IEEE Access
Multidisciplinary : Rapid Review : Open Access Journal

Received 4 July 2023, accepted 15 August 2023, date of publication 21 August 2023, date of current version 25 August 2023.

Digital Object Identifier 10.1109/ACCESS.2023.3306949

RESEARCH ARTICLE

Strategy Optimization of Multi-Component System Opportunity Maintenance for Electric Multiple Units From a Lean Maintenance Perspective

JING LI[1,2], HONG WANG[1], LÜ XIONG[3], YONG HE[1], AND CHENGSHAN YI[1]

[1]School of Mechatronic Engineering, Lanzhou Jiaotong University, Lanzhou 730070, China
[2]School of Electronics and Information Engineering, Lanzhou Jiaotong University, Lanzhou 730070, China
[3]School of Rail Traffic, Guangdong Communication Polytechnic, Guangzhou 510650, China

Corresponding author: Hong Wang (wh@mail.lzjtu.cn)

This work was supported by the National Natural Science Foundation of China under Grant 72061022.

ABSTRACT The deterioration characteristics of electric multiple units (EMUs) components can lead to complex and costly maintenance processes. This paper focuses on investigating the influence mechanism of the interaction between operation and maintenance (O&M) activities within the whole life cycle (WLC) of EMUs' components on the maintenance strategy, based on the concept of lean maintenance (LM). A linear relationship is established between operating costs and the equivalent service age to reflect the trend of the component operating conditions dynamically in relation to deterioration level and maintenance activities, and a bi-level imperfect preventive maintenance (BIPM) strategy considering operating cost (OC) is proposed at the component level. At the system level, a multi-level preventive opportunity maintenance (POM) strategy based on the opportunity maintenance mileage window (OMMW) is proposed for the serial system of EMUs to reduce the number of system downtime and minimize value waste and achieve long-term economic benefits. The experimental results demonstrated that compared to maintenance strategies that do not consider operating costs, this strategy optimizes the total maintenance cost for multi-component systems of EMUs in the long term by implementing more aggressive measures while ensuring component reliability, system availability, and schedule rationality.

INDEX TERMS Lean maintenance, operating costs, electric multiple unit, multi-level maintenance, preventive opportunity maintenance.

I. INTRODUCTION

As complex maintainable equipment with high reliability and safety requirements, electric multiple units (EMUs) typically undergo preventive maintenance (PM) after a certain mileage or time of operation [1]. However, the intricate structure of EMUs and the varying deterioration characteristics of their components contribute to increased difficulties and costs in maintenance [2]. In China, as of the end of 2022, there were 3,992 standard sets of EMUs with an accumulated operating mileage of 42,000 kilometers. Some EMUs have reached a period of intensive maintenance. Although implementing a five-level maintenance system can yield cost savings, annual maintenance expenses still account for 10%-15% of purchase costs [3], [4] without considering indirect maintenance costs such as downtime losses. **Therefore, developing a more accurate and effective maintenance strategy for EMUs is crucial to ensure their safe operation and reduce maintenance costs.**

Maintenance tasks encompass preventing and correcting equipment failures and generating revenue for the organization [5]. Lean Maintenance (LM) aims to reduce value waste in the maintenance chain through whole life cycle (WLC) management, enhancing system maintenance performance

The associate editor coordinating the review of this manuscript and approving it for publication was Yu Liu.

from a long-term strategic perspective. LM combines LM concepts with maintenance activities, forming an organic combination [6]. Numerous existing studies have reflected the idea of LM by refining maintenance strategies, including multi-category maintenance [7], multi-state maintenance [8], [9], [10], [11], [12], [13], multi-phase maintenance [14], [15], and multi-level maintenance [16], [17]. Additionally, some scholars have conducted research on WLC management within the LM concept. A common approach is to quantify all WLC activities, including operation and maintenance (O&M) costs, as costs influencing maintenance strategy decisions [18], i.e., life cycle cost (LCC), especially the O&M cost, which is regarded as an important decision basis for maintenance strategy. This method, known as life cycle cost (LCC) analysis, has been widely employed in the field of wind turbine maintenance and has proven effective in improving overall system performance and reducing total maintenance costs [19], [20], [21], [22], [23]. However, there have been relatively few studies in the field of EMU maintenance [24], and operation costs (OC) are mostly regarded as costs unaffected by component deterioration [18], ignoring the influence of component deterioration process and maintenance activities on operating costs such as energy costs and depreciation costs, which cannot dynamically reflect the correlation between the operating state of components and their maintenance activities.

LM refines maintenance at the component level, alleviating issues of over-maintenance and under-maintenance. However, complex maintenance correlations exist among components, including economic, structural, and stochastic correlations, which increase maintenance complexity [25]. This complexity is particularly pronounced in serial systems, where maintenance on any component leads to system downtime. Frequent downtime adversely affects system operation and increases maintenance costs, contradicting the waste reduction and cost reduction goals in LM [26]. In this context, employing the economic correlation between components for multi-component opportunity maintenance (OM) at the system level can effectively enhance system availability and reduce total maintenance costs [27].

The core challenge of OM lies in determining grouping rules and maintenance strategies. OM strategies can be categorized into function-based short-term optimization strategies and rule-based long-term optimization strategies. The former is designed for one decision cycle only, while the latter typically employs state thresholds such as failure rate, reliability, service age, or maintenance time windows to group components and make decisions for the entire maintenance planning period [28], [29], [30], [31], [32], [33]. OM can also be classified into preventive opportunistic maintenance (POM) and corrective opportunistic maintenance (COM) based on trigger timing [34]. COM does not apply to equipment with high availability and safety requirements. For instance, in the case of sudden failures in EMUs, prompt fault removal and system resumption take precedence over OM [27]. In POM research, some scholars have integrated it with multi-level maintenance strategies to establish more accurate POM models with multi-level maintenance measures [35], [36], [37]. However, these models have yet to be closely integrated with the WLC management concept and the maintenance applications specific to EMUs.

In summary, the following issues need to be investigated for EMUs maintenance.

(1) The maintenance complexity caused by the varying deterioration characteristics of EMUs;

(2) Traditional EMUs maintenance strategies do not emphasize the impact of operational activities, making it difficult to improve the maintenance performance of EMUs from a long-term strategic perspective;

(3) The maintenance of EMUs' components can cause frequent downtime of multi-component systems, resulting in poor system availability and high maintenance costs.

To address the above problems, this paper proposes the following solutions from the perspective of lean maintenance.

(1) Further divide traditional imperfect PM into two levels, encompassing junior PM and senior PM, based on the cost required for changes in the unit failure rate of a component, i.e. bi-level imperfect preventive maintenance (BIPM);

(2) Establish a dynamic correlation between O&M activities in terms of cost from a WLC perspective, utilizing the concept of equivalent service age as a basis for maintenance strategy decision-making;

(3) Develop a multi-component POM strategy that considers the dynamic operating status of components, aligning with waste reduction principles in LM. The objective is to reduce system downtime and lower total maintenance costs.

The rest of the paper is structured as follows: The research problem is described in Section II, A BIPM strategy based on LCC is proposed for EMUs' components in Section III, and a multi-component POM strategy based on maintenance mileage windows for EMUs is further developed in Section IV. The validation of model effectiveness is arranged in Section V. Finally, the study is summarized in Section VI.

II. PROBLEM DESCRIPTION

According to the current five-level maintenance schedule of Chinese EMUs [38], a four-level maintenance schedule (2.4×10^6km) is adopted as the maintenance planning period for a multi-component serial system of CRH3-type EMUs. Within this planning period, preventive renewal (PR) is performed at the end, while preventive maintenance (PM) and corrective maintenance (CM) are conducted on the components before that. To account for the varying deterioration characteristics of each system component, an optimal maintenance strategy and plan for each component throughout the planning period are developed using Lean Maintenance and Life Cycle Cost management concepts. Additionally, a multi-component serial system POM optimization strategy is proposed at the system level, leveraging the economic interdependency between components. To provide further clarity on the study, the following hypotheses are made:

1) The maintenance cycle for the whole vehicle is 2×10^4 km, while the component PM cycle is a multiple of this value.
2) The system consists of m components initially in a new condition, and their deterioration process follows a two-parameter Weibull distribution.
3) A total of N planned maintenance will be performed during the maintenance planning period, with only the last one being perfect maintenance (i.e., PR) and the others being imperfect maintenance (i.e., PM).
4) Any maintenance activity on the component results in system downtime.
5) Sudden component failure requires CM to restore its function as soon as possible. Therefore, CM is not involved in OM and does not change the component deterioration process.
6) The same level of maintenance activity requires the same maintenance resources and time, and the resulting fixed costs (the sum of fixed maintenance costs and downtime losses) are equivalent.

III. SINGLE COMPONENT MULTI-LEVEL PM STRATEGY

Lean management principles are introduced into the maintenance process of EMUs, with a focus on maintenance subjects, maintenance activities, maintenance effects, and cost management. To address the variability in component deterioration trends, maintenance subjects are refined at the component level. A multi-level maintenance strategy is implemented, combining multiple maintenance methods and efforts across different levels. Additionally, in-depth research on Lean Maintenance of EMUs' components is conducted, taking into account the perspective of WLC management.

A. BIPM FAILURE RATE EVOLUTION RULE

As a complex mechatronic system, the age of EMUs follows the law of non-negative continuity change. Therefore, the two-parameter Weibull distribution is used to describe the evolution rule of its component failure rate. The failure rate function can be defined as:

$$\lambda_{i,1}(l) = \frac{\beta_i}{\theta_i}\left(\frac{l}{\theta_i}\right)^{\beta_i - 1} \quad (1)$$

where $\lambda_{i,1}(l)$ is the failure rate, β_i and θ_i are the shape and scale parameters of component i.

In order to accurately represent the actual maintenance effect of component i, a service age regression factor $a_{i,k}$ and a failure rate increment factor $b_{i,k}$ are introduced to establish a hybrid failure rate evolution model, which is expressed as:

$$\lambda_{i,k+1}(l) = b_{i,k}\lambda_{i,k}(l + a_{i,k}L_{i,k}) \quad 0 < l < L_{i,k+1} \quad (2)$$

where $0 < a_{i,k} < 1$ and $b_{i,k} > 1$, the values of $a_{i,k}$ and $b_{i,k}$ can be obtained by fitting the historical maintenance data of the component.

Considering the characteristics where the effect of imperfect maintenance varies with the maintenance effort, combined with the current maintenance protocols and LM concepts, PM is further divided into two levels: junior and senior. Given that the senior PM yields a better maintenance effect than the junior PM, its service age regression factor $a^{s}_{i,k}$ and the failure rate increment factor $b^{s}_{i,k}$ are lower than the service age regression factor $a^{j}_{i,k}$ and the failure rate increment factor $b^{j}_{i,k}$ of the junior PM, i.e., $0 < a^{s}_{i,k} < a^{j}_{i,k} < 1$ and $1 < b^{s}_{i,k} < b^{j}_{i,k}$.

Combined with (2), the BIPM failure rate evolution rule is expressed as follows: the failure rate of the component after junior PM is elevated relative to the failure rate after the last PM, while the failure rate after senior PM is elevated only relative to the failure rate after the last senior PM. As shown in Fig. 1, after junior PM, $\lambda^{j+}_{i,k}$ is higher than $\lambda^{j+}_{i,k-1}$, while after senior PM, $\lambda^{s+}_{i,k+1}$ is higher than $\lambda^{s+}_{i,k-2}$ but lower than $\lambda^{j+}_{i,k}$. Where $\lambda^{j-}_{i,k}$ and $\lambda^{j+}_{i,k}$ are the failure rates before and after the kth junior PM, respectively. $\lambda^{s-}_{i,k}$ and $\lambda^{s+}_{i,k}$ denote the failure rates before and after the kth senior PM, respectively.

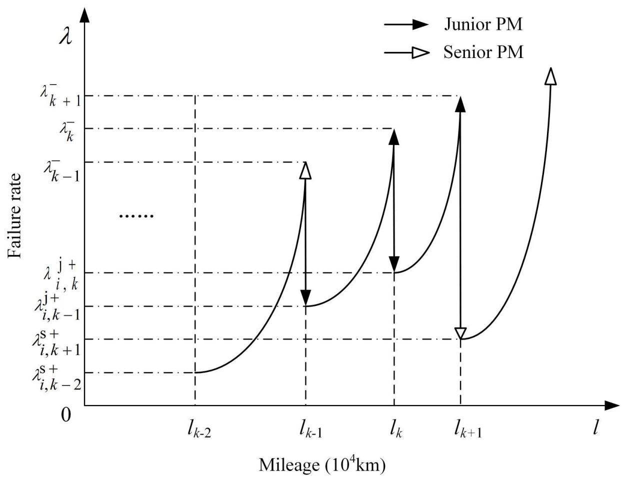

FIGURE 1. Failure rate evolution of BIPM.

The BIPM failure rate evolution rule reflects the influence of maintenance effort on the maintenance effect, which can differentiate the maintenance effect of different maintenance methods by setting a maintenance method selection factor $\varphi_{i,k}$ in the maintenance decision, and it can be defined as:

$$\varphi_{i,k} = \begin{cases} 0 & \text{Junior PM} \\ 1 & \text{Senior PM} \end{cases} \quad (3)$$

Further, the service age regression factor and the failure rate increment factor after maintenance can be expressed as:

$$a_{i,k} = (1 - \varphi_{i,k})a^{j}_{i,k} + \varphi_{i,k}a^{s}_{i,k} \quad (4)$$

$$b_{i,k} = (1 - \varphi_{i,k})b^{j}_{i,k} + \varphi_{i,k}b^{s}_{i,k} \quad (5)$$

where $a^{j}_{i,k}$ and $a^{s}_{i,k}$ are the service age regression factors of the component i after performing junior PM and senior PM, respectively; $b^{j}_{i,k}$ and $b^{s}_{i,k}$ denote the failure rate increment factors of the component i after the execution of junior PM and senior PM, respectively; $0 < a^{s}_{i,k} < a^{j}_{i,k} < 1$ and $1 < b^{s}_{i,k} < b^{j}_{i,k}$.

B. MAINTENANCE STRATEGY MODELING

LM should be reflected not only in the maintenance mode but also in the maintenance decision-making process. In this paper, the cost per unit failure rate change of components is used as the basis for maintenance mode selection, and the WLC management concept of components is reflected through LCC, focusing on the impact of components' OC on maintenance strategy to achieve lean management of maintenance decisions.

1) MAINTENANCE METHOD SELECTION STRATEGY

The LCC cost of a component mainly consists of O&M cost [24], [39], where OC includes expenses related to energy, depreciation, and other auxiliary equipment [40], depending on the service age and operating condition of the component and can be expressed as a linear function of the component deterioration level [41]. In this paper, the trend of components' OC dynamics with deterioration level is reflected in the form of equivalent service age, and combined with the established maintenance strategy of the component, a strategy for selecting the maintenance method of EMUs' component considering OC is proposed. The equivalent service age reflects the dynamic correlation between the deterioration process of a component and its maintenance effectiveness, which is expressed as:

$$\begin{cases} l_{i,k-} = L_{i,k} + a_{i,k-1}L_{i,k-1} \\ l_{i,k+} = a_{i,k}L_{i,k} \end{cases} \tag{6}$$

where $l_{i,k-}$ and $l_{i,k+}$ denote the equivalent service age of component i before and after the kth PM, respectively, and the cumulative equivalent service age after its kth PM can be deduced as:

$$\sum_{j=1}^{k} l_{i,j} = \sum_{j=1}^{k}(\prod_{m=1}^{j} a_{i,m}L_{i,j}) \tag{7}$$

The OC is dynamically related to its operating condition by the accumulated equivalent service age of the component, which is defined as:

$$C_{\text{run}}^{(i)} = c_{\text{run}}^{(i)} \sum_{j=1}^{k} l_{i,j} \tag{8}$$

where $c_{\text{run}}^{(i)}$ is the operating cost per unit mile of the component i. In this paper, based on the correlation between failure rate improvement and O&M cost [42], a cost-efficiency ratio approach is used to select maintenance methods and develop maintenance strategies by measuring the O&M cost per unit failure rate improvement value of the component after PM. According to the hybrid failure rate evolution model, the failure rates $\lambda_{i,k}^{-}$ and $\lambda_{i,k}^{+}$ before and after PM are expressed as:

$$\begin{cases} \lambda_{i,k}^{-} = \lambda_{i,k}(L_{i,k}) = b_{i,k-1}\lambda_{i,k-1}(L_{i,k} + a_{i,k}L_{i,k-1}) \\ \lambda_{i,k}^{+} = \lambda_{i,k+1}(0) = b_{i,k}\lambda_{i,k}(a_{i,k}L_{i,k}) \end{cases} \tag{9}$$

The maintenance effectiveness of a component is quantified by the failure rate improvement value $\Delta\lambda_i$, which is noted as:

$$\Delta\lambda_{i,k} = \lambda_{i,k}^{-} - \lambda_{i,k}^{+} \tag{10}$$

The WLC management concept is incorporated into the maintenance decision model in the form of cost, and the impact of the O&M cost of components on the maintenance strategy is considered. Combining (8), (9), and (10), the traditional maintenance method selection strategy based on maintenance cost is improved, and the improved cost-efficiency ratio is calculated as:

$$\psi_{i,k}^{\text{j}}(l_{i,k}) = \frac{c_{\text{j}}^{(i)} + C_{\text{run}}^{(i)}}{\Delta\lambda_{i,k}^{\text{j}}} = \frac{c_{\text{j}}^{(i)} + C_{\text{run}}^{(i)}}{b_{i,k-1}\lambda_{i,k-1}(L_{i,k} + a_{i,k}L_{i,k-1}) - b_{i,k}^{\text{j}}\lambda_{i,k}(a_{i,k}^{\text{j}}L_{i,k})} \tag{11}$$

$$\psi_{i,k}^{\text{s}}(l_{i,k}) = \frac{c_{\text{s}}^{(i)} + C_{\text{run}}^{(i)}}{\Delta\lambda_{i,k}^{\text{s}}} = \frac{c_{\text{s}}^{(i)} + C_{\text{run}}^{(i)}}{b_{i,k-1}\lambda_{i,k-1}(L_{i,k} + a_{i,k}L_{i,k-1}) - b_{i,k}^{\text{s}}\lambda_{i,k}(a_{i,k}^{\text{s}}L_{i,k})} \tag{12}$$

where $\psi_{i,k}^{\text{j}}(l_{i,k})$ and $\psi_{i,k}^{\text{s}}(l_{i,k})$ are the cost-efficiency ratio of performing junior PM and senior PM for component i at the kth PM cycle, respectively; $\Delta\lambda_{i,k}^{\text{j}}$ and $\Delta\lambda_{i,k}^{\text{s}}$ are the failure rate improvement values of junior PM and senior PM, respectively; and $c_{\text{j}}^{(i)}$ and $c_{\text{s}}^{(i)}$ are the cost of performing junior PM and senior PM, respectively.

The smaller the cost-efficiency ratio means the smaller the O&M cost required to achieve the same maintenance effect, and thus (3) can be expressed as:

$$\varphi_{i,k} = \begin{cases} 0 & \psi_{i,k}^{\text{s}}(l_{i,k}) \geq \psi_{i,k}^{\text{j}}(l_{i,k}) \\ 1 & \psi_{i,k}^{\text{s}}(l_{i,k}) < \psi_{i,k}^{\text{j}}(l_{i,k}) \end{cases} \tag{13}$$

2) TOTAL COST OF MAINTENANCE

Depending on the type of maintenance, the maintenance cost of components is divided into three parts, PM cost $C_{\text{p}}^{(i)}$, CM cost $C_{\text{r}}^{(i)}$ and PR cost $C_{\text{n}}^{(i)}$. The loss of operating revenue from maintenance activities is added to the cost model as downtime loss.

- PM Cost

PM cost $C_{\text{p}}^{(i)}$ includes maintenance costs, fixed maintenance costs, and downtime losses, where fixed maintenance costs consist of the cost of using tools, sites, etc. associated with maintenance activities. It can be defined as:

$$C_{\text{p}}^{(i)} = \sum_{k=1}^{N-1}[c_{\text{p}}^{(i)}(l_{i,k}) + c_{\text{pfix}}^{(i)}(l_{i,k}) + c_{\text{ploss}}^{(i)}(l_{i,k})] \tag{14}$$

PM costs are related to the maintenance method, which can be specifically expressed as:

$$c_{\text{p}}^{(i)}(l_{i,k}) = (1 - \varphi_{i,k})c_{\text{j}}^{(i)} + \varphi_{i,k}c_{\text{s}}^{(i)} \tag{15}$$

$$c_{\text{pfix}}^{(i)}(l_{i,k}) = (1 - \varphi_{i,k})c_{\text{pfix,j}}^{(i)} + \varphi_{i}c_{\text{pfix,s}}^{(i)} \tag{16}$$

$$c_{\text{ploss}}^{(i)}(l_{i,k}) = (1-\varphi_{i,k})c_{\text{ploss,j}}^{(i)} + \varphi_i c_{\text{ploss,s}}^{(i)} \tag{17}$$

where $c_{\text{p}}^{(i)}(l_{i,k})$, $c_{\text{pfix}}^{(i)}(l_{i,k})$ and $c_{\text{ploss}}^{(i)}(l_{i,k})$ are the single preventive maintenance cost, fixed maintenance cost, and downtime losses of component i, respectively; $c_{\text{pfix,j}}^{(i)}$ and $c_{\text{pfix,s}}^{(i)}$ are the single fixed maintenance cost of performing junior PM and senior PM, respectively; $c_{\text{ploss,j}}^{(i)}$ and $c_{\text{ploss,s}}^{(i)}$ are the downtime loss of performing junior PM and senior PM, respectively.

- CM Cost

CM cost $C_{\text{r}}^{(i)}$ includes maintenance costs, fixed maintenance costs, downtime losses, and unexpected costs, where unexpected costs are set based on the relevance of component failures, taking into account the impact of component failures on other components and systems. $C_{\text{r}}^{(i)}$ is related to component failure rates and can be expressed as:

$$C_{\text{r}}^{(i)} = (c_{\text{r}}^{(i)} + c_{\text{rfix}}^{(i)} + c_{\text{rloss}}^{(i)} + c_{\text{racc}}^{(i)}) \sum_{k=1}^{N} \int_{l_{i,k-1}}^{l_{i,k}} \lambda_{i,k}(l)dl \tag{18}$$

where $c_{\text{r}}^{(i)}(l_{i,k})$ is the unit failure maintenance cost, $c_{\text{rfix}}^{(i)}(l_{i,k})$ is the fixed maintenance cost, $c_{\text{rloss}}^{(i)}(l_{i,k})$ is the downtime losses, and $c_{\text{racc}}^{(i)}(l_{i,k})$ is the unexpected cost.

- PR Cost

Components are usually replaced at the end of the maintenance planning period. PR cost $C_{\text{n}}^{(i)}$ includes replacement maintenance costs, downtime losses and fixed maintenance costs, which can be expressed as:

$$C_{\text{n}}^{(i)} = c_{\text{n}}^{(i)} + c_{\text{nfix}}^{(i)} + c_{\text{nloss}}^{(i)} \tag{19}$$

where $c_{\text{n}}^{(i)}$ is the single replacement maintenance cost, $c_{\text{nfix}}^{(i)}$ is the fixed maintenance cost, and $c_{\text{nloss}}^{(i)}$ is the downtime losses. In summary, the total cost of maintenance of EMUs' components over a maintenance planning period is expressed as:

$$C_{\text{unit}}^{(i)} = C_{\text{p}}^{(i)} + C_{\text{r}}^{(i)} + C_{\text{n}}^{(i)} \tag{20}$$

IV. MULTI-COMPONENT SYSTEM WITH MULTI-LEVEL POM STRATEGY

A. POM STRATEGY

In a multi-component serial system, POM leverages the downtime of a component for maintenance to address the maintenance needs of other components in the system that have not yet reached the PM condition but fall within the window of opportunity [8]. The opportunity window is typically determined based on the range of threshold values of PM decision variables such as reliability threshold, remaining service age of the component, and maintenance time [43]. In this paper, the component maintenance mileage window is used as the opportunity window for POM decision-making, taking into account the current practice of mileage-based maintenance of Chinese EMUs, and group maintenance is performed on all components that fall into the opportunity maintenance mileage window (OMMW), denoted as ΔL:

$$\Delta L = l_{\text{p}}^{(i)} - l_{\text{o}}^{(i)} \tag{21}$$

where $l_{\text{p}}^{(i)}$ is the timing of PM execution for component i, and $l_{\text{o}}^{(i)}$ is the timing of POM execution for component i. The specific POM strategy is shown in Fig. 2. When the system runs to PM timing $l_{\text{p}}^{(c)}$ for component c, PM is performed on component c, while POM is performed on component b that has not yet triggered PM timing but falls into its opportunity window $\left[l_{\text{o}}^{(b)}, l_{\text{p}}^{(b)}\right]$ and component a does not perform any maintenance operation because of $l_{\text{p}}^{(c)} \notin \left[l_{\text{o}}^{(a)}, l_{\text{p}}^{(a)}\right]$. In Fig. 2, $R^{(i)}$ is the reliability of component i and $R_{\text{p}}^{(i)}$ is the PM reliability threshold.

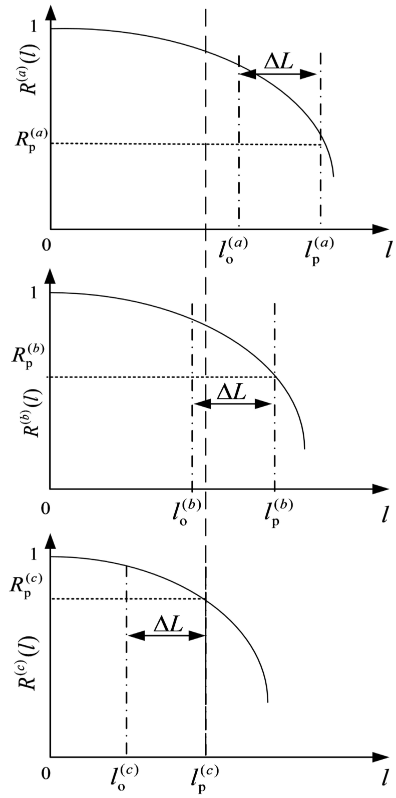

FIGURE 2. OMMW-based POM schematic.

B. MULTI-LEVEL POM STRATEGY

In this paper, a multi-level POM strategy for coordinating system level maintenance plans with total maintenance cost as the optimization objective is proposed based on component maintenance plans [37], with the following decision-making process:

1) Solve for the reliability threshold $R^{(i)}$ of each component that minimizes $C_{\text{unit}}^{(i)}$ and the corresponding maintenance schedule to obtain the PM timing $l_{\text{p}}^{(i)}$ of each component and the maintenance mode selection factor.
2) Assign values to ΔL such that $\Delta L = 2\tau$, τ is the natural number, but since OM cannot advance long-term maintenance plans [44], ΔL should not be taken to be too large and should be 5% and 15% of the component PM cycle [30].

TABLE 1. Deterioration parameters of components and maintenance costs.

(cost unit: CNY ¥)

Component	β_i	θ_i	PM junior $c_{\mathrm{j}}^{(i)}$	PM junior $c_{\mathrm{pfix,j}}^{(i)}$	PM junior $c_{\mathrm{ploss,j}}^{(i)}$	PM senior $c_{\mathrm{s}}^{(i)}$	PM senior $c_{\mathrm{pfix,s}}^{(i)}$	PM senior $c_{\mathrm{ploss,s}}^{(i)}$	CM $c_{\mathrm{r}}^{(i)}$	CM $c_{\mathrm{rfix}}^{(i)}$	CM $c_{\mathrm{rloss}}^{(i)}$	PR $c_{\mathrm{racc}}^{(i)}$	PR $c_{\mathrm{n}}^{(i)}$	PR $c_{\mathrm{nfix}}^{(i)}$	PR $c_{\mathrm{nloss}}^{(i)}$
1	2.9000	84.2400	400	350	400	650	500	600	3,000	1,000	1,000	2,500	500	300	500
2	2.8061	81.7201	650			1,200			4,500			3,000	700		
3	3.7247	88.5127	450			900			3,500			2,000	600		
4	3.3000	75.0000	350			580			2,000			1,500	400		

TABLE 2. PM optimization results for each component with different values of $c_{\mathrm{run}}^{(i)}$.

(mileage unit: 10^4km, cost unit: CNY ¥)

Component	$c_{\mathrm{run}}^{(i)}$	Maintenance interval sequence	Maintenance mode sequence	$R^{(i)}$	$C_{\mathrm{p}}^{(i)}$	$C_{\mathrm{r}}^{(i)}$	$C_{\mathrm{unit}}^{(i)}$
1	0	50-40-32-22-16-12-30-24	0-0-0-0-0-1-0-0	0.80	9,800	15,146	26,246
	100	46-36-28-20-14-26-22-16-18	0-0-0-0-1-0-0-1-0	0.85	11,550	12,251	25,101
	200	50-40-30-20-30-26-22	0-0-0-1-0-1-0	0.81	9,250	13,152	23,702
	300	52-42-32-36-30-26	0-0-1-0-1-1	0.78	8,700	13,458	23,458
2	0	52-42-32-24-16-12-8-20	0-0-0-0-0-0-1-0	0.75	12,100	25,117	38,717
	100	44-36-28-20-14-10-24-20-14-18	0-0-0-0-0-1-0-0-1-0	0.84	15,800	19,039	36,339
	200	46-36-28-20-14-26-22-16-18	0-0-0-0-1-0-0-1-0	0.83	14,400	18,110	34,010
	300	54-44-34-24-36-30	0-0-0-1-0-0	0.73	9,300	21,332	32,132
3	0	50-42-32-26-18-14-10-6-26	0-0-0-0-0-0-0-1-0	0.89	11,600	9,146	22,146
	100	50-42-32-26-18-14-10-26	0-0-0-0-0-0-1-0	0.89	10,400	8,504	20,304
	200	52-44-34-26-20-14-28	0-0-0-0-0-1-0	0.87	9,200	8,722	19,322
	300	50-42-32-26-18-30-26	0-0-0-0-1-0-0	0.89	9,200	7,253	17,853
4	0	48-40-32-24-16-12-8-26-22	0-0-0-0-0-0-1-0-0	0.79	10,480	13,151	24,831
	100	46-38-30-22-16-28-24-16	0-0-0-0-1-0-0-1	0.82	9,960	10,423	21,583
	200	48-40-30-22-30-26-22	0-0-0-1-0-1-0	0.79	8,860	10,897	20,957
	300	54-44-32-38-30-26	0-0-1-1-1-1	0.73	8,920	11,863	21,983

3) Assuming that component c is the first to meet the preventive maintenance condition, i.e. $l_{\mathrm{p}}^{(c)} = \min l_{\mathrm{p}}^{(i)}$, then $l_{\mathrm{p}}^{(c)}$ is used as the system POM trigger timing to determine whether it falls within the OMMW of other component $\{b\}$. If $l_{\mathrm{p}}^{(c)} \in \left[l_{\mathrm{o}}^{(b)}, l_{\mathrm{p}}^{(b)}\right]$, then component $\{b\}$ is advanced from $l_{\mathrm{p}}^{(b)}$ to $l_{\mathrm{p}}^{(c)}$ for PM, otherwise, the maintenance schedule of component $\{b\}$ is maintained.

Components keep their maintenance levels in the maintenance plan constant during the POM process, but their POM fixed cost changes with the POM level. When components in the POM undergo senior maintenance, it is referred to as a senior POM; when junior maintenance is performed on all components in the POM, it is a junior POM. Let the maintenance mode decision factor for the qth POM be χ_q, and it can be denoted as:

$$\chi_q = \begin{cases} 0 & \text{junior POM, } \psi_q^{(1)} \cup \psi_q^{(2)} \cup \cdots \cup \psi_q^{(m)} = 0 \\ 1 & \text{senior POM, } \psi_q^{(1)} \cup \psi_q^{(2)} \cup \cdots \cup \psi_q^{(m)} = 1 \end{cases} \tag{22}$$

a) The following discussion addresses the maintenance cost sub-case for the component i at the qth POM. $\chi_q = 0$ indicates that all components within the OMMW undergo junior PM and the component i can save PM fixed costs, and its POM cost is expressed as:

$$c_{\mathrm{o,j}}^{(i)} = c_{\mathrm{j}}^{(i)} \tag{23}$$

b) $\chi_q = 1$ indicates that there are components within OMMW undergoing senior PM. In this case, if the POM trigger condition is senior PM, the PM fixed cost of the component i can be saved; if the senior POM trigger condition is junior PM, it means that one or more components in the opportunity group perform senior PM. When the component i undergoes junior PM, its POM cost is expressed as:

$$c_{\mathrm{o,j}}^{(i)} = c_{\mathrm{j}}^{(i)} + \left(c_{\mathrm{pfix,s}}^{(i)} + c_{\mathrm{ploss,s}}^{(i)}\right) - \left(c_{\mathrm{pfix,j}}^{(i)} + c_{\mathrm{ploss,j}}^{(i)}\right) \tag{24}$$

When the component i undergoes senior PM, and it is decisive for the system POM level, its PM fixed cost cannot be saved, and it can be expressed as:

$$c_{\mathrm{o,s}}^{(i)} = c_{s}^{(i)} + c_{\mathrm{pfix,s}}^{(i)} + c_{\mathrm{ploss,s}}^{(i)} \tag{25}$$

Otherwise, it can save PM fixed costs and can be expressed as:

$$c_{\mathrm{o,s}}^{(i)} = c_{s}^{(i)} \tag{26}$$

Therefore, the POM cost of the component i over the entire planning period is expressed as:

$$C_{\mathrm{POM}}^{(i)} = \mu_{\mathrm{o,j}}^{(i)} c_{\mathrm{o,,j}}^{(i)} + \mu_{\mathrm{o,s}}^{(i)} c_{\mathrm{o,s}}^{(i)} + \mu_{\mathrm{p,j}}^{(i)} \left(c_{\mathrm{j}}^{(i)} + c_{\mathrm{pfix,j}}^{(i)} + c_{\mathrm{ploss,j}}^{(i)}\right) + \mu_{\mathrm{p,s}}^{(i)} \left(c_{s}^{(i)} + c_{\mathrm{pfix,s}}^{(i)} + c_{\mathrm{ploss,s}}^{(i)}\right) \tag{27}$$

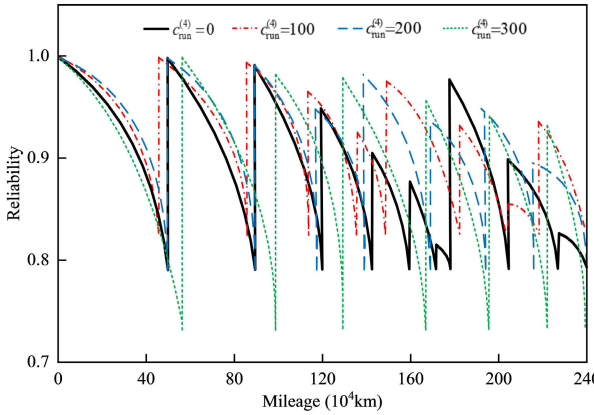

FIGURE 3. Reliability evolution of component 4 with different $c_{run}^{(4)}$.

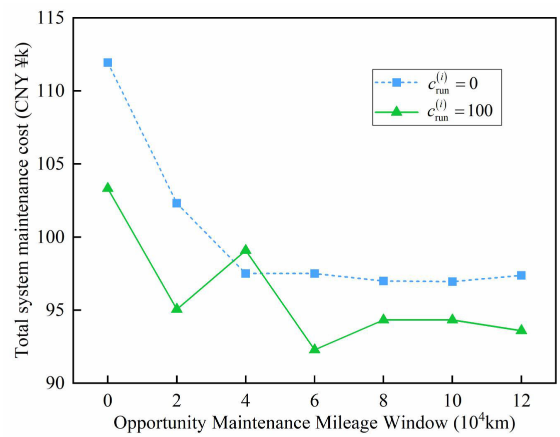

FIGURE 4. Comparison of the optimization results of two POM strategies.

where $\mu_{o,j}^{(i)}$ and $\mu_{o,s}^{(i)}$ are the number of junior POM and senior POM, respectively; $\mu_{p,j}^{(i)}$ and $\mu_{p,s}^{(i)}$ are the number of junior PM and senior PM, respectively; $c_{o,j}^{(i)}$ and $c_{o,s}^{(i)}$ are the cost of junior POM and senior POM, respectively.

4) Update the component maintenance plan with reliability as a constraint after POM, and repeat process 3 until all components operate mileage beyond the maintenance planning period, at this time, the total cost of system maintenance is expressed as:

$$C_{sys} = \sum_{i=1}^{m} C_{POM}^{(i)} + \sum_{i=1}^{m} C_{r}^{(i)} + \sum_{i=1}^{m} C_{n}^{(i)} \tag{28}$$

5) It returns to process 2 for the next cycle of calculation until the specified OMMW range is exceeded, so as to obtain C_{sys} when ΔL takes different values. The POM plan is developed for each component at the system level with C_{sys} minimization as the optimization objective.

V. EXAMPLE ANALYSIS

The effectiveness and feasibility of the proposed POM strategy are verified step by step from single to multiple components through a series of scenario analyses involving both component level and system level analysis of four

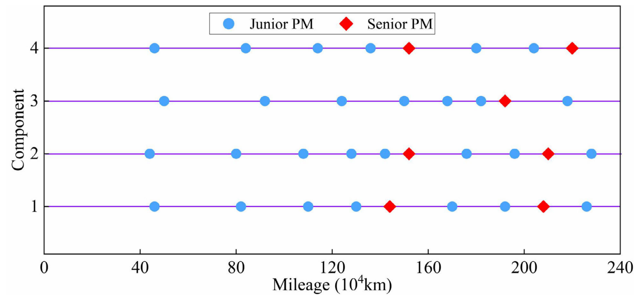

FIGURE 5. Schematic diagram of multi-component PM plan.

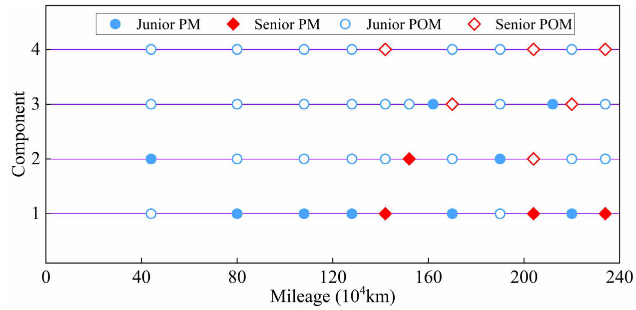

FIGURE 6. Schematic diagram of multi-component POM plan.

economically relevant components of an electromechanical system of EMUs. In Section V-A, the performance degradation and maintenance costs of the components are illustrated. In Section V-B, the impact of considering OC on the maintenance economy in the component PM strategy is discussed comparatively, and the effectiveness of the proposed PM strategy is verified by sensitivity analysis. Finally, in Section V-C, the multi-component POM strategy is further analyzed and studied based on the comparative results in Section V-B.

A. PARAMETER SETTING

The deterioration characteristics and PM strategies of 4 tandem components of an electromechanical system of EMUs were selected for case analysis. Factors associated with decreased service age for junior PM and senior PM of the components are $a_j = k/(6k+7)$ and $a_s = k/(7k+7)$, and factors increasing failure rate are $b_j = (12k+1)/(8k+1)$ and $b_s = (12k+1)/(11k+1)$. The deterioration parameters and maintenance costs of each component are set as shown in Table 1, where the deterioration parameters refer to the data fitting results of literature [27], [28]. In addition, based on the availability and safety requirements of EMUs components, the minimum reliability threshold of the component is set to $R_{min} = 0.70$ [44], i.e., when the reliability of the component reaches R_{min}, it undergoes PM immediately.

B. OPTIMIZATION RESULTS AND SENSITIVITY ANALYSIS OF PM STRATEGY FOR COMPONENT LEVEL

To verify the effectiveness of the proposed component PM strategy in Section III-B, different values of $c_{run}^{(i)}$ are taken for the components, where $c_{run}^{(i)} = 0$ represents the OC not

TABLE 3. Comparison of optimization results of multi-component PM and POM.

(mileage unit: 10^4km, cost unit: CNY ¥)

Component	PM Maintenance interval sequence	$\mu_{p,j}$	$\mu_{p,s}$	$C_p^{(i)}$	$C_r^{(i)}$	$\sum C_{unit}$	POM Maintenance interval sequence	$\mu_{p,j}$	$\mu_{p,s}$	$\mu_{o,j}$	$\mu_{o,s}$	$C_{POM}^{(i)}$	$C_r^{(i)}$	$\sum C_{POM}$
1	46-82-110-130-144-170-192-208-226	7	2	11,550	12,251	103,327	44-80-108-128-142-170-190-204-220-234	5	3	2	0	10,300	13,394	92,282
2	44-80-108-128-142-152-176-196-210-228	8	2	15,800	19,039		44-80-108-128-142-152-170-190-204-220-234	2	1	7	1	10,850	20,315	
3	50-92-124-150-168-182-192-218	7	1	10,400	8,504		44-80-108-128-142-152-162-170-190-212-220-234	2	0	8	2	10,000	7,701	
4	46-84-114-136-152-180-204-220	6	2	9,060	10,423		44-80-108-128-142-170-190-204-220-234	0	0	7	3	4,190	10,132	

being taken into account. The corresponding PM strategy optimization results are summarized in Table 2. The results show that, under the premise of ensuring the reliable operation of the components, the influence of OC on the PM model can increase the number of senior PM in the maintenance plan or advance the timing of senior PM to ensure that the components can obtain better maintenance results in the PM stage. Accordingly, the CM cost of components is reduced, leading to savings in the total maintenance cost. Using this method, the $C_{unit}^{(i)}$ of each component ($i = \{1, 2, 3, 4\}$) exhibited different degrees of reduction; the lowest reduction was $\{4.36\%, 6.14\%, 8.32\%, 11.47\%\}$ and the highest reduction could reach $\{10.62\%, 17.01\%, 19.38\%, 15.6\%\}$, especially in cases where the reliability threshold is similar after optimization, the cost-saving effect is more obvious. In this respect, component 3 further demonstrated that a PM strategy based on O&M costs is more economically efficient than a strategy considering only maintenance costs.

Fig. 3 shows the maintenance effect of PM for component 4 when taking different $c_{run}^{(4)}$ values in terms of the reliability evolution process. It was found that among the eight PM of $c_{run}^{(4)} = 0$, the senior PM was performed only when its reliability after the 6th maintenance ($R = 0.82$) reached a value close to its PM reliability threshold (0.79). Accordingly, its maintenance is less effective and requires more maintenance interventions. In contrast, the three PM strategies considering OC all used multiple senior PM activities and early intervention to keep the post-maintenance reliability relatively high, thus achieving cost savings by reducing the number of PM events and failure rates. Meanwhile, as $c_{run}^{(4)}$ was increased, the number of senior PM activities increased, and at $c_{run}^{(4)} = 300$, senior PM was performed four times, and it can be proved that if $c_{run}^{(4)}$ continues to increase, the number of senior PM activities will continue to increase until all PM activities are performed as senior PM, since the maintenance mode selection strategy for the component within a PM cycle depends on both O&M cost and failure rate improvement value. Once the component operating mileage reaches a certain level, OC will exceed the maintenance cost. At this point, the maintenance mode selection strategy becomes primarily determined by the failure rate improvement value. As a result, all PM activities adopt the senior PM approach, as it offers better failure rate improvement compared to junior PM.

C. SYSTEM LEVEL POM STRATEGY OPTIMIZATION RESULTS

The optimization results in Section V-B are used to optimize the two POM strategies (strategy 1 and strategy 2), taking $\Delta L = \{2, 4, 6, 8, 10, 12\}$ for $c_{run}^{(i)} = 0$ and $c_{run}^{(i)} = 100$, respectively, as shown in Fig. 4. For Strategy 1, the minimum system maintenance total cost value was achieved at $\Delta L = 10$ and amounts to 96,952 CNY (RMB), while strategy 2 attained the minimum system maintenance total cost value of 92,282 CNY at $\Delta L = 6$. Strategy 2 saved 4.82% compared to the optimal maintenance cost of strategy 1, indicating a smaller but still significant cost reduction. However, as shown in Table 2, the overall reliability of each component in strategy 1 was lower than in strategy 2, leading to a lower system reliability of strategy 1 than strategy 2, i.e., strategy 2 makes the system more reliable with a lower maintenance cost. Meanwhile, according to the PM cycle of each component and the requirement that the value of OMMW should not exceed 15% of the PM cycle of the component [30], the OMMW range of EMUs' components should not exceed 80,000 km. Accordingly, strategy 1 is deemed unrealistic, making strategy 2 the more reasonable and feasible option in terms of rationality, reliability, and cost-effectiveness.

To further analyze the effectiveness of the proposed strategy, the component level PM strategy with $c_{run}^{(i)} = 100$ was compared with the system level POM strategy with $\Delta L = 6$. The maintenance plans for each component are shown in Fig. 5 and Fig. 6, and the results are shown in Table 3. Compared with the PM strategy, the POM strategy achieved the purpose of reducing the system maintenance cost by adjusting the timing of component maintenance within the window of opportunity and performing maintenance on components in groups. All four components in the system achieved cost savings in PM by leveraging the benefits of opportunity grouping. Moreover, the greater the number of POM instances, the higher the savings in PM costs. Taking component 4 as an example, even though its number of maintenance instances increased from 8 to 10, all of its maintenance methods involved POM. Consequently, Component 4 achieved the most substantial reduction in PM costs, with a significant decrease of 53.77%. Conversely, Component 3 experienced a smaller decrease in PM costs as its maintenance instances increased by 4. In addition, the POM strategy could reduce the risk of component failure by advancing its maintenance timing, but the increase in the number of POM also increased the risk of component failure. Accordingly, the CM costs of all four components exhibited different degrees of change. Finally, through the POM strategy, the number of system downtime was reduced from 35 to 13, and the total system maintenance cost was reduced by 11,045 CNY (10.69%), achieving the goal of optimizing the system maintenance cost while ensuring the reliable operation of the system.

VI. CONCLUSION

Aiming at the long-term maintenance waste problem in the field of EMUs maintenance, and based on the concept of lean management, this paper proposed a multi-level POM strategy for EMUs maintenance, focusing on maintenance economy and utilizing LLC as the basis for decision-making. The strategy integrated various aspects such as maintenance mode, maintenance cost, and maintenance relevance to implement lean maintenance for the multi-component serial system of EMUs. A single-component multi-level PM decision model was established, considering the interactions between O&M activities and dynamically correlating OC with the equivalent service age. Based on this, a multi-level POM optimization model was further developed for the EMUs' multi-component system, considering overall system availability and economy in the long term.

Our results demonstrated that by establishing a dynamic correlation between OC and the equivalent service age, we could accurately reflect the component's operating condition as its deterioration level and maintenance effectiveness changed. As the equivalent service age increased, the component's PM strategy adopted more aggressive and effective maintenance methods, resulting in greater cost-effectiveness than the PM strategy that did not consider OC. This economic advantage was reflected at the component level, where the cost advantage of the LCC-based PM strategy accumulated, and at the system level, where the POM strategy effectively reduced system downtime and optimized overall maintenance costs.

Under the guidance of the lean management concept, LM was identified as the long-term development direction in equipment maintenance. This paper focused on the BIPM strategy for EMUs' components, which only partially reflected the essence of lean maintenance. Future work will aim to improve the multi-level PM strategy for EMUs' components by incorporating real-time inspection data and historical maintenance data to develop multi-state and multi-level POM strategies. This approach will further reduce unnecessary waste in the maintenance process through more accurate maintenance plans and measures. Additionally, other factors in component WLC management should be considered to assess their impact on the maintenance strategy. From a long-term strategic perspective, a maintenance strategy will be developed specifically for EMUs' multi-component system.

REFERENCES

[1] R. P. Nicolai and R. Dekker, "Optimal maintenance of multi-component systems: A review," in *Complex System Maintenance Handbook*. London, U.K.: Springer, 2006, pp. 263–286.

[2] H. Zhao, Z. Huang, and Y. Mei, "High-speed EMU TCMS design and LCC technology research," *Engineering*, vol. 3, no. 1, pp. 122–129, Feb. 2017.

[3] B. Lin, J. Wu, R. Lin, J. Wang, H. Wang, and X. Zhang, "Optimization of high-level preventive maintenance scheduling for high-speed trains," *Rel. Eng. Syst. Saf.*, vol. 183, pp. 261–275, Mar. 2019.

[4] W. H. Zhang, Q. F. Li, and D. L. Song, "Thoughts on health management and condition-based maintenance of rolling stocks," *China Mech. Eng.*, vol. 32, no. 4, pp. 379–389, Apr. 2021.

[5] C. Davies and R. M. Greenough. (2010). *Measuring the Effectiveness of Lean Thinking Activities Within Maintenance*. [Online]. Available: http://www.plant-maintenance.com/articles/Lean_Maintenance.pdf

[6] S. Mostafa, S.-H. Lee, J. Dumrak, N. Chileshe, and H. Soltan, "Lean thinking for a maintenance process," *Prod. Manuf. Res.*, vol. 3, no. 1, pp. 236–272, Jan. 2015.

[7] Q. Zhang, Z. Fang, and J. Cai, "Preventive replacement policies with multiple missions and maintenance triggering approaches," *Rel. Eng. Syst. Saf.*, vol. 213, Sep. 2021, Art. no. 107691.

[8] J. Chen, M. Q.-H. Meng, and M. J. Zuo, "Selective maintenance optimization for multi-state systems," in *Proc. Eng. Solutions Next Millennium, IEEE Can. Conf. Electr. Comput. Eng.*, May 1999, pp. 1477–1482.

[9] Y. Zhou, T. R. Lin, Y. Sun, Y. Bian, and L. Ma, "An effective approach to reducing strategy space for maintenance optimisation of multistate series-parallel systems," *Rel. Eng. Syst. Saf.*, vol. 138, pp. 40–53, Jun. 2015.

[10] J. Hu, A. Xu, B. Li, and H. Liao, "Condition-based maintenance planning for multi-state systems under time-varying environmental conditions," *Comput. Ind. Eng.*, vol. 158, Aug. 2021, Art. no. 107380.

[11] Y. Cao, J. Luo, and W. Dong, "Optimization of condition-based maintenance for multi-state deterioration systems under random shock," *Appl. Math. Model.*, vol. 115, pp. 80–99, Mar. 2023.

[12] Y. Chen, Y. Liu, and T. Jiang, "Optimal maintenance strategy for multi-state systems with single maintenance capacity and arbitrarily distributed maintenance time," *Rel. Eng. Syst. Saf.*, vol. 211, Jul. 2021, Art. no. 107576.

[13] A. F. Shahraki, O. P. Yadav, and C. Vogiatzis, "Selective maintenance optimization for multi-state systems considering stochastically dependent components and stochastic imperfect maintenance actions," *Rel. Eng. Syst. Saf.*, vol. 196, Apr. 2020, Art. no. 106738.

[14] C. Duan, C. Deng, and B. Wang, "Multi-phase sequential preventive maintenance scheduling for deteriorating repairable systems," *J. Intell. Manuf.*, vol. 30, no. 4, pp. 1779–1793, Apr. 2019.

[15] X. Zhou, Y. Li, L. Xi, and J. Lee, "Multi-phase preventive maintenance policy for leased equipment," *Int. J. Prod. Res.*, vol. 53, no. 15, pp. 4528–4537, Aug. 2015.

[16] A. Khatab and E.-H. Aghezzaf, "Selective maintenance optimization when quality of imperfect maintenance actions are stochastic," *Rel. Eng. Syst. Saf.*, vol. 150, pp. 182–189, Jun. 2016.

[17] Z. Su, A. Jamshidi, A. Núñez, S. Baldi, and B. De Schutter, "Multi-level condition-based maintenance planning for railway infrastructures—A scenario-based chance-constrained approach," *Transp. Res. C, Emerg. Technol.*, vol. 84, pp. 92–123, Nov. 2017.

[18] C. J. Fourie and T. G. Tendayi, "A decision-making framework for effective maintenance management using life cycle costing (LCC) in a rolling stock environment," *South Afr. J. Ind. Eng.*, vol. 27, no. 4, pp. 142–152, Dec. 2016.

[19] M. El-Naggar, A. Sayed, M. Elshahed, and M. El-Shimy, "Optimal maintenance strategy of wind turbine subassemblies to improve the overall availability," *Ain Shams Eng. J.*, vol. 14, no. 10, Oct. 2023, Art. no. 102177.

[20] R. Martin, I. Lazakis, S. Barbouchi, and L. Johanning, "Sensitivity analysis of offshore wind farm operation and maintenance cost and availability," *Renew. Energy*, vol. 85, pp. 1226–1236, Jan. 2016.

[21] X. Li, D. Ouelhadj, X. Song, D. Jones, G. Wall, K. E. Howell, P. Igwe, S. Martin, D. Song, and E. Pertin, "A decision support system for strategic maintenance planning in offshore wind farms," *Renew. Energy*, vol. 99, pp. 784–799, Dec. 2016.

[22] P. Bangalore and M. Patriksson, "Analysis of SCADA data for early fault detection, with application to the maintenance management of wind turbines," *Renew. Energy*, vol. 115, pp. 521–532, Jan. 2018.

[23] J. Mcmorland, C. Flannigan, J. Carroll, M. Collu, D. Mcmillan, W. Leithead, and A. Coraddu, "A review of operations and maintenance modelling with considerations for novel wind turbine concepts," *Renew. Sustain. Energy Rev.*, vol. 165, Sep. 2022, Art. no. 112581.

[24] H. K. Jun and J. H. Kim, "Life cycle cost modeling for railway vehicle," in *Proc. Int. Conf. Electr. Mach. Syst. (ICEMS)*, Oct. 2007, pp. 1989–1994.

[25] R. P. Nicolai and R. Dekker, "A review of multi-component maintenance models," *Econom. Inst. Repr.*, pp. 289–296, 2007. [Online]. Available: https://www.researchgate.net/publication/46434158

[26] J. R. Dirnberger and C. P. L. Barkan, "Lean railroading for improving railroad classification terminal performance: Bottleneck management methods," *Transp. Res. Rec., J. Transp. Res. Board*, vol. 1995, no. 1, pp. 52–61, Jan. 2007.

[27] G. Liu, S. Chen, H. Jin, and S. Liu, "Optimum opportunistic maintenance schedule incorporating delay time theory with imperfect maintenance," *Rel. Eng. Syst. Saf.*, vol. 213, Sep. 2021, Art. no. 107668.

[28] X. Zhou and X. Ning, "Maintenance gravity window based opportunistic maintenance scheduling for multi-unit serial systems with stochastic production waits," *Rel. Eng. Syst. Saf.*, vol. 215, Nov. 2021, Art. no. 107828.

[29] M. Li, X. Jiang, and R. R. Negenborn, "Opportunistic maintenance for offshore wind farms with multiple-component age-based preventive dispatch," *Ocean Eng.*, vol. 231, Jul. 2021, Art. no. 109062.

[30] A. Erguido, A. C. Márquez, E. Castellano, J. L. Flores, and J. F. G. Fernández, "Reliability-based advanced maintenance modelling to enhance rolling stock manufacturers' objectives," *Comput. Ind. Eng.*, vol. 144, Jun. 2020, Art. no. 106436.

[31] B. Lu and X. Zhou, "Opportunistic preventive maintenance scheduling for serial–parallel multistage manufacturing systems with multiple streams of deterioration," *Rel. Eng. Syst. Saf.*, vol. 168, pp. 116–127, Dec. 2017.

[32] R. Mena, P. Viveros, E. Zio, and S. Campos, "An optimization framework for opportunistic planning of preventive maintenance activities," *Rel. Eng. Syst. Saf.*, vol. 215, Nov. 2021, Art. no. 107801.

[33] H. Shi, J. Zhang, E. Zio, and X. Zhao, "Opportunistic maintenance policies for multi-machine production systems with quality and availability improvement," *Rel. Eng. Syst. Saf.*, vol. 234, Jun. 2023, Art. no. 109183.

[34] H. C. Vu, P. Do, M. Fouladirad, and A. Grall, "Dynamic opportunistic maintenance planning for multi-component redundant systems with various types of opportunities," *Rel. Eng. Syst. Saf.*, vol. 198, Jun. 2020, Art. no. 106854.

[35] B. R. Sarker and T. I. Faiz, "Minimizing maintenance cost for offshore wind turbines following multi-level opportunistic preventive strategy," *Renew. Energy*, vol. 85, pp. 104–113, Jan. 2016.

[36] D.-H. Dinh, P. Do, and B. Iung, "Multi-level opportunistic predictive maintenance for multi-component systems with economic dependence and assembly/disassembly impacts," *Rel. Eng. Syst. Saf.*, vol. 217, Jan. 2022, Art. no. 108055.

[37] G. Liu, S. Chen, T. Ho, X. Ran, B. Mao, and Z. Lan, "Optimum opportunistic maintenance schedule over variable horizons considering multi-stage degradation and dynamic strategy," *Rel. Eng. Syst. Saf.*, vol. 225, Sep. 2022, Art. no. 108572.

[38] Y. Wang, Y. Gao, X. Yu, I. A. Hansen, and J. Miao, "Optimization models for high-speed train unit routing problems," *Comput. Ind. Eng.*, vol. 127, pp. 1273–1281, Jan. 2019.

[39] S. N. Kamble and B. Rajiv, "Machine health monitoring with life cycle cost analysis by condition monitoring," *Mater. Today, Proc.*, vol. 52, pp. 893–897, Jan. 2022.

[40] R. Yaping, Z. Xingchen, L. Lu, C. Yao, and S. Yiwei, "Life cycle cost analysis of urban rail transit vehicle," in *Proc. 8th Int. Conf. Measuring Technol. Mechatronics Autom. (ICMTMA)*, Mar. 2016, pp. 375–378.

[41] B. Liu, S. Wu, M. Xie, and W. Kuo, "A condition-based maintenance policy for degrading systems with age- and state-dependent operating cost," *Eur. J. Oper. Res.*, vol. 263, no. 3, pp. 879–887, Dec. 2017.

[42] H. Dui, S. Si, and R. C. M. Yam, "A cost-based integrated importance measure of system components for preventive maintenance," *Rel. Eng. Syst. Saf.*, vol. 168, pp. 98–104, Dec. 2017.

[43] X. Zhou and K. Shi, "Capacity failure rate based opportunistic maintenance modeling for series-parallel multi-station manufacturing systems," *Rel. Eng. Syst. Saf.*, vol. 181, pp. 46–53, Jan. 2019.

[44] É. Thomas, É. Levrat, and B. Iung, "Overview on opportunistic maintenance," *IFAC Proc. Volumes*, vol. 41, no. 3, pp. 245–250, 2008.

JING LI received the B.S. degree in computer information management from Xidian University, Xi'an, China, and the M.S. degree in mechanical and electrical engineering from Lanzhou Jiaotong University, Lanzhou, China, where she is currently pursuing the Ph.D. degree in vehicle engineering. Her current research interests include rail vehicle reliability analysis and preventive maintenance strategy research.

HONG WANG received the B.S. degree in railroad vehicles and the M.S. degree in rolling stock from the Lanzhou Railway Institute, Lanzhou, China. He is currently a Professor with the Department of Vehicle Engineering, Lanzhou Jiaotong University, Lanzhou. In 2018, he served as a member of the 7th Vehicle Committee of the Chinese Railway Society. His research interests include theoretical and experimental research on fatigue strength reliability design of rolling stock and mechanical components, and research on preventive maintenance strategies for rail vehicle equipment.

LÜ XIONG received the B.S. degree in mechanical design and manufacturing and automation from Xi'an Technological University, Xi'an, China, and the M.S. and Ph.D. degrees in vehicle engineering from Lanzhou Jiaotong University. His research interests include vehicle component reliability and preventive maintenance strategies.

YONG HE received the B.S. degree in vehicle engineering from Dalian Jiaotong University, Dalian, China, and the M.S. and Ph.D. degrees in vehicle engineering from Lanzhou Jiaotong University, Lanzhou, China. His research interests include maintenance decision, fault diagnosis, and reliability engineering.

CHENGSHAN YI received the B.S. degree in transportation from Beihua University, Jilin, China, and the M.S. degree in vehicle engineering from Lanzhou Jiaotong University, Lanzhou, China, where he is currently pursuing the Ph.D. degree in vehicle engineering. His current research interests include vehicle component reliability and preventive maintenance strategies.