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Fault Analysis and Preventive Maintenance of Rocket Vertical Assembly and Test Plant System

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Abstract

Complex industrial systems often consist of many components whose degradation and failure affect the condition and performance of the entire system. To improve system reliability and minimize total system costs, preventive maintenance (PM) of other components is required while the system's failed components are being repaired. In this paper, a maintenance cost index is proposed for the Rocket Vertical Assembly and Test Plant (RVATP) system considering various types of costs that affect the total expected cost of the system. Based on this index, a maintenance strategy analysis is performed for the RVATP. The sequence of preventive maintenance of components under two maintenance strategies is studied, and the number of preventive maintenance components under cost constraint is discussed. Finally, the RVATP is analyzed as an example. The results show that the maintenance cost index is not only related to the location of components in the system and associated costs, but also to the importance of preventive maintenance components. Simulation results also show the applicability of the maintenance cost index.

Keywords- Reliability, Maintenance cost, Preventive maintenance, Maintenance strategy.

Acronyms and Nomenclatures

RVATP	Rocket Vertical Assembly and Test Plant
MCI	Maintenance Cost Index
PM	Preventive Maintenance
FTA	Fault Tree Analysis
R_q	The reliability of component q
λ_q	The failure rate of component q
C^{TE}	The total expected cost of the system
ε_s^q	The cost of system downtime when component q failed
ε_q	The maintenance cost of component q
$\varepsilon_{l,PM}$	The PM cost of component l
$\varphi(\cdot)$	The structure function of the system
d_l	The decision variable
$I_{q,l}^{MCI}$	The MCI of component l when component q failed

1. Introduction

As one of the subsystems of China's space engineering, the space launch site system is an important part of space engineering and is the starting point for successfully sending spacecraft into space. The space launch site system consists mainly of the launch area and the technical area. The launch area is mainly responsible for the launch of rockets and spacecraft, and its main ground facilities are launch towers, while the technical area is mainly responsible for the testing and assembly of rockets and spacecraft, and the Rocket Vertical Assembly and Test Plant (RVATP) is the main ground facility of the technical area. The RVATP is an important place for general assembly and rocket testing. The platform hydraulic system, vertical transfer gate, sliding gate, double trolley bridge crane, lifting work platform, movable table auxiliary platform, cable auxiliary platform, and key equipment or systems such as the fire protection system and air conditioning system are the keys to ensuring the normal operation of this system. Due to the complex composition of the above equipment and the special working environment, the mechanical, hydraulic, and electrical systems are prone to various failures.

Complex industrial systems often consist of many different components, and the probability of system failure increases over time due to component failure, degradation, or other causes. When a component in the system fails, it can cause the entire system to fail and shut down, which not only seriously affects the reliability and efficiency of the system but also causes a lot of downtime costs, which is obviously a result engineers do not want to see. Also, a system or component failure is an appropriate maintenance opportunity. In order to improve system performance and reliability, preventive maintenance of other components is required, along with repair of faulty components. When a critical component fails, causing system downtime, PM can be performed not only on that component but also on other components. When a non-critical component fails, the system does not shut down, and PM can be performed on other non-critical components at this time (Cavalcante et al., 2018). Appropriate preventive maintenance can improve the reliability and quality of other components and reduce the probability of future failure of that component, thereby improving the overall reliability of the system (Chen et al., 2021). Kumar & Kumar (2021) used Markov models and sensitivity analysis to determine which Tripod Turnstile Machines have the greatest impact on system reliability and can provide guidance for preventive maintenance measures. However, due to cost budget and maintenance resource constraints, it is usually not possible to perform preventive maintenance on other components at the same time. And the cost and importance measure of maintenance vary from component to component. Therefore, a method is needed to determine the maintenance priorities of different components in order to maximize the use of resources.

There has been a great deal of research on maintenance and preventive maintenance. Jiang et al. (2020) studied selective maintenance strategies for multi-task systems and proposed a new selective maintenance model for systems performing multiple consecutive tasks. Liu et al. (2017) proposed a maintenance strategy for a degraded system whose operating cost depends on the lifetime and degradation state of the system. Dhiman & Kumar (2023) reveal the most critical and least critical component of the ULT freezer, which helps the maintenance department plan the maintenance strategy accordingly. Gao et al. (2020) considered two models of maintenance strategies, namely scheduling maintenance at the end of each production cycle and scheduling maintenance at each set point. Wu et al. (2017) applied the concept of risk summarization to optimize maintenance strategies for a set of different systems to overcome data sparsity. Zhao et al. (2007) studied a maintenance model considering the system structure and applied it to a railway system. Nguyen et al. (2015) developed a cost model to find optimal maintenance decision variables considering the predicted reliability of components, economic dependence, and location of components in the system. Yamane et al. (2021) modeled the maintenance of some infrastructures where preventive maintenance must be extended. The expected maintenance cost rate is established using the cumulative damage model, and the optimal strategy to minimize it is considered. Three basic models considering natural hazards and their extensions are discussed.

From a cost point of view, downtime costs can be saved by PM when considering the maintenance of critical components (Mokhtar et al., 2018). However, in order to avoid unnecessary downtime costs, PM triggered by the failure of a non-critical component cannot be performed on the component that caused the system failure. Generally, based on cost information, the maintenance cost of a critical component is higher than the maintenance cost of a non-critical component. In a previous study, Huynh et al. (2015) developed a predictive maintenance model that considers economic dependencies, where a multilevel decision-making approach combines system-level and component-level maintenance. Zong et al. (2013) presented a maintenance strategy based on the proposed average cost function to optimize resource allocation. Chien et al. (2021) proposed maintenance quantities and maintenance cycles for the optimal PM strategy. The total expected cost of the system has been studied in several literatures. Naaz et al. (2023) evaluated the characteristic reliability of a refrigeration system using a universal generating function technique and calculated the expected cost of the system. Ram et al. (2023) used the universal generating function technique to identify the reliability and characteristic reliability of a k-out-n-multiplex solar panel system, together with a computational analysis of the system's expected cost. Sadiya et al. (2023) analyzed the reliability and expected cost of the system by using techniques to evaluate the reliability of the system and the signature reliability of different models. However, the types of costs considered in the above studies may be less when compared to engineering practice.

In general, the selection of different preventive maintenance components results in different system costs, with maintenance costs for critical components in the system being higher than those for non-critical components. Therefore, an appropriate maintenance strategy must be developed to guide the selection of preventive maintenance components to minimize the impact of cost factors in the selection process. Wei et al. (2022) developed a continuous discrete-state Markov chain model describing the stochastic process of single-component deterioration and extended the model to multi-state tandem systems, illustrating that preventive maintenance and side-effect costs should not be optimized for each component individually, but rather from the overall perspective of the tandem system. Dui et al. (2022b) proposed a cost-based prioritization approach for multi-state machine preventive maintenance based on buffer capacity, and discussed three machine maintenance strategies. A cost-based selective maintenance model was investigated by Dao et al. (2016) to maximize total system profit. In practice, it is often not possible to perform preventive maintenance on every component of the system due to maintenance capacity constraints. Therefore, the available resources need to be fully utilized to maximize the reliability of the system (Dui et al., 2022a). In terms of cost-based reliability, Dui et al. (2019) proposed a joint composite importance measure to guide the selection of PM components, giving the number of PM components based on cost constraints to maximize the performance gain of the system.

Importance measure in reliability engineering has the advantage of easily identifying weak points in a system and characterizing the impact of components on the system, providing valuable information for system maintenance, and thus is widely used in the selection of PM components (Dui et al., 2021b). The purpose of constructing an importance measure is to obtain partial derivatives of different system functions (e.g., system maintenance cost function, system reliability function, system performance function, etc.) with respect to component reliability. At this stage, the main research direction of importance measure is maintenance optimization. Zhang et al. (2020) used Griffith importance measure to determine the maintenance order of components. Dui et al. (2021a) extended some important measures to answer the question of PM component selection under corrective maintenance. Wu et al. (2016) proposed a component repair priority importance measure to determine which components can be selected for preventive maintenance. In addition, considering the cost and time of component repair, Dui et al. (2017) proposed a comprehensive cost-based importance measure to identify components or groups of components that can be selected for preventive maintenance.

When maintenance resources (e.g., maintenance costs, etc.) are limited, it is necessary to maximize the performance of the system with the lowest maintenance costs. It is necessary to consider various maintenance costs based on engineering practice. At the same time, a problem needs to be considered. Which components and how many components should be selected for PM based on cost constraints? Choosing different components for PM may lead to different maintenance strategies when different components fail. Therefore, it is meaningful to consider multiple types of costs to propose a maintenance cost index that can guide the selection of maintenance components.

This paper proposes a maintenance cost index for the RVATP and discusses the PM component selection problem under two maintenance strategies. The sequence of preventive maintenance of components under two maintenance strategies is investigated and the number of preventive maintenance components under cost constraints is discussed. Finally, the RVATP is analyzed as an example to verify the applicability of the method. The maintenance cost index proposed in this paper has some theoretical significance in other engineering fields.

The rest of this paper is organized as follows: Section 2 describes the RVATP system. Section 3 provides an analysis of the total expected maintenance cost of the RVATP and proposes a maintenance cost index for the RVATP. Section 4 illustrates the applicability and effectiveness of the proposed method, using RVATP as an example. Finally, Section 5 summarizes the full paper and provides an outlook for future research.

2. Fault Analysis of Rocket Vertical Assembly and Test Plant System

In this section of the analysis, a fault tree is first constructed for the RVATP as a means of identifying the most frequently failing components and their failure modes. Fault Tree Analysis (FTA) is a top-down deductive failure analysis methodology that uses Boolean logic to combine lower-order events to analyze undesired states in a system. FTA is mainly used in the fields of safety engineering and reliability engineering to understand the causes of system failures and to find the best way to reduce the risk or identify the incidence of a safety incident or a specific system failure. By using fault trees in RVATP, the basic events that cause system failure can be found intuitively. Before building a fault tree, first determine the top event of that fault tree. The most undesired event of the whole system is the failure of the RVATP, which is the top event, while its intermediate events are the failure of the platform hydraulic system, the failure of the vertical transfer gate, the failure of the sliding gate, the failure of the double trolley bridge crane, the failure of the air conditioning system and the failure of the fire protection system. Each intermediate event in its subsystem can continue to decompose down as a top event to build the fault tree for each subsystem separately. The basic events that lead to the failure of each subsystem are derived, and the failure modes corresponding to each event and the main performance indicators of the components can be found.

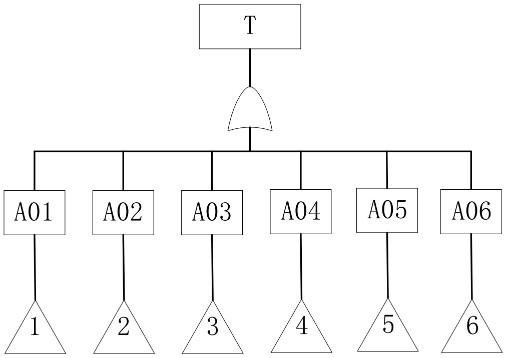

Figure 1. Fault tree of the RVATP.

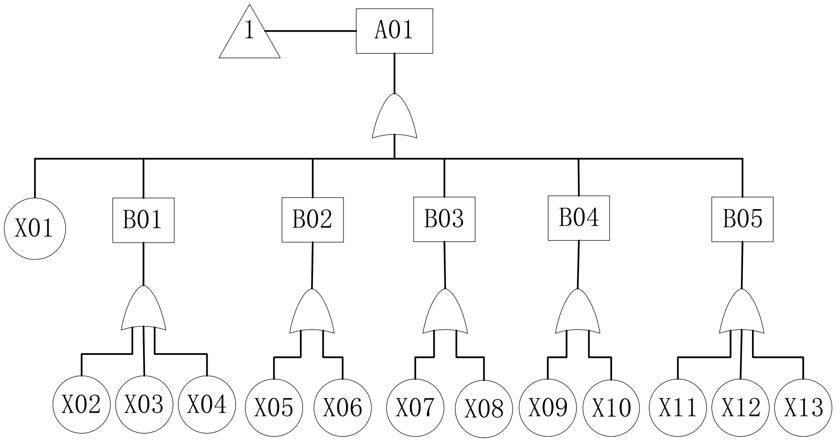

Figure 2. Fault tree of platform hydraulic system.

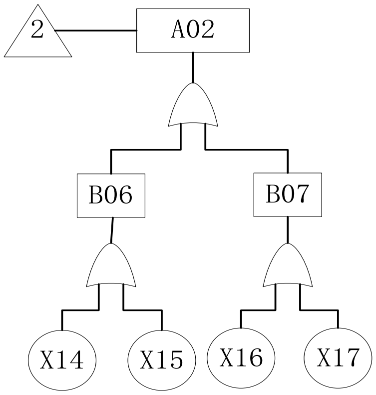

Figure 3. Fault tree of vertical transfer gate.

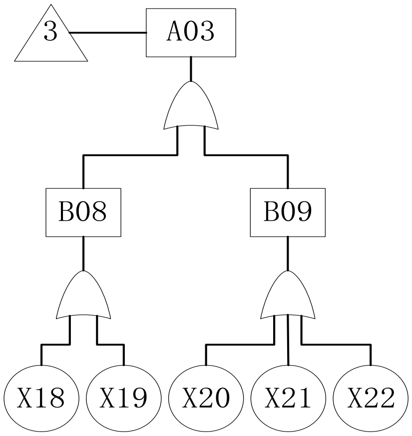

Figure 4. Fault tree of sliding door.

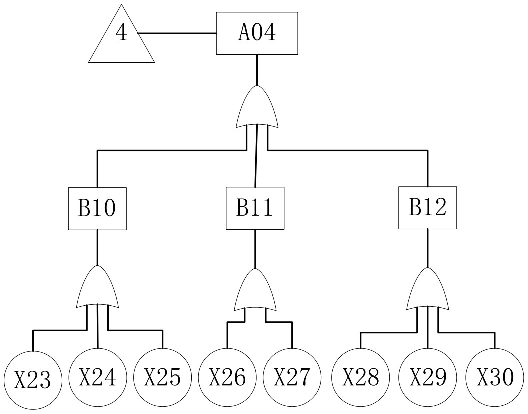

Figure 5. Fault tree of double trolley bridge crane.

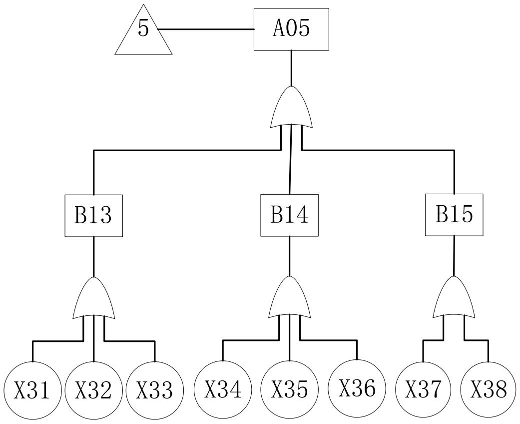

Figure 6. Fault tree of air conditioning system.

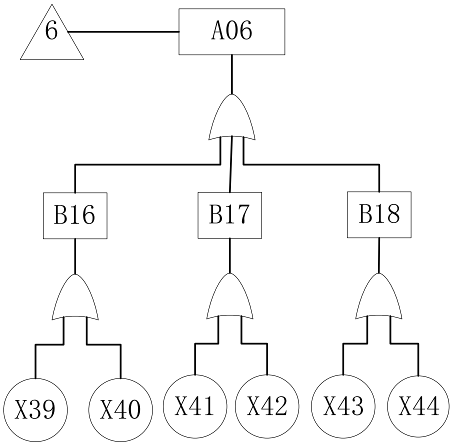

Figure 7. Fault tree of fire protection system.

Figures 1-7 show the fault trees associated with RVATP. Figure 1 shows the fault tree of the RVATP system, which has failure modes corresponding to the top-level events of each subsystem. These subsystems are the platform hydraulic system, vertical transfer gate, sliding door, double trolley bridge crane, air conditioning system, and fire protection system. The fault trees for each subsystem are shown in Figures 2 to 7, respectively. Continuing to decompose the failure modes of these subsystems downward, intermediate events B01 to B18 and basic events X01 to X44 can be obtained. By analyzing these fault trees, Table 1 can be obtained, which shows the fault tree events and codes for the RVATP system. Table 1 shows that each subsystem in the RVATP is the top-level event of the sub-fault tree, and these subsystems can continue to be decomposed down to the component level. Intermediate events B01 to B18 represent different part failure events, respectively, according to where these intermediate events are located on their part bodies. Failure of any of these components can lead to degraded performance or even failure of the RVATP. In order to ensure that the RVATP is up to the task, the important components corresponding to B01 to B18 need to be subjected to preventive maintenance measures.

Table 1. Fault tree event codes and names of the RVATP.

Code	Name
T	Rocket Vertical Assembly and Test Plant failure
A01	Platform hydraulic system failure
A02	Vertical transit gate failure
A03	Sliding door failure
A04	Double trolley bridge crane failure
A05	Air conditioning system failure
A06	Fire protection system failure
B01	Hydraulic pump failure
B02	Electric motor failure
B03	Proportional valve failure
B04	Hydraulic motor failure
B05	Each platform cylinder failure
B06	Solenoid valve failure
B07	Throttle valve failure
B08	Solenoid valve failure
B09	Throttle valve failure
B10	Inverter motor failure
B11	Brake failure
B12	Reducer failure
B13	Compressor failure
B14	Blower failure
B15	Ventilation duct failure
B16	Fire hydrant failure
B17	Flue gas control failure
B18	Fire protection network failure
X01	Abnormal hydraulic oil temperature
X02	Abnormal hydraulic pump oil discharge volume
X03	Hydraulic pump output pressure failure
X04	Abnormal noise or vibration of hydraulic pump
X05	Abnormal motor vibration
X06	Motor power failure
X07	Abnormal displacement of proportional valve spool
X08	Proportional valve filter port clogged
X09	Excessive load pressure of hydraulic motor
X10	Hydraulic motor outlet flow abnormal
X11	High load pressure of each cylinder
X12	Abnormal vibration of each cylinder
X13	Abnormal hydraulic oil flow of each cylinder
X14	Solenoid valve coil failure
X15	Solenoid valve spool failure

Table 1 continued…

X16	Throttle flow adjustment failure
X17	Increased leakage in the throttle valve
X18	Abnormal position of the main door
X19	Abnormal vibration of the gate body
X20	Abnormal variable frequency motor power
X21	Abnormal vibration of inverter motor
X22	Inverter motor case with electricity
X23	Abnormal variable frequency motor power
X24	Abnormal vibration of inverter motor
X25	Inverter motor case with electricity
X26	Lack of brake fluid in the brake
X27	Brake pad wear
X28	Abnormal speed reducer vibration
X29	Reducer oil seal leakage
X30	Abnormal output pressure of reducer oil pump
X31	Compressor blocking and abnormal load
X32	Abnormal compressor vibration and shaft displacement
X33	Insufficient cooling
X34	Blower motor overload
X35	Insufficient blower flow
X36	Blower abnormal vibration and noise
X37	Poorly connected air ducts
X38	Abnormal vibration and noise
X39	Hydrant pressure stabilization failure
X40	Fire pump power failure
X41	Smoke exhaust valve starts abnormally
X42	Abnormal power of range hoods
X43	Abnormal vibration of fire protection pipe network
X44	Leakage caused by failure of pipe network seals

Weibull distribution is widely used in reliability engineering, and is particularly applicable to the form of distribution of wear accumulation failure in electromechanical products. It is widely used for data processing of various life tests because it can easily infer its distribution parameters using probability values. In this paper, we assume that the 18 important components obey the Weibull distribution $W(\theta, \gamma, t)$, and the scale parameters and shape parameters of the failure time and repair time of each component are shown in Table 2.

Table 2. Parameters related to component failure time and repair time.

Code	θ_{1i}	γ_{1i}	θ_{2i}	γ_{2i}
B01	2045	2.43	8	2
B02	4385	1.95	10	2
B03	3015	2.24	4	3
B04	2045	2.43	4	2
B05	3364	1.21	6	2
B06	3015	2.24	2	3
B07	3015	2.24	7	2
B08	3015	2.24	12	3
B09	3015	2.24	15	2
B10	4385	1.95	4	2
B11	3207	2.11	8	2
B12	3207	2.11	8	2
B13	3321	1.97	7	2
B14	3532	2.01	14	3
B15	1722	2.12	12	2
B16	2249	1.44	15	2
B17	3159	2.17	12	2
B18	1722	2.12	15	3

θ is the scale parameter and γ is the shape parameter. By some properties of the Weibull distribution, the reliability function of component q can be obtained as $R_q(t) = exp[-\left(\frac{t}{\theta}\right)^{\gamma-1}]$ and the failure rate as $\lambda_q(t) = \frac{\gamma}{\theta}\left(\frac{t}{\theta}\right)^{\gamma-1}$. The reliability function and failure rate function of the components will be applied in case studies.

Repair costs and PM costs for each important component can be obtained from some historical data. These costs are given by Table 3.

Table 3. Costs associated with RVATP.

Code	ε_q	$\varepsilon_{q,PM}$	Code	ε_q	$\varepsilon_{q,PM}$
B01	29875	15531	B10	33157	21364
B02	33157	21364	B11	16814	13593
B03	15211	10468	B12	16814	13593
B04	29875	15531	B13	21357	17436
B05	11855	8264	B14	19412	13827
B06	15211	10468	B15	12864	8673
B07	15211	10468	B16	12733	9431
B08	15211	10468	B17	20415	16933
B09	15211	10468	B18	12864	8673

The various types of failure modes derived from fault tree analysis have different degrees of impact on overall system performance, as each failure mode affects the performance of the corresponding component. As a result, the system status is classified according to the occurrence of failure modes. Different failure modes cause degradation of the performance of the corresponding components, and the performance indicators of the components corresponding to these states are given. There are 46 main states, states 1 to 44 being the intermediate states of the RVATP, state 45 being the complete failure state, and state 46 being the perfect operating state. These data are given in Table 4.

Table 4. System status and corresponding performance index.

No.	State	Performance Index
1	X01	Hydraulic oil temperature
2~4	X02/X03/X04	Hydraulic pump output pressure
5~6	X05/X06	Motor output power
7~8	X07/X08	Proportional valve output flow
9~10	X09/X10	Hydraulic motor output pressure
11~13	X11/X12/X13	Vibration of the cylinder
14~15	X14/X15	Solenoid valve control precision
16~17	X16/X17	Throttle valve control precision
18~19	X18/X19	Gate displacement
20~22	X20/X21/X22	Motor output stability
23~25	X23/X24/X25	Motor output stability
26~27	X26/X27	Restraining driving force
28~30	X28/X29/X30	Matching precision
31~33	X31/X32/X33	Lifting pressure
34~36	X34/X35/X36	Conveying gas medium
37~38	X37/X38	Drafting efficiency
39~40	X39/X40	Fire hydrant output
41~42	X41/X42	Flue gas removal efficiency
43~44	X37/X38	Leakage
45	0	Reliability
46	1	Reliability

3. Analysis of Preventive Maintenance of RVATP Considering the Expected Cost

In this section, the cost function associated with component repair in the RVATP is first analyzed, and the PM cost function when failed components are critical and non-critical components, respectively, is discussed. Second, a maintenance cost index for the RVATP is proposed to guide the selection priority of PM components. Finally, an integer planning function based on the cost constraints of the RVATP is given for different strategies and used to determine which components can be used for PM.

3.1 Total Expected Cost

In selecting components to be improved, the goal must be to minimize the total expected value of the RVATP maintenance costs. In this section, the total expected maintenance cost of the system is studied for the following specific scenarios, where three different maintenance costs are considered.

Once a component failure is detected, the maintenance team will repair it immediately. And only the failure of critical components will result in the failure of the RVATP. When the failed component is a critical component, resulting in system downtime costs for the RVATP, preventive maintenance can be performed on other components. When the failed component is not a critical component, the failure of this component will not cause the RVATP to shut down, and PM activities can then be performed on other non-critical components that do not constitute a cut set, incurring only the cost of repairing the component and the PM cost of the other components. Denote C^{TE} as the total expected maintenance cost of the RVATP. Denote ε_s^q as the cost of system downtime due to failure of component q. Denote $\varepsilon_{PM}^q(t)$ as the cost of preventive maintenance of other components after the failure of component q. Since the failed component q may be a critical or non-critical component, two expressions are subsequently used to discuss both cases. At this point, in addition to the PM cost, the total expected maintenance cost of the system over the time interval $(0, t)$ can be given as,

$$C^{TE}(t) = \sum_{q=1}^{m} \{ \left\{ \varepsilon_s^q p_{s(<K)}^q(t) + \varepsilon_q + \varepsilon_{PM}^q(t) \right\} p_0^q(t) \} \tag{1}$$

m is the number of components in the RVATP; $p_{s(<K)}^q(t)$ is the probability that the system performance is below the threshold K caused by the failure of component q at time t, when a shutdown of the RVATP occurs. ε_q is the repair cost of failure of component q. $p_0^q(t)$ is the probability of failure of component q at time t. The state of part q can be represented by x_q, which can be expressed as $x_q(t) = 1$ if part q is in normal operation at time t and $x_q(t) = 0$ otherwise. Denote by $\varphi(X(t))$ the structure function of the RVATP at the time t whose value domain is $\{0,1\}$ and $\varphi\big(X(t)\big) = \varphi\big(x_1(t), x_2(t), \cdots, x_m(t)\big)$. The state of the system can be given by this function can be given by the state of the components in the system according to the structure of the system. For example, $\big(0_q, 1_{\neq q}\big)$ means that part q fails and the other parts work normally. $p_{s(<K)}^q(t)$ can be expressed as $\Pr\big[\varphi\big(0_q, 1_{\neq q}\big) < K\big]$, i.e., the probability that the system performance is less than the threshold K when the component q fails and the other components are working normally. $p_0^q(t)$ can be expressed as $\Pr\big[x_q(t) = 0\big]$, i.e., the probability of failure of the component q. The reliability of part q can also be expressed as $p_q(t)$ and $p_q(t) = \Pr\big[T_q > t\big]$, with T_q being the life time of part q.

When a part fails, preventive maintenance can be performed on other parts. When preventive maintenance is performed on a part, it means that the part is still in proper working condition. For example, when part q fails, PM is performed on part l. Part l works normally and its reliability is $p_l(t) = \Pr[x_l(t) = 1]$. The expression for $\varepsilon_{PM}^q(t)$ when the failure component q is critical and non-critical, respectively, is discussed next.

Assuming that component q is a critical component, if its failure occurs when a shutdown occurs in the RVATP, the PM cost of other components at time t is,

$$\varepsilon_{PM}^{q}(t) = \sum_{l=1,l\neq q}^{m}\{\varepsilon_{l,PM}p_1^l(t)p_{s(=0)}^q(t)\} = \sum_{l=1,l\neq q}^{m}\{\varepsilon_{l,PM}\Pr[x_l(t) = 1]\} \tag{2}$$

$\varepsilon_{l,PM}$ denotes the PM cost of component l. When PM measures are performed on part l, part l must stop working. $\Pr\left[\varphi\left(0_q, 0_l, 1_{\neq q,l}\right) = 0\right]$ represents the probability that the RVATP is in a shutdown state when parts q and l stop working and the other parts do not stop working. Since component q is a critical component, the system is bound to shut down at this time with a probability of 1. At this point, it is not considered that PM on other components will affect the operation of the RVATP.

When the failed component q is a non-critical component, and the RVATP is not down at this time, then there is a limit to the number of components that can be subjected to PM measures, because PM cannot be performed on other critical components. If PM is performed for another non-critical part l, there should be two requirements for this part: i.e., part l is not a critical part and part l and the failed part q do not form a cut set, i.e., an ensemble of the underlying events that lead to the shutdown of the RVATP.

Assuming that component q is a non-critical component, if it fails, the PM cost of the other components at time t is,

$$\varepsilon_{PM}^{q}(t) = \sum_{l=1,l\neq q}^{m}\{\varepsilon_{l,PM}\Pr[x_l(t) = 1]\Pr\left[\varphi\left(0_q, 0_l, 1_{\neq q,l}\right) \geq K\right]\} \tag{3}$$

$\Pr\left[\varphi\left(0_q, 0_l, 1_{\neq q,l}\right) \geq K\right]$ denotes the probability that the system remains in normal operation when component q and component l fail and the other components are working normally. The RVATP operates normally and does not incur system downtime cost.

3.2 Maintenance Cost Index

After giving the cost function of how to select components for PM, the partial derivative of the cost function of the system with respect to the reliability of components can be solved based on the idea of importance measure. It can characterize the extent to which PM of a non-faulty component will impact the total expected system cost when fixing a faulty component. This partial derivative is called the Maintenance Cost Index (MCI) of RVATP. Next, the expression of MCI is analyzed for two cases in which the failed component is critical or not.

Assuming that component q is a critical component, the MCI corresponding to component l that performs PM in the case of its failure can be defined as,

$$I_{q,l}^{MCI}(t) = -\frac{\partial C^{TE}(t)}{\partial p_l(t)} \tag{4}$$

$I_{q,l}^{MCI}(t)$ represents the degree of impact of the PM cost to component l on the total expected cost of the system when component q fails.

Assuming that component q is a non-critical component, the MCI corresponding to component l that performs PM in case of its failure can be defined as,

$$I_{q,l}^{MCI}(t) = -\varphi\left(0_q, 0_l, 1_{\neq q,l}\right)\frac{\partial C^{TE}(t)}{\partial p_l(t)} \tag{5}$$

$\left(0_q, 0_l, 1_{\neq q,l}\right)$ represents that both part q and part l fail, while all other parts work normally. The system structure function $\varphi\left(0_q, 0_l, 1_{\neq q,l}\right) = 0$ when the component selected for PM is a critical component or forms a cut set with the failed component, otherwise $\varphi\left(0_q, 0_l, 1_{\neq q,l}\right) = 1$. The system structure function $\varphi(\cdot)$ is mainly used to prevent the PM component from being a critical component and causing system downtime.

Since RVATP indicates the impact of the PM cost of the selected component on the total expected system cost, a higher value means a higher cost benefit of performing PM on that component. Ranking the MCI values of all components in ascending order yields a prioritized list of component PMs. MCI can effectively guide component PM strategy for RVATP and minimize total system maintenance costs.

3.3 Maintenance Strategies

In the practical application of the RVATP, in addition to the maintenance strategies discussed in the previous section, two maintenance strategies are proposed for discussion based on the characteristics of MCI.

***Policy* 1.** Dispatch maintenance personnel to perform repairs to the failed component and trigger PM measures only when the system fails. When a non-critical component fails, the component is not repaired immediately, but is delayed until the system fails.

***Policy* 2.** Regardless of whether the component is critical or non-critical, maintain the component and trigger PM immediately upon its failure. Other components can perform PM at the same time.

For Policy 1, it is assumed that the failed component cannot be repaired immediately unless the RVATP fails. When the system fails, the engineer will inspect the entire system, which is used to determine the cause of the failure. The cause of system downtime may be due to the fact that the faulty parts are critical parts, or it may be due to the fact that the faulty parts are all non-critical parts but form a cut set. Suppose there are *n* minimum cut sets in the RVATP, $q_1, q_2, \cdots, q_{y_z}$ is the *q*th cut set in the system, and the number of components in this cut set is y_z. When all components in this cut set fail, it will cause the system to shut down. At this time, PM measures can be applied to other components.

Under this policy, the system is down because at least one cut set fails, or a critical component fails, and PMs can be performed on other components. The cost function for critical component failure has already been discussed, and the total expected maintenance cost function for the RVATP is discussed next when there is a minimum cut set failure. First, assume that the maintenance cost incurred during the time interval $(0, t)$ consists of three components, including: the cost of system downtime due to the failure of the minimum cut set, the cost of repairing all components in the failed minimum cut set, and the cost of PM for all components in that system except the failed components. It is possible to obtain,

$$C_{CS}^{TE}(t) = \sum_{q=1}^{n}\{\varepsilon_s^q + \sum_{i=1}^{y_z} \varepsilon_{y_z} + \sum_{l=1}^{m-y_z} \varepsilon_{PM}^l \, p_1^l(t)\} p_0^{q_1,q_2,\cdots,q_{y_z}}(t) \tag{6}$$

ε_s^q represents the cost of system downtime due to the failure of the minimal cut set. ε_{y_z} represents the maintenance cost of all components in the failed minimal cut set. $\sum_{l=1}^{m-y_z} \varepsilon_{PM}^l$ represents the PM cost of all components except the failed components. $p_1^l(t)$ represents the probability that all components except the failed component work properly. $p_0^{q_1,q_2,\cdots,q_{y_z}}(t)$ represents the probability that the minimum cut set $q_1, q_2, \cdots, q_{y_z}$ fails. Since the failure of the minimum cut set also leads to system downtime, it is not necessary to distinguish here whether the PM component is critical or not. In order to explore the impact of PM component *l* on the total expected system cost when a cut set fails and causes system downtime, MCI can be defined as,

$$I_{CS,l}^{\mathrm{MCI}}(t) = -\frac{\partial C_{CS}^{TE}(t)}{\partial p_l(t)} \tag{7}$$

For Policy 2, it is assumed that a component can be immediately identified once it fails. When a component failure is identified, repair is performed immediately and PM can be performed simultaneously on other non-faulty components. When a critical component fails, PM can be performed on all other components. When a non-critical component fails, as this strategy can perform PM measures on other components simultaneously, it is necessary to identify whether other non-critical components form a cut set with that component to prevent downtime in the RVATP. In this case, only the total expected cost function for the RVATP in case of failure of non-critical components needs to be given as,

$$C_S^{TE}(t) = \sum_{q=1}^{m}\{\left\{\varepsilon_S^q p_{s(<K)}^q(t) + \varepsilon_q + \varepsilon_{PM}^{S,p}(t)\right\} p_0^q(t)\} \tag{8}$$

$$\varepsilon_{PM}^{S,p}(t) = \sum_{i=1}^{n}\{\, \varepsilon_{l_i,PM} p_1^{l_i}(t) p_{s(\geq K)}^q(t)\} \tag{9}$$

$\varepsilon_{PM}^{S,p}(t)$ represents the PM cost to other components in the system after the failure of component q. The number of PMs that can be executed simultaneously in this system is n. $\varepsilon_{l_i,PM}$ represents the PM cost of component l_i. $p_1^{l_i}(t)$ represents the probability that component $l_i$works properly, which can be expressed in terms of the structure function asPr$\left[x_{l_i}(t) = 1\right]$. $p_{s(\geq K)}^q(t)$ represents the probability that the system state is greater than the threshold K after the failure of the component q. In terms of the structure function, this can be expressed as Pr$\left[\varphi\left(0_q, 0_{l_1}, 0_{l_2}, \cdots, 0_{l_i}, 1_{\neq q,l_1,l_2,\cdots,l_i}\right) \geq K\right]$. Similarly, we can define the MCI of policy 2 as,

$$I_{S,l}^{\mathrm{MCI}}(t) = -\frac{\partial C_S^{TE}(t)}{\partial p_l(t)} \tag{10}$$

$$I_{S,l}^{\mathrm{MCI}}(t) = -\varphi\left(0_q, 0_l, 1_{\neq q,l}\right)\frac{\partial C_S^{TE}(t)}{\partial p_l(t)} \tag{11}$$

In the practical application of the RVATP, it may be more common to consider specific cost constraints for the PM strategy. Therefore, to perform PM for other components one by one when one component fails, we need to solve the following integer planning problem.

$$max \sum_{l=1,l\neq q}^{m} I_{q,l}^{\mathrm{MCI}}\, d_l \tag{12}$$

which is subject to $\sum_{l=1,l\neq q}^{m} \varepsilon_{l,PM} \leq C$. Where $\varepsilon_{l,PM}$ represents the PM cost of component l. C is the maintenance cost budget for the RVATP. d_l is a decision variable that can only have a value of 0 or 1 and is used to indicate whether to select the component for PM.

For Policy 1, Equation (12) can be slightly changed:

$$max \sum_{l=1,l\neq q}^{m} I_{CS,l}^{\mathrm{MCI}}\, d_l \tag{13}$$

which is subject to $\sum_{l=1,l\neq q_1,q_2,\cdots,q_{y_z}}^{m} \varepsilon_{l,PM} \leq C$.

For Policy 2, when the failed component is a critical component, preventive maintenance can be performed on any component at the same time because its failure causes the failure of the RVATP. Therefore, only the case where the failed component is a non-critical component needs to be considered. If the failed component is a non-critical component, when it fails, preventive maintenance cannot be performed on other critical components, and preventive maintenance cannot be performed on other non-critical components that can form a cut set with this component. According to Equation (12) and the influence of the system structure, the following integer plan can be obtained as,

$$max\varphi\left(0_q, x_{l_1}, x_{l_2}, \cdots, x_{l_i}, 1_{\neq q,l_1,l_2,\cdots,l_i}\right)\sum_{l=1,l\neq q}^{m} I_{S,l}^{\mathrm{MCI}}\, d_l \tag{14}$$

which is subject to $\sum_{l=1,l\neq q}^{m} \varepsilon_{l,PM} \leq C$. The structure function $\varphi\left(0_q, x_{l_1}, x_{l_2}, \cdots, x_{l_i}, 1_{\neq q,l_1,l_2,\cdots,l_i}\right)$ is used to determine that the selected PM component will not cause the RVATP to shut down.

4. Case Study

In this section, the above maintenance optimization model is applied to the RVATP. As the most important link before rocket launch, the RVATP will cause huge economic loss and serious social impact if the failure of key components causes system failure. Appropriate PM policies for the RVATP can reduce the probability of system failure and maintenance costs, thus avoiding negative impacts on society. This section analyses the RVATP using the proposed MCI to further illustrate the practical application and effectiveness of MCI.

The composition of the RVATP is relatively complex. From Figure 1 to Figure 7, we can understand that the system has six subsystems, which mainly include platform hydraulic system, vertical transfer gate, sliding gate, double trolley bridge crane, air conditioning system and fire protection system. Among all mechanical systems, pumps, motors and electronic control systems are devices with a relatively high frequency of failure, and their failure will cause subsystem failure. Therefore, in the RVATP, the critical components are B01, B02, B04, B10, B14, and B17, and the other components are non-critical components. According to the composition structure of the RVATP, we can know that parts B01 and B04 are the same type of parts, so their MCI values are the same. Similarly, B02 and B10 are the same type of motor, B03, B06, B07, B08, and B09 are all valve type components, B11 and B12 are both brakes, and B15 and B18 are the same pipe network. In the next analysis, only one of these components is simulated due to the same maintenance cost, PM cost, and maintenance-related parameters for the same class of mechanical components.

The MCI value of a component is related to its repair and PM costs in case of failure, and as maintenance costs increase, so does the MCI. This means that it is more valuable to perform PM on a component when it fails and causes the system to incur higher maintenance costs. When a component fails, MCI is related to the component's location in the system. the impact of the component location of the PM on the MCI value depends only on whether the component is a critical component. Below, a more specific analysis of MCI values for critical and non-critical component failure scenarios is shown in Figures 8 and 9.

When a critical component fails, it causes a shutdown of the RVATP so that PM measures can be performed on all other components. Figure 8 shows the variation in MCI values over time when a critical component fails. MCI is affected not only by the cost associated with its PM component, but also by the reliability of the other components selected for PM. It's clear that the MCIs of different PM components selected are interleaved. It can be found that when the same critical component fails, the MCI values of all PM components available for selection differ in size at the same time, when the priority of its PM can be determined based on the size of the MCI value. It is worth noting that the priority of PM parts changes as time changes. And, when critical failed parts are different, MCI values and repair priorities for the same PM parts are also different. For example, when component B01 or B04 fails, the PM priority of the other components at *t*=50 is B02, B14, B03, B17, B15, B16, B11, B13, B05. At *t*=90, the PM priority of the other components is B02, B03, B14, B15, B16, B17, B11, B13, B05. When component B02 or B10 fails, the PM priorities of other components at *t*=50 are B01, B03, B15, B14, B11, B17, B16, B13, B05. And at *t*=90, the PM priorities of the other components are B01, B03, B15, B16, B11, B14, B17, B13, B05.

In practice, PM is not performed for all components that have not failed, and PM measures can be more rationally scheduled to reduce costs by prioritizing component repairs at different moments. This can show the practical applicability of the model.

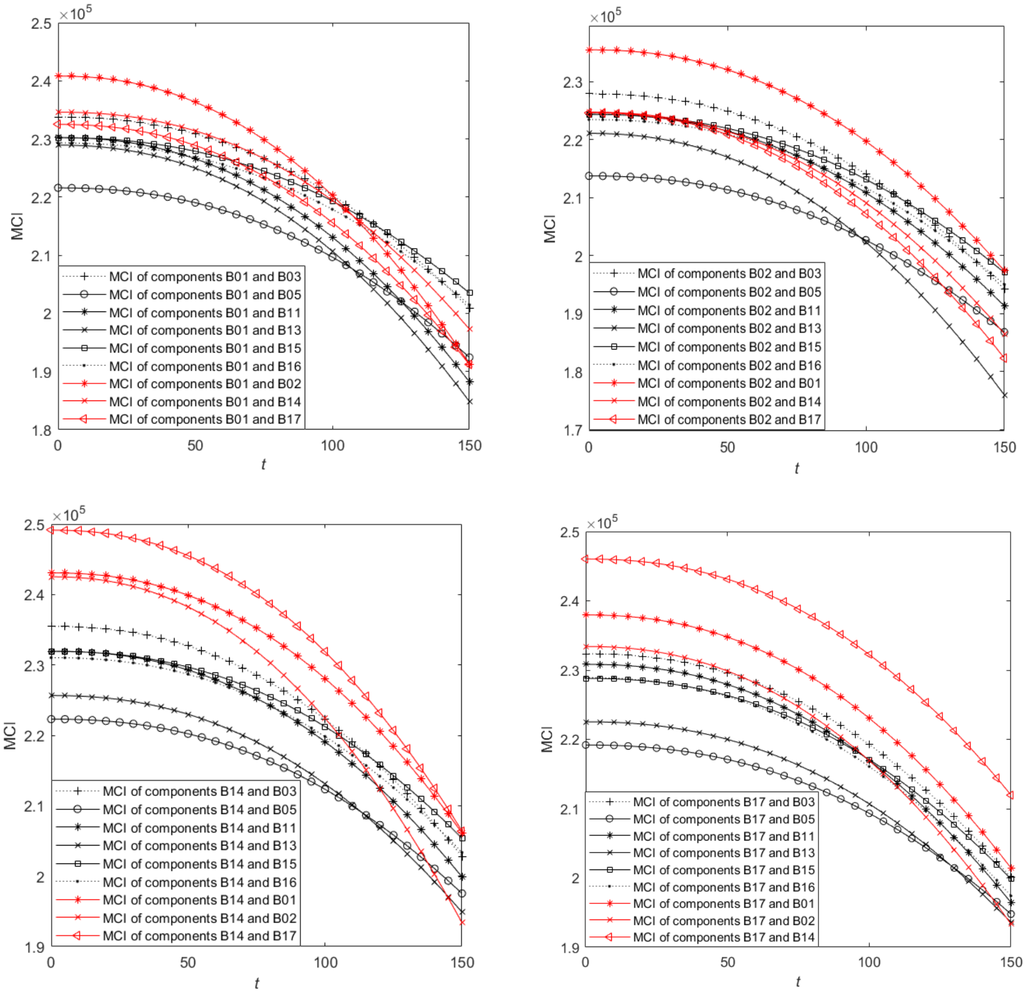

Figure 8. MCI when critical component fails.

Figure 9 shows the change in the MCI value corresponding to the PM component when the non-critical component fails. When non-critical parts B03, B05, B11, B13, B15, and B16 fail, PM cannot be performed on critical parts in order to reduce downtime losses as no system shutdown occurs. At this time, PM measures can only be performed on non-critical parts that do not form a cut set with the failed part. For example, when non-critical component B03 fails, components that can be subject to preventive maintenance operations at *t*=50 are B05, B11, B13, B15, and B16, at which point the preventive maintenance priorities for these components are B05, B16, B13, B15, and B11. And at *t*=90, the PM priorities for the other components are B16, B05, B13, B11, and when the non-critical component B15 fails, the components that can perform PM operations at *t*=50 are B05, B11, B13, B03, and B16, at which time the preventive maintenance priorities for these components are B03, B16, B11, B13, and B05. At *t*=90, PM priorities for other components are B03, B16, B05, B11, and B13.

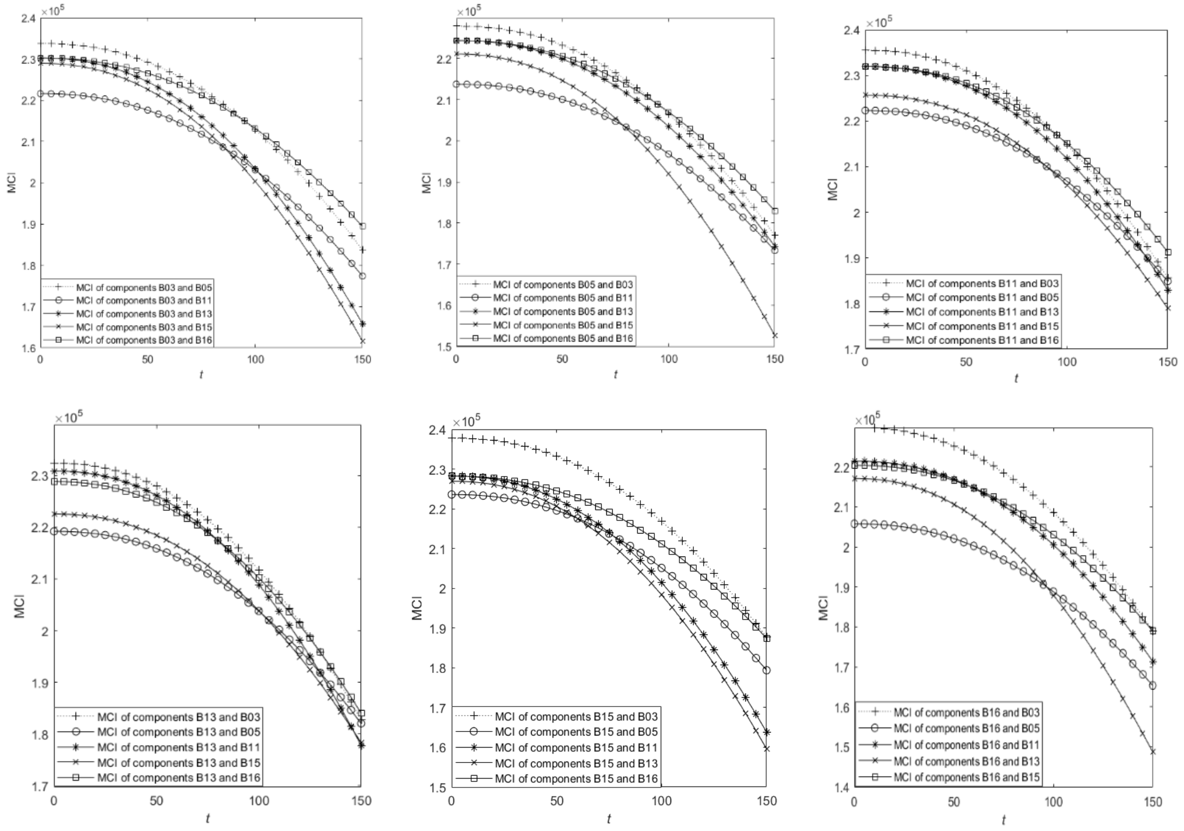

Figure 9. MCI when non-critical component fails.

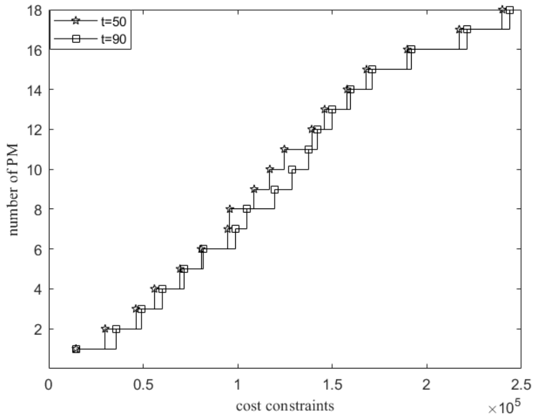

Figure 10. Number of components for PM under the cost constraints.

From the above simulation results for critical and non-critical components, it can be concluded that the priority of components ranked based on MCI values changes over time. The components selected for the PM may be different at different points in time. In addition, the components selected for PM may be different if different components fail. This demonstrates the flexibility and usefulness of MCI to provide repairers with an optimal total repair cost repair order in the event of component failure.

Figure 10 shows the relationship between the number of components performing PM and the cost constraint when the critical component B01 fails. Depending on the variation of the cost constraint, the number of PM components that can be selected under this condition can be determined. For example, when t=50 and the cost constraint is 100000, the optimal number of components to perform PM is 8. When t=90, the optimal number of parts to perform PM is 7. This happens also due to the change in PM component priority. This shows that in engineering practice, it is necessary to determine the number of components for PM at the right point in time due to the maintenance cost constraint, and provides some guidance for the maintenance strategy of the RVATP.

5. Conclusions and Future Work

This paper discusses the maintenance costs associated with the total expected cost of the system based on the idea of importance measure and the actual situation of RVATP. The MCI applicable to the system is proposed. The optimal PM order of the system PM components for different failure component cases is analyzed. Finally, the number of PM components under different cost constraints is derived based on solving the objective function with cost as the constraint.

The application of the method is illustrated by numerical example analysis. The numerical example shows that RVATP maintenance cost indices are not only related to the location of components in the system and associated costs, but also to the importance of PM components. This demonstrates the applicability of PM measures determined by the RVATP Maintenance Cost Index. Also, considering different types of costs and cost constraints, it can provide effective support for engineers' maintenance decisions in practice. Meanwhile, the MCI proposed in this paper can be generalized to similar engineering domains. It can provide managers with optimal maintenance decisions that can meet various resource constraints in practice.

However, in engineering practice, components tend to be polymorphic as well. This determines a more diverse state of the system. Moreover, this paper assumes that both the repair cost and PM cost are fixed, which may affect the maintenance strategy to some extent. Future work will focus on extending the proposed MCI to systems with multiple component states and analyzing how maintenance costs follow component states.

Conflict of Interest

The authors confirm that there is no conflict of interest to declare for this publication.

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