Wagon PHM State Model Based on AHP and Gray Clustering Model

Xiuru Li
School of Computer and Information Technology Beijing Jiaotong University
China Engineering Research Center of Network Management Technology for High Speed Railway of MOE
Beijing, China
17120462@bjtu.edu.cn

Honghui Li
School of Computer and Information Technology Beijing Jiaotong University
China Engineering Research Center of Network Management Technology for High Speed Railway of MOE
Beijing, China
hhli@bjtu.edu.cn

Yanhui Bai
School of Computer and Information Technology Beijing Jiaotong University
China Engineering Research Center of Network Management Technology for High Speed Railway of MOE
Beijing, China
baiyh@bjtu.edu.cn

Yuhang Duan
School of Computer and Information Technology Beijing Jiaotong University
China Engineering Research Center of Network Management Technology for High Speed Railway of MOE
Beijing, China
18120463@bjtu.edu.cn

***Abstract*—In order to extend the service life of the wagon and improve the efficiency, this paper presents the index system of the PHM system of the wagon and builds a state model to analysis the wagon status based on AHP and the gray clustering.**

Keywords- Prognostics and systems health management; Grey Theory; cluster analysis; analytic hierarchy process; railway wagon

I. INTRODUCTION

In the process of using heavy locomotives, wear and damage of the freight car is unavoidable. Excessive maintenance frequency can increase costs significantly, but low maintenance frequency may lead to accidents. How to find the right time for vehicle repair has become a major problem in rail freight [1].

Prognostics and systems health management (PHM) is an enabling discipline of technologies and methods with the potential of solving reliability problems that have been manifested due to complexities in design, manufacturing, environmental and operational use conditions, and maintenance. PHM has been successfully applied in aerospace, power, machinery manufacturing, engineering structural safety and other fields, with direct economic and beneficial value in these fields [2-8].

The application research of PHM technology in the operation of railway wagons has just started. It is urgent to establish a scientific and reasonable PHM state model of railway wagon, which provides reference for the design and development of railway PHM system, and lays a foundation for the maintenance of railway wagons. The wagons state model is a model that quantitatively analyzes the state of the wagons and obtains the state classification according to the wagons state parameters, and is the core model of the PHM system. Combined with the structural composition and design and use characteristics of the railway wagon, the PHM detection index of the wagon is selected. The research on the state model based on the indicator system will help the establishment and improvement of the data-driven wagon PHM system, which will improve the repairs level of railway wagons.

The analytic hierarchy process (AHP) is a structured technique for organizing and analyzing complex decisions, based on mathematics and psychology [9, 10].

Clustering is a technique that tries to discover underlying substructures in a set of unlabeled objects. The aim of clustering analysis is to partition a given dataset into clusters so that the points within a cluster are relatively close with respect to some measure. Clustering analysis has been widely used for data analysis as an active subject in several research fields such as statistics, pattern recognition and machine learning [11, 12].

Professor Deng Julong proposed the grey variable weight clustering model (Deng, 1986), and Professor Liu Sifeng

978-1-7281-0860-5/19/$31.00 ©2019 IEEE

proposed the grey fixed weight clustering evaluation model (Liu, 1993), the grey cluster evaluation models using end-point triangular whitenization weight functions (Sifeng and Yongda, 1993; Liu Sifeng, 1991; Sifeng, 2006), and the grey cluster evaluation models using centre-point triangular whitenization weight functions (Sifeng and Naiming, 2011; Sifeng Liu, 2011; Sifeng Liu and Forrest, 2012), etc. These models are all used widely. The grey clustering takes the uncertainty system as the main research object, and extracts valuable information from the generation and development of some known information, to realize the correct description and effective control of the system [13-16].

II. COMPOSITION OF WAGON PHM SYSTEM

As shown in Figure 1, PHM system consists of three parts: information collection system, communication system, and information processing system. Firstly, the raw data is collected by the sensors by the information collection system. Then it transmitted to the information processing system through the communication system, stored in the data warehouse. And then it is processed by the data processing program to generate the maintenance plan and shows on WEB pages.

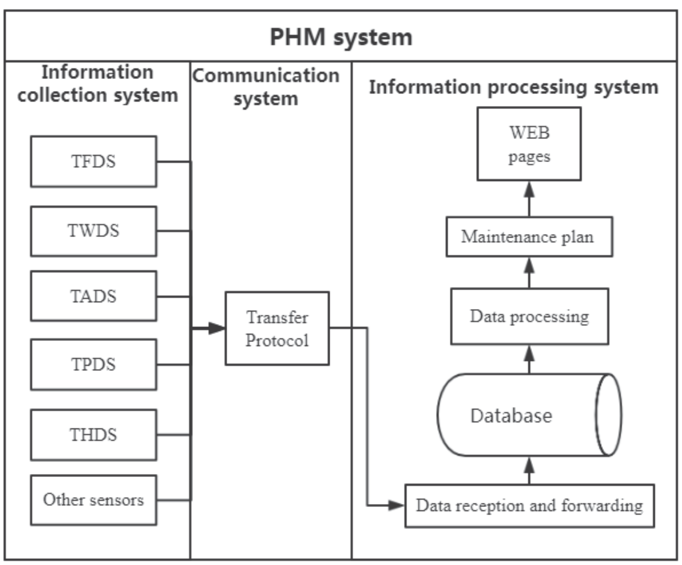

Figure 1. Wagon PHM system architecture

III. RULE TO SELECT INDICATORS

A. Monitoring object

The monitoring object is the carrier for monitoring the implementation of indicators, such as bearings, wheel sets, brake shoes and so on. The analysis of the monitored objects in terms of function and performance helps to monitor the analysis, selection and determination of indicators.

Traditional wagon repairs divide the components into two categories: monitoring equipment and non-monitoring equipment [17], as shown in Figure 2. So there are two corresponding maintenance strategies: pre-repair and regular maintenance.

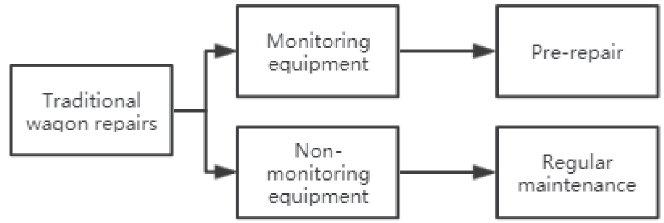

Figure 2. Traditional wagon repairs

In the PHM system, it is impossible and unnecessary to monitor all the equipment. It is only necessary to select the key components that have a great influence on the function, safety and reliability of the wagon with data processing and analysis. The choice of monitoring objects mainly considers the importance of the object, the failure rate of the object and the evolution of the state. The monitoring objects can be divided into five types, and the selection principle is shown in Figure 3.

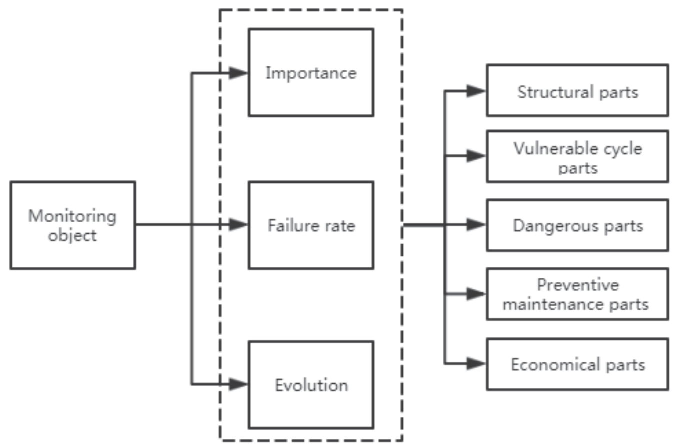

Figure 3. Wagon PHM system monitoring object

- Structural parts. Structural parts are the supporting structure of the wagon. Those parts mainly struts the transmission of loads and movements and are the basics of loading and transporting goods, such as the wagon steel structure.
- Vulnerable cycle parts. Vulnerable cycle parts are subject to periodic motion functions and are consumable parts. They are indispensable parts and need to be kept in a healthy state, such as brake shoes.
- Dangerous parts. It can cause serious damage to wagon when Dangerous parts failure happened. It is necessary to determine the working condition in time and reduce the risk of those parts, such as hooking devices.
- Preventive maintenance parts. Preventive maintenance parts require preventive maintenance, including replacement and repairs timely, such as the axle.
- Economical parts. The repair cost of Economical parts is high. PHM system would reduce the cost.

Compared with the traditional wagon repairs, the complexity of the object classification of the PHM system is higher than that of the traditional wagon repairs as well as the repairs accuracy. The repair cost is reduced as the indemnification of safety, and it is more scientific and reliable.

B. Principle to select monitoring indicators

At present, there is no unified and effective monitoring index system in railway wagon to support PHM technology, and a single indicator can't assist the application of PHM technology. The selection of maintenance indicators is not as good as possible. If there are too many indicators, monitoring data will be redundant, and data processing is difficult. If the indicators are too small, the monitoring data may be incomplete and the truck status cannot be accurately determined. Therefore, on the basis of the selection of monitoring objects, a scientific and complete monitoring index system is established to comprehensively and objectively evaluate the state of the wagon, which is the basis of PHM system [18].

The selection of wagon monitoring indicators should follow the following principles:

- Scientific. The physical meaning of the evaluation indicators is clear, the monitoring and statistical methods are standardized, and the indicators should reflect the state characteristics of the wagon and its development rules. At the same time, the objectivity of the indicators should be increased as much as possible to reduce the subjectivity.
- Completeness. From the perspective of overall and comprehensive, the indicator system should comprehensively consider various factors affecting the running status of the wagon. The evaluation index and the evaluation target can be organically linked to form a well-defined whole. It is necessary to avoid the indicator system being too simple or too complicated.
- Accessibility. The indicator system has a clear hierarchy. It also takes into account the relationship between qualitative and quantitative, local and overall, current and long-term. The index data is easily obtained through real-time monitoring, testing or statistical analysis. The data acquisition cost is low and the data quality is reliable.
- Independence. Indicators must be independent, and the indicators at the same level do not contain and overlap each other. The indicator system is simple and clear, and is easy to apply.

IV. CONSTRUCTION OF STATE MODEL CONSTRUCTION

A. Selection of detailed indicators

The composition and complexity of different wagon types are different, resulting in differences in detailed indicators. Therefore, detailed indicators need to be analyzed and selected according to the actual system. However, different wagon types also have many in common. Some detailed indicators can be used as general indicators. Under the premise that the indicators meet the principle to select monitoring indicators, these general-purpose detailed indicators can be divided into white indicators and gray indicators. When the indicator can monitor the perception, the obtained indicator data is determined, and we refer to such an indicator as a white indicator. When the indicator cannot determine the acquisition, such as only through the maintenance personnel's maintenance log to determine the approximate range, this indicator is called the gray indicator, as shown in Table I.

TABLE I. DETAILED INDICATORS

Type	White indicator	Gray indicator
Structural parts	Use mileage of structural parts	Integrity Rungs
Vulnerable cycle parts	Bearing temperature, Wheel diameter, Brake abrasion	Bearing stability
Dangerous parts	Dangerous parts use mileage	Hook device crack
Preventive maintenance parts	Spring inner diameter wear, Bogie use mileage	Spring fatigue
Economical parts	Air brakes use mileage	Brake pipe leakage

B. Calculation of indicator weight

The wagon system is a complex system and different components may need to monitor the same type of indicator. This may result in detailed indicators being attributed to different overall indicators at the same time, resulting in cross-over phenomenon, which leads to confusion in monitoring and data processing. An effective approach is analytic hierarchy process, which obtains the objective weight of each indicator. The set vector of this weight is the AHP weight vector:

$$A=[a_{\alpha},a_2,a_3,\dots a_n] \tag{1.1}$$

When the system has 5 indicators and 3 results, the AHP model is shown in Figure 4.

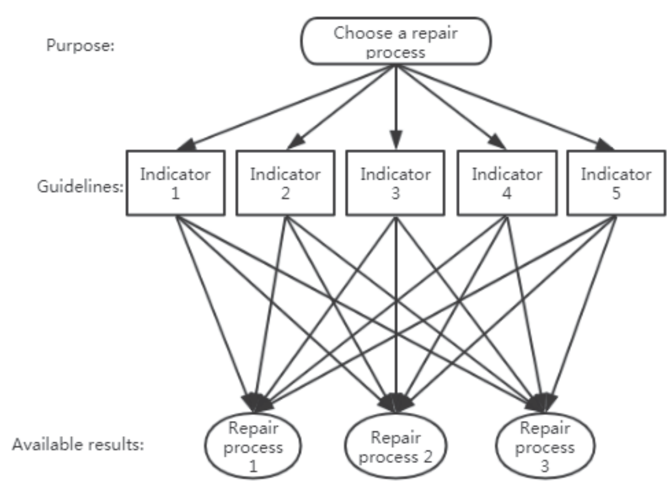

Figure 4. AHP model

Then compare each indicator, analyze the relative importance between the five indicators, and after the consistency analysis, get a 5X5 importance comparison matrix:

$$A[5,5]=\begin{bmatrix} a_{1,1} & a_{1,2} & a_{1,3} & a_{1,4} & a_{1,5} \\ a_{2,1} & a_{2,2} & a_{2,3} & a_{2,4} & a_{2,5} \\ a_{3,1} & a_{3,2} & a_{3,3} & a_{3,4} & a_{3,5} \\ a_{4,1} & a_{4,2} & a_{4,3} & a_{4,4} & a_{4,5} \\ a_{5,1} & a_{5,2} & a_{5,3} & a_{5,4} & a_{5,5} \end{bmatrix} \quad (1.2)$$

Where $a_{i,j}$ represents the importance ratio between the i-th indicator and the j-th indicator. This matrix reflects the relative importance of each indicator.

Then normalize the matrix by row:

$$b_{i,j}=\frac{a_{i,j}}{\sum_{j=1}^{5} a_{i,j}} \quad (1.3)$$

And then sum each column, which is the weight of the indicator:

$$c_j=\sum_{i=1}^{5} b_{i,j} \quad (1.4)$$

The result of AHP is the set of indicator weights for each indicator:

$$[c_1, c_2, c_3, c_4, c_5] \quad (1.5)$$

C. State model establishment

Based on the detailed indicators and indicators weights, a gray cluster model is constructed to obtain an accurate state assessment. The model building process is as follows:

- Calculate the whitening function of the gray indicator;
- Find the product of all indicators data and the indicators weight as hierarchical points;
- Select m hierarchical points as the cluster point and calculate the distance of the m points; (m is the length of result set)
- Using a cluster algorithm, constantly calculating a better solution makes the cluster point more representative of the data set.
- Multiple operations to get the final cluster point, which is the cluster model;
- Substituting multiple sets of data into the model. The recommended repair process corresponding to the data of the group is obtained, and compared with the manual evaluation result. If the result does not match, the next gray cluster will be performed until the results match.

V. CONCLUSION

PHM system is a hotspot of the combination of industrial field and academic theory. Applying PHM system to the field of railway wagon will greatly improve the efficiency, reduce the cost, and reduce the accident rate of wagons troubleshooting, which would make great economic efficiency and social benefits. The establishment of the state model is the focus of research on the PHM system of wagon. Based on the construction process experience of PHM system in military, electromechanical and aviation, the wagon state model and a detailed index system suitable for the model is established. And the indicators weight is calculated with AHP objectively. On this basis, the grey cluster model is applied to a large amount of data, which provides technical support for the application of wagon PHM.

ACKNOWLEDGMENT

This research was supported by Technology Innovation Project of Shenhua Group (Grant No. SHGF-17-56).

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