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Application of Reliability-Centered Maintenance in Metro Door System

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ABSTRACT Metro door system (MDS) is one of the most important and fault-prone parts of metro train. Reliability-centered maintenance (RCM) is a systematic engineering process for determining the preventive maintenance requirements of equipment and optimizing the maintenance system. This paper is motivated to apply RCM to the maintenance of metro door system. Firstly, the subsystems and components of MDS are introduced. Then a fuzzy FMECA method is proposed to define the hazard degree of 10 failure modes from 5 components with high failure rate to conduct reliability analysis. Finally, reliability-centered maintenance strategy is made after maintenance mode decision and calculation of maintenance interval cycle, which provides theoretical basis to the maintenance of the metro train.

INDEX TERMS Metro door system, fuzzy FMECA, reliability-centered maintenance, maintenance strategy.

I. INTRODUCTION

Metro transportation has the advantages of large transportation capacity, fast running speed, good timeliness, high safety, space saving, energy saving and air pollution reduction [1]. It has become one of the main means of transportation for large and medium-sized cities, and is playing an important role in alleviating urban traffic congestion [2]. Since the door is the channel for passengers to enter and go out of the train, it should be reliable [3]. But due to the dense flow and the severe overload during peak hours, which cause the door to squeeze and vibrate, making the Metro Door Systems (MDS) become one of the most fault-prone parts in the entire vehicle [4]. Therefore, the development of proper maintenance strategies for metro door systems is of great significance for the smooth operation of trains.

RCM is a systematic engineering process for determining the preventive maintenance requirements of equipment and optimizing the maintenance system [5]. The RCM methodology provides a practical and structured approach for arriving at a satisfactory maintenance strategy for each component of a given system. In choosing a strategy, the methodology takes into account safety requirements, maintenance costs, and costs of lost production [6]. Its basic processes include: identifying the causes, modes and effects of the system possible failures; determining the optimal maintenance mode of the equipment by using standardized logical decision-making and calculating the maintenance interval cycle by mathematical model, and finally optimizing the maintenance strategy of the system with the goal of lowest maintenance cost on the basis of the reliability of the equipment [7]. The RCM analysis includes the following steps, as shown in Figure 1:

This paper aims to apply the RCM method to the MDS to develop a maintenance strategy, making it scientific and reliable.

II. METRO DOOR SYSTEM

A. COMPOSITION OF MDS

A technical system generally comprises several subsystems and components that are interconnected in such a way that the system can perform a set of required functions [8]. The composition of MDS is as shown in Table 1 [9].

B. WORKING PRINCIPLE OF MDS

On the basis of the structural characteristics and movement track of the metro door, it can be divided into four types:

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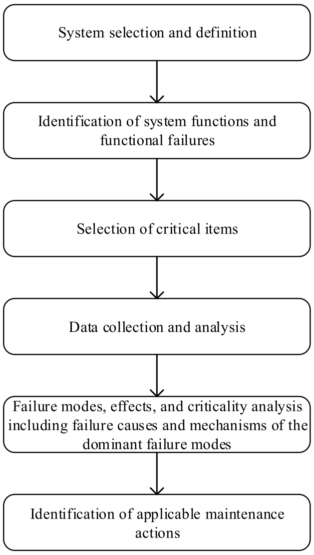

FIGURE 1. The RCM analysis process.

TABLE 1. The basic subsystems and components.

System	Subsystems	Components
Metro door system	Electrical control unit	Electronic door control unit (EDCU), Lock-in switch (S1), Off position switch (S4), Emergency unlock switch (S3), Isolation switch (S2), Close bottom
	Drive unit	Driving motor, Screw, Nut assembly
	Support device	Long guide column, Short guide column, Linear bearing
	Carrying gantry device	Tank chain, Rubber buffer head, Eccentric wheel 1&2
	Guiding device	Upper slide, Upper slide roller, Lower slide, Lower swing arm assembly
	Closing stabilizer	Balance roller, Lower stop pin, Threshold block
	Door leaf	Glass door, Sealant strip
	Emergency unlocking device	Emergency exit device, Emergency access device, End unlock assembly
	Isolation lock device	Disconnector assembly

external swinging door, external sliding door, internal sliding door, and sliding plug door, and this article is mainly for the analysis of a certain sliding plug door [10]. The movement of door system is controlled by an EDCU and driven by a motor [11]. The door page starts to move from the fully closed state. The motor drives the screw nut pair, causing the action of the carrying gantry, long guide column, pylon, lower roller, and finally making the door leaf swing out under the guidance of the guiding system. After reaching the full swing state, the guiding system controls the straight translation of the door leaf, so that the door page moves parallelly to the side of the vehicle. Then during the translation process, the carrying gantry allows the door leaf to slide freely along the long guide column until the door page is fully open. In this way, the movement of the door in the direction of X and Y is realized, and the action of the plug is completed [12].

III. FUZZY FMECA FOR MDS

A. FMECA METHOD

FMECA is a way to evaluate potential failure modes and their effects as well as causes in a systematic and structured mode [13]. It is a procedure for analysis of potential failure modes within a system using the classification by severity or evaluation of the failure's effect upon the system. It also includes a Criticality Analysis (CA) which is used to chart the probability of failure modes against the severity of their consequences [14]. Therefore, through FMECA, it is possible to timely find weaknesses of the system security and further takes effective improved measures in order to increase the security grade of the system [15]. Before FMECA, FMEA is usually performed as a part of it.

Based on the fault data, in this part, EDCU, switch, isolation lock device, driving motor and screw nut are selected for analysis, as shown in Table 2.

The traditional FMECA method uses Risk Priority Number (RPN) analysis to evaluate the risk associated with each failure mode, but it suffers from some problems [16]. The fuzzy FMECA method uses fuzzy theory to process uncertain information, and quantifies the analysis results of FMECA, so that the risk of failure can be clearly presented [17]–[19]. The process of fuzzy FMECA method is as follow:

1) ESTABLISH THE FACTOR SET

Usually U is used to indicate the factor set, and the factor set of the failure mode k is:

$$U^k = \left\{u_1^k, u_2^k, \cdots, u_n^k\right\} \tag{1}$$

where u_i^k is the i-th factor, i = 1, 2, ..., n.

2) ESTABLISH THE EVALUATION SET

The evaluation set is a collection of elements that the evaluator may make as a result of the evaluation of the evaluation object, usually expressed by V:

$$V^k = \left\{v_1^k, v_2^k, \cdots, v_n^k\right\} \tag{2}$$

where v_j^k is the j-th grade of the evaluation set.

3) ESTABLISH EVALUATION MATRICES FOR EACH FAILURE MODE

In this step, an expert group is established by many experts. every member needs to give an evaluation rating for each influencing factor. the evaluation set of u_i^k can be obtained

TABLE 2. The FMEA for MDS.

Number	Components	Function	Failure Mode	Failure Cause	Fault level	Compensation Measures
1	EDCU	Signal reception, motor drive, state detection, alarm	Functional failure	Damaged components	II	Maintain, replace if necessary
2			Plug loosening	Poor wiring process	III	Tighten the plug
3	Switch (S1-S4)	Opening and closing, unlocking, isolation	Abnormal wiring and fastening	Untimely adjustment	III	Adjust the switch position
4			Functional failure	Quality defect	II	Fasten, adjust the installation
5			Insufficient allowance	Vibration and shock	III	Adjust or replace
6	Isolation lock device	Faulty door isolation	Functional failure	Vibration	III	Adjust, replace parts
7	Driving motor	drive	Functional failure	Internal structure damage	III	Replace
8			Abnormal noise	Insufficient lubrication	IV	Strengthen lubrication
9	Screw nut	lock	breakage	Fracture or loss of parts	III	Refill or replace
10			Loose	Abnormal position of the guide post	IV	Adjust the guide post

as follow:

$$\begin{cases} R_i^k = \left\{ \dfrac{S_{i1}^k}{S}, \dfrac{S_{i2}^k}{S}, \cdots, \dfrac{S_{im}^k}{S} \right\} = \left\{ r_{i1}^k, r_{i2}^k, \cdots, r_{im}^k \right\} \\ \sum_{j=1}^{m} r_{ij} = 1 \end{cases} \tag{3}$$

where S is the quantity of experts, r_{im}^k is the membership degree of the i-th factor u_i^k at factor level v_j^k.

Then fuzzy level evaluation matrix of failure mode k can be obtained as follow:

$$R_k = \left[R_1^k, R_2^k, \cdots, R_n^k \right]^T = \begin{bmatrix} r_{11}^k & r_{12}^k & \cdots & r_{1m}^k \\ r_{21}^k & r_{22}^k & \cdots & r_{2m}^k \\ \vdots & \vdots & \ddots & \vdots \\ r_{n1}^k & r_{n2}^k & \cdots & r_{nm}^k \end{bmatrix} \tag{4}$$

4) DETERMINE THE WEIGHT OF EACH FACTOR

The appropriateness of weight determination plays an important role in comprehensive evaluation result. it is common to use analytic hierarchy process (ahp) method to get weight sets W:

$$\begin{cases} W = (\omega_1, \omega_2, \cdots, \omega_i), \quad 0 < \omega_i < 1, \ i \in [1, n] \\ \sum_{i=1}^{m} \omega_i = 1 \end{cases} \tag{5}$$

where ω_i is the weight of i-th factor.

TABLE 3. Relative importance of factors.

a_{ij}	Meaning
1	a_i is as important as a_j
3	a_i is slightly more important than a_j
5	a_i is obviously more important than a_j
7	a_i is more important than a_j
9	a_i is definitely more important than a_j
2,4,6,8	a_i is more important than a_j between levels

In the AHP method, judgment matrix A is established with reference to Table 3.

$$A = \begin{bmatrix} a_{11} & a_{12} & \cdots & a_{1n} \\ a_{21} & a_{22} & \cdots & a_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ a_{n1} & a_{n2} & \cdots & a_{nn} \end{bmatrix} \tag{6}$$

where a_{ij} is the relative importance of u_i and u_j.

Maximum eigenvalue and its corresponding eigenvector $\xi = (x_1, x_2, \cdots, x_n)$ can be calculated according to judgment matrix A. W can be used as a weight set for each factor after the normalization of ξ.

Before normalization, a consistency check must be performed on the judgment matrix A to determine whether the weight distribution is reasonable. The test formula is:

$$R_c = I_C / I_R \tag{7}$$

TABLE 4. Level of factor sets.

Influence factor	1	2	3	4
Occurrence	Rarely happen	Occasionally happen	Sometimes happen	Frequently happen
Severity	Mild	Moderate	Severe	Catastrophic
Detection	Accurate to detect	Uneasy to detect	Difficult to detect	Unable to detect
Maintainability	Debug	Re-install	Replace	Unable to repair

where R_C is judgment matrix random consistency ratio; I_C is judgment matrix general consistency index, $I_C = \frac{\lambda_{\max}-n}{n-1}$ is the average random consistency index of the judgment matrix.

When $R_C < 0.1$, it is considered that the consistency of the judgment matrix A is within a reasonable range. Otherwise, the judgment matrix should be appropriately modified so that the consistency value is within a reasonable range.

5) FUZZY COMPREHENSIVE EVALUATION

The factor weight set of failure mode k should be rewritten as vector mode:

$$B^k = W^k R^k = \left[\omega_1^k, \omega_2^k, \cdots, \omega_1^k\right] \begin{bmatrix} r_{11}^k & r_{12}^k & \cdots & r_{1m}^k \\ r_{21}^k & r_{22}^k & \cdots & r_{2m}^k \\ \vdots & \vdots & \ddots & \vdots \\ r_{n1}^k & r_{n2}^k & \cdots & r_{nm}^k \end{bmatrix} = \left(b_1^k, b_2^k, \ldots, b_n^k\right) \quad (8)$$

where B^k is the fuzzy comprehensive vector in failure mode k; b_n^k is the fuzzy evaluation of factor weight in failure mode k.

6) DETERMINE THE COMPREHENSIVE HAZARD LEVEL

For a more intuitive result, B^k is treated by weighted average method, so that a simple value C^k is obtained to indicate the comprehensive hazard level of the failure mode k to the system:

$$C^k = B^k V^T \quad (9)$$

B. FMECA FOR MDS

1) ESTABLISH THE FACTOR SET

The factor set is as follows: {Occurrence, Severity, Detection, Maintainability}.

2) DETERMINE THE EVALUATION SET

The factor sets are divided into 4 parts: V={1, 2, 3, 4}. The criteria for the classification of different influencing factors is shown in Table 4.

3) ESTABLISH FUZZY EVALUATION MATRIX OF FAILURE MODE

For the failure mode 1, after evaluated by the expert group, the fuzzy set of the occurrence is given as $R_1^1 = \{0, 0.2, 0.3, 0.5\}$; The fuzzy set of the severity is given as $R_2^1 = \{0, 0.3, 0.6, 0.1\}$; The fuzzy set of the detection is given as $R_3^1 = \{0, 0.6, 0.2, 0.2\}$; The fuzzy set of the maintainability is given as $R_4^1 = \{0, 0.2, 0.5, 0.3\}$. Therefore, it is acquired that the fuzzy matrix of failure mode 1 is:

TABLE 5. Weight of each influencing factor of failure mode 1.

Influencing factor	u_1	u_2	u_3	u_4	weight ω_i
u_1	1	3	6	4	0.5529
u_2	1/3	1	3	2	0.2262
u_3	1/6	1/3	1	1/3	0.0706
u_4	1/4	1/2	3	1	0.1503

$$R^1 = \begin{bmatrix} 0 & 0.2 & 0.3 & 0.5 \\ 0 & 0.3 & 0.6 & 0.1 \\ 0 & 0.6 & 0.2 & 0.2 \\ 0 & 0.2 & 0.5 & 0.3 \end{bmatrix} \quad (10)$$

4) DETERMINE THE SET OF FACTOR WEIGHTS FOR EACH FAILURE MODE

For the failure mode 1, the weight of each influencing factor is shown in Table 5.

After the calculation of the judgment matrix, it is acquired that the maximum eigenvalue is 4.0813, and its corresponding eigenvector $\xi = [0.8917, 0.3648, 0.1139, 0.2425]$.

Then consistency test is carried out to get $I_C = 0.020$. Since A is a fourth-order matrix, taking $I_R = 0.89$. According to Eq. (7), $R_C = 0.030 < 0.1$. Therefore, the weight set corresponding to the factor set for determining failure mode 1 is $W_1 = [0.5529, 0.2262, 0.0706, 0.1503]$.

5) CARRY OUT LEVEL 1 FUZZY COMPREHENSIVE EVALUATION

The Level 1 fuzzy comprehensive evaluation vector of failure mode 1 is: $B^1 = W^1 R^1 = [0, 0.2618, 0.5823, 0.1558]$. In the same way, under the condition of $W^1 = W^2 = \cdots W^n$, the fuzzy comprehensive evaluation vector of other failure modes can be obtained, as shown in Table 6:

6) DETERMINE THE COMPREHENSIVE HAZARD DEGREE

The comprehensive hazard degree can be calculated through the formula $C^k = B^k V^T$, as shown in Table 6.

From the table 4, the value sequence of every failure mode can be obtained, that $C^8 < C^{10} < C^7 < C^5 < C^9 < C^2 < C^6 < C^3 < C^4 < C^1$. Based on the value sequence, it can be learned that the most hazardous component is EDCU, and it is followed by switch, isolation lock device, screw nut and driving motor. Therefore, the weaknesses of the door system are identified, which provides the basis to RCM analysis.

IV. RELIABILITY ANALYSIS

Reliability is the probability that a product will perform its specified function under specified conditions, specified time and prescribed capacity. It is generally denoted as R [20], [21].

TABLE 6. Fuzzy comprehensive evaluation results.

Number	B^i	C^i
1	$[0, 0.2509, 0.3909, 0.3583]$	3.1074
2	$[0.2052, 0.6040, 0.1907, 0]$	1.9855
3	$[0.0945, 0.5738, 0.3317, 0]$	2.2371
4	$[0, 0.1811, 0.6482, 0.1707]$	2.9896
5	$[0.4976, 0.1813, 0.2985, 0.0226]$	1.8461
6	$[0.4423, 0.2083, 0.1783, 0.1710]$	2.0780
7	$[0.4946, 0.3638, 0.1416, 0]$	1.6469
8	$[0.7184, 0.2378, 0.0438, 0]$	1.3254
9	$[0.3870, 0.3132, 0.2547, 0.0451]$	1.9578
10	$[0.5909, 0.3864, 0.0226, 0]$	1.4317

Metro door system is mainly composed of mechanical and electronic components. It is assumed that the life of each component follows an exponential distribution, then the reliability function expression can be described as:

$$R(t) = e^{-\lambda t} \tag{11}$$

where λ is the component failure rate, $R(t)$ is the component reliability at time t, and $0 < R(t) < 1$.

The cumulative distribution function and the probability density function are [22], [23]:

$$F(t) = 1 - R(t) = 1 - e^{-\lambda t} \tag{12}$$

$$f(t) = \lambda e^{-\lambda t} \tag{13}$$

The failure rate function under the exponential distribution can be expressed as:

$$\lambda(t) = \lambda \tag{14}$$

For the repairable system, the working time between two adjacent faults is represented by the mean time between failure (MTBF) [24], [25]. The connection between MTBF and λ can be described as:

$$MTBF = \frac{1}{\lambda} \tag{15}$$

Based on the operation and maintenance records, the fault interval data can be obtained by counting and filtering.

According to classic solving method, the point estimate of MTBF can be calculated as:

$$MTBF = \frac{\sum_{i=1}^{n} \Delta t}{n} \tag{16}$$

where Δt is the failure interval; n represents the total times of fault.

Therefore, the MTBF and fault rate of components can be obtained, as shown in table 7.

V. MAINTENANCE DECISION FOR MDS

A. MAINTENANCE MODE DECISION FOR MDS

RCM logic decision diagram is convenient and intuitive, and usually used for determining which maintenance mode is suitable and effective [26]. The logic decision diagram is based on the completion of FMECA. From the current domestic and international research situation, the design and expression of logic decision diagrams are different, but the fundamental idea of design is consistent [27], [28]. Therefore, an optimization analysis method combining logic decision diagram and grey situation decision method is proposed to determine equipment maintenance strategy, as shown in Figure 2 [29].

TABLE 7. The reliability evaluation index.

Number	MTBF/d	λ/h^{-1}
1	34.718	1.2002E-03
2	84.692	4.9196E-04
3	79.336	5.2521E-04
4	43.267	9.6301E-04
5	83.649	4.9813E-04
6	54.176	7.6908E-04
7	59.823	6.9650E-04
8	121.433	3.4313E-04
9	55.293	7.5354E-04
10	74.476	5.5946E-04

TABLE 8. Maintenance method decision table.

Number	Components	Maintenance mode
1	EDCU	Regular replacement
2		Regular inspection
3	Switch (S1-S4)	Regular inspection
4		Regular inspection
5		Condition-based maintenance
6	Isolation lock device	Regular replacement
7	Driving motor	Regular replacement
8		Care and maintenance
9	Screw nut	Regular replacement
10		Regular inspection

Maintenance strategies are mainly classified into preventive maintenance and corrective maintenance [30]. Preventive maintenance methods mainly include the following four types: maintenance, regular replacement, condition-based maintenance, and regular inspection. Corrective maintenance methods mainly include post-failure maintenance and redesign [5]. After the logic decision analysis step, based on the existing maintenance mode of the metro company, the maintenance mode decision table of MDS can be obtained, as shown in table 8.

B. RELIABILITY-CENTERED MAINTENANCE STRATEGY DEVELOPMENT

For complex systems such as MDS, the maintenance interval cycle is not accurate just in view of empirical and

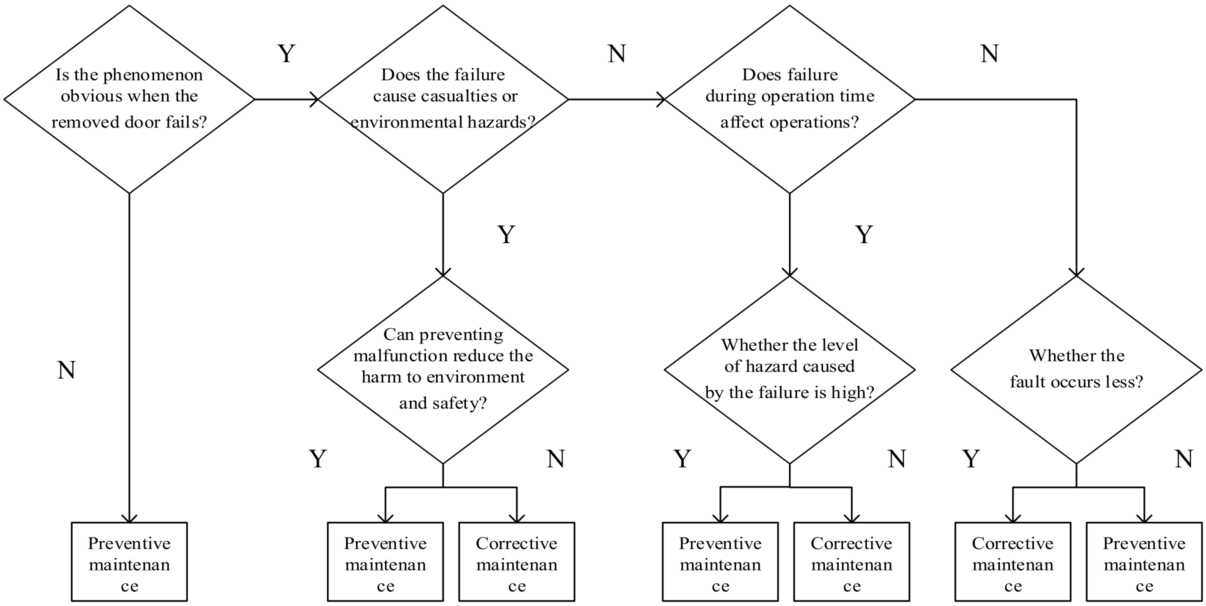

FIGURE 2. Logic decision diagram.

qualitative analysis. It is also necessary to obtain a more accurate and reasonable maintenance interval cycle by introducing a mathematical model. Therefore, regular maintenance model is selected to carry out maintenance interval cycle calculation. The common regular maintenance model is based on task reliability, based on maximum availability and minimum maintenance costs [26]. For exponential distribution systems, calculation models based on maximum availability and minimum maintenance costs are not applicable. So, in this section, the average availability model is selected to calculate the maintenance cycle.

The average life means that the equipment is continuously fault-free under the specified conditions, it can be written as:

$$E(T) = \int_0^\infty t \cdot f(t)\, dt \tag{17}$$

And it is known from the reliability theory that:

$$f(t) = \frac{dF(t)}{dt} = \frac{-dR(t)}{dt} = -R'(t) \tag{18}$$

Bring Eq. (18) into Eq. (17) to get:

$$E(T) = \int_0^\infty t \cdot \left[R'(t)\right] dt = \int_0^\infty R(t) dt \tag{19}$$

The average availability of the equipment is:

$$A(T) = \frac{E(T)}{T} \tag{20}$$

Because life obeys exponential distribution, so that:

$$A(T) = \frac{E(T)}{T} = \frac{1-e^{-\lambda t}}{\lambda T} \tag{21}$$

Suppose that the equipment does not fail within the specified time interval [0, t], then after Taylor's formula expansion, $e^{-\lambda t}$ in the Eq. (21) can be written as:

$$e^{-\lambda t} = 1 - \lambda T + \frac{(\lambda T)^2}{2!} - \frac{(\lambda T)^3}{3!} + \frac{(\lambda T)^4}{4!} - \cdots + \frac{(\lambda T)^n}{n!} \tag{22}$$

Bring Eq. (22) into Eq. (21) to get:

$$A(T) = \frac{\lambda T - \frac{(\lambda T)^2}{2!} + \frac{(\lambda T)^3}{3!} - \frac{(\lambda T)^4}{4!} + \cdots - \frac{(-\lambda T)^n}{n!}}{\lambda T} \tag{23}$$

Since this equation cannot solve T, but when n=4, the value of $\frac{(-1)^{n-1}\lambda T^n}{n!}$ can be negligible, that Eq. (23) can be simplified to:

$$A(T) = 1 - \frac{\lambda T}{2!} + \frac{(\lambda T)^2}{3!} \tag{24}$$

Solved by Eq. (24) to get:

$$T = \frac{1.5 - \sqrt{6A - 3.75}}{\lambda} \tag{25}$$

where T is the time of maintenance interval cycle.

After RCM analysis, reliability-centered maintenance strategy is formulated based on the RCM analysis. The maintenance strategy outline mainly includes: failure mode, maintenance mode, maintenance work content, maintenance interval cycle. Generally, the combination of maintenance policies and development of preventive program should be based on existing maintenance systems and regular intervals [31]. Besides, it is designed to balance cost and benefits [32]. Therefore, we choose the A=0.8 as the referential availability, then maintenance outline of MDS can be shown in table 9:

TABLE 9. Reliability-centered maintenance outline for MDS.

Components	Failure mode	Maintenance mode	Maintenance work content	Maintenance interval cycle/h
EDCU	Functional failure	Regular replacement	Maintain, replace if necessary	396.024
	Plug loosening	Regular inspection	Tighten the plug	966.096
Switch (S1-S4)	Abnormal wiring and fastening	Regular inspection	Adjust the switch position	905.016
	Functional failure	Regular inspection	Fasten, adjust the installation	493.560
Isolation lock device	Functional failure	Regular replacement	Adjust, replace parts	617.605
Driving motor	Functional failure	Regular replacement	Replace	682.416
Screw nut	breakage	Regular replacement	Refill or replace	630.744
	Loose	Regular inspection	Adjust the guide post	849.576

VI. CONCLUSION

In this paper, RCM analysis is applied in the determination of the maintenance strategy for the MDS. Firstly, RCM theory and MDS are introduced. Then in the second part, a fuzzy FMECA method combining FMECA analysis and analytic hierarchy process (AHP) is carried out to quantitatively identify high-risk parts of the system. In the third part, based on historical fault data, we assume that the components follow the exponential distribution to calculate their failure rate. And in the last part, the components maintenance modes are made from a RCM logic decision diagram and maintenance cycle is calculated in the typical availability, so that RCM strategy is finally developed. Through the development of RCM strategy, business decisions for maintenance will become more reliable to achieve uniformity of safety and economy.

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