}}, \gamma_{\mathrm{E4}}]$, W is the weight vector of the mechanical system of the scraper conveyor.

The health values of each component and conveyor mechanical system are:

$$H_{\mathrm{Ei}} = 1 - \gamma_{\mathrm{Ei}} \tag{17}$$

$$H_U = 1 - \gamma_U \tag{18}$$

H is positively correlated with the health status of the component, and H $\in$ [0, 1]. By computing the health value, a quantitative evaluation of the health statuses of both individual components and the entire mechanical system of the scraper conveyor is conducted. Table 2 delineates the correspondence between the health values and the respective health conditions.

**Table 2.** Relationship between health values and health status

| Health values | 1–0.9600 | 0.9599–0.9 | 0.8999–0.8 | 0.7999–06 | 0.5999–0 |
|---|---|---|---|---|---|
| Health status | Health | Sub health | Mild pathological state | Moderate pathological state | Severe pathological state |

## 4. Case Analysis

**Table 3.** Index detection data of the mechanical system of the scraper conveyor

| Numble | Indicator | Data1/mm | Data2/mm |
|---|---|---|---|
| Line pan | Thickness of deck plate / $A_{11}$ | 41 | 43 |
| | Width of top deck inner groove / $A_{12}$ | 735 | 738 |
| | Width of top deck inner opening / $A_{13}$ | 546 | 544 |
| | Thickness of upper edge / $A_{14}$ | 22 | 21 |
| | Height of upper edge / $A_{15}$ | 142 | 140 |
| Rack bar | Thickness of rack bar / $A_{21}$ | 178 | 180 |
| | Height of front side panel / $A_{22}$ | 97 | 105 |
| | Thickness of front side panel / $A_{23}$ | 39 | 44 |
| | Thickness of meshing point / $A_{24}$ | 57.5 | 59.5 |
| Flight bar | Length of flight bar / $A_{31}$ | 638 | 645 |
| | Thickness of flight bar / $A_{32}$ | 113 | 112 |
| | Width of flight bar / $A_{33}$ | 120 | 121 |
| Sprocket | Width of tooth / $A_{41}$ | 119 | 120 |
| | Height of chain nest / $A_{42}$ | 54 | 53 |
| | Thickness of the chain nest / $A_{43}$ | 45 | 42 |
| | Width of chain nest / $A_{44}$ | 118 | 115 |
| | Width of middle tooth / $A_{45}$ | 105 | 110 |

A case study of a scraper conveyor at a certain mine working face was conducted and subsequently analyzed. This conveyor has been in operation for eleven months at the underground 1101 working face, and, as mining activities at this face have concluded, there are plans to relocate the equipment to a new working face. Before transferring the equipment, it is essential to assess the health status of the mechanical system of the scraper conveyor to determine the necessity of carrying out maintenance work. The wear conditions of the mechanical system of the scraper conveyor have been empirically measured, and a selection of the data is presented as follows.

### 4.1. AHP for Calculating Weights

Taking the line pan as an instance, the indicator weights of the line pan are computed using the AHP. Initially, indicators within set {$A_{11}$, $A_{12}$, $A_{13}$, $A_{14}$, $A_{15}$} are compared pairwise, leading to the construction of matrix $A_1$:

$$\boldsymbol{A}_1 = \begin{bmatrix} 1 & 3 & 2 & 4 & 6 \\ 0.33 & 1 & 0.8 & 1.5 & 2 \\ 0.5 & 1.25 & 1 & 1.7 & 3 \\ 0.25 & 0.67 & 0.59 & 1 & 2 \\ 0.17 & 0.5 & 0.33 & 0.5 & 1 \end{bmatrix}$$

The maximum eigenvalue of paired comparison matrix $A_1$ is $\lambda_{max} = 5.0398$. The conformance index of $A_1$ is $CI = (5.0398 - 5)/(5 - 1) = 0.0099$. The random consistency ratio of $A_1$ is $CR = 0.0099/1.12 = 0.0089$. Because $0 < CR < 0.10$, the matrix $A_1$ meets the consistency requirement. The eigenvector corresponding to $\lambda_{max}$ is calculated and normalized to attain the weight vector $\boldsymbol{W_1}^{(1)} = [0.4423, 0.1676, 0.2066, 0.1134, 0.0701]$ based on the AHP.

Employing this method enables the calculation of the weight vectors for other components at the component level based on the AHP. Specifically, the weight vectors for the rack bar, flight bar, and sprocket are represented as $\boldsymbol{W_2}^{(1)} = [0.086, 0.2415, 0.1544, 0.5181]$, $\boldsymbol{W_3}^{(1)} = [0.6814, 0.216, 0.1026]$, and $\boldsymbol{W_4}^{(1)} = [0.0663, 0.1284, 0.4739, 0.2822, 0.0492]$, respectively. The weight vectors for the scraper conveyor's mechanical system based on the AHP is $\boldsymbol{W} = [0.2718, 0.0883, 0.1575, 0.4824]$.

### 4.2. Fuzzy Statistical Method for Calculating Weights

Taking the line pan as an instance, the indicator weights of the line pan are computed using the fuzzy statistical method. Combining the physical significance of the five indicators associated with the line pan, these indicators are classified into categories according to their fuzzy distribution forms, as shown in Table 4.

**Table 4.** Index parameters of the line pan

| Testing index | Thickness of deck plate /$A_{11}$ | Width of top deck inner groove /$A_{12}$ | Width of top deck inner opening /$A_{13}$ | Thickness of upper edge /$A_{14}$ | Height of upper edge /$A_{15}$ |
|---|---|---|---|---|---|
| Critical value / mm | $20 \le A_{11} \le 50$ | $722 \le A_{12} \le 762$ | $532 \le A_{13} \le 552$ | $10 \le A_{14} \le 30$ | $132 \le A_{15} \le 162$ |
| Distribution form | Benefit type | Cost type | Cost type | Benefit type | Cost type |

The critical values are determined based on a comprehensive consideration of factory specifications of the equipment, historical operational records, and maintenance logs. Indicators $A_{12}$, $A_{13}$, and $A_{15}$ are categorized as cost-type, while $A_{11}$ and $A_{14}$ are classified as benefit-type. The membership degrees for each of the five health levels are calculated, and an indicator evaluation matrix is constructed. Following Equations (1)-(7), the weight vector for the line pan based on the fuzzy statistical method is $\boldsymbol{W_1}^{(2)} = [0.4113, 0.1781, 0.1921, 0.1407, 0.0778]$.

Employing this method enables the calculation of the weight vectors for other components at the component level based on the fuzzy statistical method. Specifically, the weight vectors for the rack bar, flight bar, and sprocket are represented as $\boldsymbol{W_2}^{(2)} = [0.057, 0.2491, 0.1593, 0.5345]$, $\boldsymbol{W_3}^{(2)} = [0.6231, 0.2141, 0.1628]$, and $\boldsymbol{W_4}^{(2)} = [0.0977, 0.162, 0.4187, 0.2493, 0.0724]$, respectively.

### 4.3. Entropy Weight Method for Calculating Weights

Taking the line pan as an instance, the indicator weights of the line pan are computed using the entropy weight method. Initially, formula (8) is employed to normalize the original matrix. Subsequently, we utilize formula (9) to ascertain the information entropy of the indices, denoted as $E_j = [E_1, E_2, E_3, E_4, E_5] = [0.9887, 0.9923, 0.9957, 0.9975, 0.9911]$. Lastly, in accordance with formula (10), the weight vector based on the entropy weight method is $\boldsymbol{W_1}^{(3)} = [0.3254, 0.2227, 0.123, 0.0719, 0.257]$.

Employing this method enables the calculation of the weight vectors for other components at the component level based on the entropy weight method. Specifically, the weight vectors for the rack bar, flight bar, and sprocket are represented as: $\boldsymbol{W_2}^{(3)} = [0.0252, 0.2515, 0.4018, 0.3216]$, $\boldsymbol{W_3}^{(3)} = [0.4651, 0.4651, 0.0699]$ and $\boldsymbol{W_4}^{(3)} = [0.2146, 0.0272, 0.2864, 0.1668, 0.305]$, respectively.

### 4.4. Cooperative Game Method for Calculating Weights

Taking the line pan as an instance, the indicator weights of the line pan are computed using the cooperative game method. Initially, the consistency parameters for each weight vector are ascertained based on formula (11). Thereafter, by employing formulas (12)-(14), the index weights utilizing the cooperative game theory approach are calculated to be $\boldsymbol{W_1} = [0.4035, 0.1843, 0.1818, 0.1144, 0.116]$.

Employing this method enables the calculation of the weight vectors for other components at the component level based on the cooperative game method. Specifically, the weight vectors for the rack bar, flight bar, and sprocket are represented as: $\boldsymbol{W_2} = [0.0565, 0.2474, 0.233, 0.4631]$, $\boldsymbol{W_3} = [0.5998, 0.2852, 0.115]$ and $\boldsymbol{W_4} = [0.0943, 0.1344, 0.4314, 0.2565, 0.0834]$, respectively.

The weight values of the indicator parameters for each component of the scraper conveyor's mechanical system are summarized and compared, as illustrated in Figure 5. It is observed that the index weight values computed using the cooperative game theory method lie between those derived separately by the AHP, the fuzzy statistical method, and the entropy weight method. When considering the integration of these three methods, the calculation results stemming from the cooperative game method approach are discerned to be more accurate.

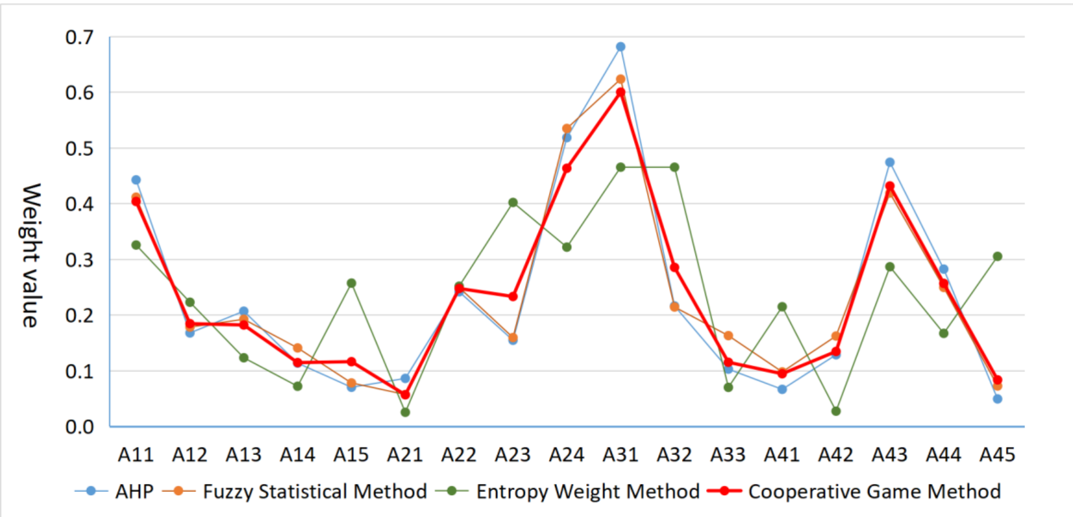



**Figure 5.** Weight values of various indicators in the mechanical system of the scraper conveyor

### 4.5. Calculate Health Values

According to the membership function, the membership values of each component indicator are calculated to determine the status information of each component. The state sequence vectors of the line pan, rack bar, flight bar, and sprocket are output as follows: $\boldsymbol{K}_1 = (0, 0, 1, 0, 0)$, $\boldsymbol{K}_2 = (0, 1, 0, 0)$, $\boldsymbol{K}_3 = (0, 0, 1)$, $\boldsymbol{K}_4 = (0, 0, 0, 0, 1)$. Utilizing formula (15), the impact factors of each indicator on the line pan, rack bar, flight bar, and sprocket are calculated and denoted as $\gamma_{\mathrm{E1}} = 0.1818$, $\gamma_{\mathrm{E2}} = 0.2474$, $\gamma_{\mathrm{E3}} = 0.115$, $\gamma_{\mathrm{E4}} = 0.0834$, respectively. Using formula (16), the impact factor of each component on the mechanical system of the scraper conveyor is calculated as $\gamma_U = 0.1296$. Using formulas (17) and (18), the health values of the line pan, rack bar, flight bar, sprocket, and scraper conveyor mechanical system are obtained as follows: $H_{\mathrm{E1}} = 0.8182$, $H_{\mathrm{E2}} = 0.7625$, $H_{\mathrm{E3}} = 0.885$, $H_{\mathrm{E4}} = 0.9166$, $H_U = 0.8704$.

## 5. Discussion

Upon consultation with Table 3, it is determined that the line pan is in a mild pathological state, the rack bar is in a moderate pathological state, the flight bar is in a mild pathological state, the sprocket is in a sub-healthy state, and the scraper conveyor mechanical system is in a mild pathological state.

Examination of the on-site photographs illustrated in Figure 6 indicates substantial wear on the upper edge of the line pan and the terminal section of the flight bar. Post-repair, these components are anticipated to be operational for subsequent use at a new working face. The tooth column of the rack bar is extensively worn, exhibiting noticeable gnawing phenomena, thus warranting a replacement of the rack bar. In contrast, the sprocket displays minor wear, which does not necessitate repair. Case analysis has verified that the analysis results, obtained via the method delineated in this article, are congruent with the actual operational condition of the scraper conveyor's mechanical system.


(a) (b) (c)

**Figure 6.** Operation status of (a) line pan and flight bar, (b) rack bar, and (c) sprocket.

## 6. Conclusions

This paper utilizes key indicators of the scraper conveyor mechanical system's crucial components-line pan, flight bar, rack bar, and sprocket-as initial assessment data, ensuring that the evaluation results of the scraper conveyor mechanical system's health status are rational and effective.

The cooperative game method approach employed amalgamates the AHP, fuzzy statistical method, and entropy weight method into a comprehensive weight evaluation method that embodies both subjective and objective significance. This overcomes the shortcomings inherent in determining weights through each of these methods individually, resulting in a more accurate integrated system weight.

Taking the operational data of a scraper conveyor in a particular mine as an example, a comparison between the evaluation results and actual conditions indicates that the application of immune principles and cooperative game method to the health status assessment of the scraper conveyor mechanical system yields accurate evaluation outcomes.

## Acknowledgments

This work was financially supported by the Ningxia Autonomous Region Key R&D Project "Research and application of key technologies for reverse bottom chain transportation screening and crushing system which is used in gateroad" (project number: 2023BDE92012).

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