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A Selective Maintenance Decision Method for Phased-Mission Systems Considering the Consequences of Failures

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Owing to the hierarchical configuration, mission phasing, and diverse failure modes inherent in phased-mission systems (PMS), the consequences of failures occurring during mission execution exhibit considerable variability. This paper addresses the complexities of maintenance decision-making arising from mission requirements and the differentiated consequences of failures under constrained maintenance resources. A selective maintenance decision method that incorporates failure consequence considerations is proposed. Initially, a novel severity index for failure consequences is developed, encompassing four dimensions: safety, environmental impact, usability, and economic factors, thereby facilitating precise quantification of failure impacts. Subsequently, a selective maintenance decision model is formulated based on the system's current state, integrating constraints such as mission cycles within each phase, maintenance opportunity windows, resource limitations, and the severity hierarchy of failure consequences. The primary objective is to optimize the mission reliability of PMS, thus informing the system maintenance strategy. Finally, a numerical case study is conducted to validate the feasibility and efficacy of the proposed approach.

Keywords: Selective maintenance, phased-mission system, failure consequence, mission reliability.

1. Introduction

Phased-mission systems (PMSs) are extensively employed across domains such as aerospace, intelligent manufacturing, and engineering construction. From a structural hierarchy standpoint, a PMS is composed of nested subsystems and components with different functions, each performing distinct functions that collectively support the overall system operation. In terms of mission phasing, the system is required to perform a series of consecutive missions, with maintenance activities conducted during the intervals separating these missions. Regarding failure diversity, the variation in operating environments, workload intensities, and service demands across different mission phases results in complex and heterogeneous failure modes within the PMS. These characteristics substantially complicate the processes of failure prediction, identification, and maintenance within PMSs, potentially impairing the successful completion of missions and increasing the risk of safety incidents, environmental harm, or significant economic losses. Consequently, it is imperative to perform a risk assessment on the failure modes of the PMS during the maintenance time window and to develop a selective maintenance decision model.

In recent years, priority-based selective maintenance strategies have been continuously advanced in theoretical and practical research across multiple fields. In terms of considering maintenance priority indicators, Relkar, A. S. identified key equipment by means of FMEA and failure occurrence, in combination with influencing factors such as production and safety. Zhou N. et al. quantified power grid losses caused by failures and established a cost-benefit oriented maintenance ranking method. Powichrowska, O. determined equipment maintenance priorities based on energy consumption, machine criticality and its impacts on the supply chain. Rabie K. developed a weighted multi-criteria risk priority number model to integrate multiple indicators for determining equipment maintenance priorities. Yang, Z. et al. proposed an OLE-centered maintenance priority strategy, assigning priorities according to equipment downtime intervals and mean recovery time. In terms of selective maintenance decision-making models, Cao, H. et al. synthesized the maintenance, structural and reliability importance of equipment, and proposed a selective maintenance model based on the maintenance priority index. Wang, X. et al. analyzed the deterioration factors of equipment status, divided maintenance priorities through deterioration state prediction, and constructed a scheduling model for multi-equipment maintenance. Sun, Y. correlated energy loss and environmental impact with system degradation, incorporated them into the maintenance priority determination of multi-state systems, and built a selective maintenance decision-making model.

These studies have broadened the scope of factors considered in selective maintenance; however, certain limitations remain. Specifically, they do not provide a systematic framework for analyzing and quantifying failure consequences. Moreover, the current decision models exhibit limited adaptability to PMSs and do not adequately incorporate the multi-stage dynamic nature of such systems. Consequently, this undermines the rigor and scientific validity of maintenance decision-making processes.

In response to the aforementioned challenges, this paper proposes a selective maintenance decision-making method for PMSs that incorporates failure consequences. By considering the constraints imposed by different mission phases and the dynamic operational status of PMSs, this method quantitatively assesses the failure consequences from four dimensions, prioritizes maintenance activities accordingly, and develops an optimized selective maintenance decision model. The main innovative points are as follows:

(i) A quantitative method is proposed for the failure consequence severity indicator, which considers the interrelationships among various failure modes and enables a multidimensional quantitative analysis of the failure consequence severity indicators across four dimensions: safety, environmental impact, usability, and economic factors.

(ii) A refined selective maintenance decision model, tailored to the dynamic characteristics of PMSs, is developed. Maintenance priorities are determined according to failure consequences, with the objective of maximizing mission reliability. Considering the varying dynamic constraints of PMSs throughout different mission phases, the optimal maintenance subset is identified.

2. Quantitative Method for Failure Consequence Severity

A quantitative method is proposed to assess the safety, environmental, usability, and economic impacts resulting from failures. This method enables precise quantification of the severity of failure consequences associated with distinct failure modes and ultimately facilitates the prioritization of maintenance activities for various components.

(i) Safety Consequence (SC)

The safety consequence involves the effects on personnel safety resulting from a certain failure mode. The Safety Risk Priority (SRP) metric serves as a metric to quantify these safety-related outcomes.

SRP incorporates several critical factors: the safety severity (S) of a failure mode, which quantifies the potential impact on personnel safety resulting from the failure; the probability of occurrence (Q), indicating the likelihood of a specific failure mode will manifest within a component during the mission phase; and the detectability (D) of safety-related failures, reflecting the difficulty in detecting the failure mode that may lead to safety consequences. The formula for SRP is presented as Eq.(1).

$$SRP = Q \times S \times D \tag{1}$$

(ii) Environmental Consequence (E_nC)

The environmental consequence pertains to the harm inflicted upon the natural environment caused by a certain failure mode. The pollutant index *OM* is established by quantifying the pollutant emissions linked to a particular failure mode. The corresponding relationship between *OM* and E_nC, where E_nC is a value ranging from 0 to 1, is presented in Table 1..

$$OM = \frac{S_{failure}}{S_{std}} \tag{2}$$

where, $S_{failure}$ represents the pollutant monitoring data, and S_{std} represents the pollutant standard data.

Table 1. Evaluation Criteria for Environmental Consequence Index

OM	E_nC	Consequence description
0~1	0	No environmental hazard
1.1~1.5	0.3	Minor environmental hazard
1.6~2	0.5	Obvious environmental hazard
2~3	0.7	Major environmental hazard
>3	1	Huge environmental hazard

(iii) Usability Consequence (UC)

The usability consequence mainly refers to the effects of a specific failure mode on the ability of the PMS to accomplish its intended mission. Considering the structural complexity inherent to PMSs, the mutual interactions among equipment failure modes in the actual operation and maintenance environment are incorporated, so as to characterize the usability consequences more accurately when a failure occurs.

The usability consequence is quantified by assessing the degradation of the component under the failure mode within a specific mission phase. It is defined by computing the system coupled reliability ($R_S(t)$) at the end of the subsequent mission phase, assuming no maintenance activities are performed. Taking the series system as an example, the coupled reliability calculation formula is as Eq.(3).

$$R_S(t) = R_{C1}(t) \times R_{C2}(t) \times \ldots \times R_{Cn}(t) \tag{3}$$

where, t represents the mission cycle of the subsequent mission phase; $R_{Ci}(t)$ represents the coupled reliability of the i-th component.

The interdependencies among component failure modes are categorized into three categories: unidirectional relationship (Un), radiative relationship (Ra), and cascading relationship (Ca).

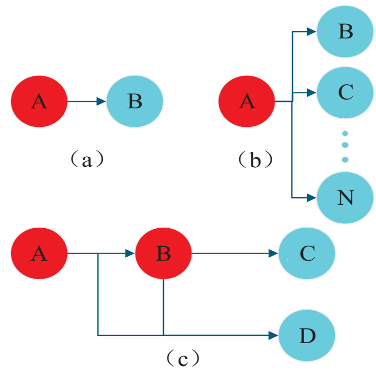

Fig. 1. Schematic Diagram of Coupling Relationship

(a) Unidirectional relationship (Un)

It refers to the impact of one failure mode on another. The interaction between failure mode A and B is expressed herein.

$$R_{Cb}(t) = R_b(t) \times \left[1 - \alpha_{ab} \times \left(1 - R_a(t)\right)\right] \tag{4}$$

where, α_{ab} represents the coupling coefficient of A on B; $R_b(t)$, $R_a(t)$ represents the reliability of B and A, $R_{Cb}(t)$ represents the coupled reliability of B under the influence of A.

(b) Radiative relationship (Ra)

It refers to the impact of one failure mode on multiple other failure modes. The subsequent formula illustrates the influence exerted by failure mode A on failure modes B through N.

$$\begin{aligned} R_{Cb}(t) &= R_b(t) \times \left[1 - \alpha_{ab} \times \left(1 - R_a(t)\right)\right] \\ R_{Cc}(t) &= R_c(t) \times \left[1 - \alpha_{ac} \times \left(1 - R_a(t)\right)\right] \\ &\vdots \\ R_{Cn}(t) &= R_n(t) \times \left[1 - \alpha_{an} \times \left(1 - R_a(t)\right)\right] \end{aligned} \tag{5}$$

(c) Cascading relationship (Ca)

It refers to the sequential effects initiated by an individual failure mode. The subsequent formula illustrates the cascading interactions among failure modes A, B, C, and D.

$$\begin{aligned} R_{Cc}(t) &= R_c(t) \times \left[1 - \alpha_{bc} \times \left(1 - R_b(t)\right)\right] \\ R_{Cd}(t) &= R_d(t) \times \begin{bmatrix} 1 - \alpha_{bd} \times \left(1 - R_b(t)\right) \\ -\alpha_{ad} \times \left(1 - R_a(t)\right) \end{bmatrix} \end{aligned} \tag{6}$$

The formula for calculating the coupling coefficient α in the previously mentioned equations is provided below.

$$\alpha_{ij} = F_{ij} \times \omega_f + L_{ij} \times \omega_l + I_{ij} \times \omega_p \tag{7}$$

$$st.\begin{cases} 0 \le F_{ij}, L_{ij}, I_{ij} \le 1 \\ \omega_f + \omega_l + \omega_\rho = 1 \\ 0 \le \omega_f, \omega_l, \omega_\rho \le 1 \end{cases} \tag{8}$$

where, F_{ij}, L_{ij}, I_{ij} represent the function, load, and failure correlation coefficients of failure mode i on j, respectively; ω_f, ω_l, ω_ρ are the corresponding weighting factors.

(iv) Economic Consequence (E_cC)

The economic consequence mainly describes the direct and indirect financial losses associated with failure modes, encompassing maintenance costs induced by failures (C_i), production losses due to downtime (C_t), and failure risk costs incurred during the mission phase (C_m).

$$\begin{aligned} C &= \left(C_i + C_t + C_m\right) \times Q\left(t\right) \\ Q\left(t\right) &= 1 - R(t) \end{aligned} \tag{9}$$

where, C represents the total cost; $Q(t)$ represents the failure occurrence probability; $R(t)$ represents the reliability.

(v) Maintenance Priority Indicator

The entropy weight method is employed to determine the weights of safety, environmental, usability, and economic consequence indicators, ultimately deriving the maintenance priority indicators.

$$\begin{aligned} r_{ij} &= \frac{q_{ij} + 1}{\sum_{k=1}^{m} (q_{kj} + 1)} \\ e_j &= -\frac{1}{\ln m} \sum_{i=1}^{m} r_{ij} \ln r_{ij} \end{aligned} \tag{10}$$

where, e_j represents entropy value; q_{ij} represents the standardized value of the i-th evaluation object under the j-th index； r_{ij} represents the translated and normalized proportion of the i-th evaluation object under the j-th index; m represents the number of evaluation objects.

The formulas for calculating the comprehensive evaluation score are as follows:

$$\omega_j = \frac{1 - e_j}{\sum_{j=1}^{4} 1 - e_j} \tag{11}$$

$$S_i = \sum_{j=1}^{4} \omega_j \cdot y_{ij} \tag{12}$$

where, S_i represents overall score of the i-th component; ω_j represents entropy weight of the j-th failure consequence; y_{ij} represents standardization indicators.

3. Selective Maintenance Decision Modelling

3.1. *Mission Reliability*

Mission reliability describes the probability that a system will successfully achieve its designated objectives under defined conditions and within a specified timeframe. The overall PMS reliability is determined by aggregating the reliability metrics of individual components. This aggregated measure serves to represent the probability that the PMS will fulfil its intended objectives during the subsequent mission phase.

Concentrating on the series-parallel PMS, the Wiener process is employed to develop the system's degradation failure model, enabling the computation of mission reliability for the subsequent mission phase. The definition of the Wiener process is as follows:

If a continuous-time stochastic process $\{X(t), t \ge 0\}$ follows the Wiener process with respect to time, the degradation process of the component can be described by the Eq.(13).

$$X\left(t\right) = X_0 + \mu t + \sigma W\left(t\right) \tag{13}$$

where, μ is the drift coefficient, representing the degradation rate; σ is the diffusion coefficient, representing the volatility of the component performance degradation; X_0 represents the initial degradation amount; and $W(t)$ represents the stochastic process term.

The formula for calculating the mission reliability is as Eq.(14):

$$R_i\left(t\right) = P\left(X\left(t\right) < D\right) = \Phi\left(\frac{D - X_0 - \mu t}{\sigma\sqrt{t}}\right) \tag{14}$$

where, D represents the failure threshold; $R_i(t)$ represents the reliability of the i-th component without considering interdependencies.

3.2. *Selective Maintenance Decision Model*

In response to decision-making dilemmas of PMS due to failure consequences and limited maintenance resources, A selective maintenance decision model is developed. Specifically, the model takes the mission cycle of each phase, maintenance opportunity window, limited resource availability, and the maintenance priority as constraints. The principal aim of the model is to maximize the overall reliability of the PMS mission.

3.2.1. *Model assumptions*

(i) According to the characteristics of the PMS, maintenance operations are performed on equipment when it enters the maintenance window. If a failure occurs during the mission phase, minimal maintenance is adopted.

(ii) At most three different pieces of equipment can be maintained simultaneously, and each component can only be maintained by one person at a time.

(iii) The PMS does not operate during non-mission phases, and its degradation state is ignored.

3.2.2. *Maintenance operations*

Maintenance operations are categorized into three types: no maintenance, imperfect maintenance, and perfect maintenance. Among them, imperfect maintenance is characterized by three distinct levels of restorative effect, which can restore the component's condition by 30%, 50%, and 80%, respectively. The calculation of the maintenance time under different types of maintenance operations is shown in Eq. (15).

$$T_m = \begin{cases} 0, & i = 0 \\ iT_p, & i = 0.3, 0.5, 0.8 \\ T_p, & i = 1 \end{cases} \tag{15}$$

where, T_m represents the maintenance time; T_p represents the perfect maintenance time; i represents the degree of the maintenance.

3.2.3. *Selective maintenance decision model*

The goal of selective maintenance optimization is to maximize the success probability of the next mission by identifying and maintaining the most critical components.

Based on the established maintenance priority ranking, components are maintained in sequence to determine the maintenance subset that maximizes the overall mission reliability of the system. The maintenance decision model is formulated as Eq. (16).

$$\begin{aligned} &Max \quad R_S(t) \\ &st. \begin{cases} T_{total} = T_{m1} + T_{m2} + \ldots T_{mn} \le x \times T_C \\ 0 \le x \le 3, x \in N \\ p_1 > p_2 > \ldots > p_n \end{cases} \end{aligned} \tag{16}$$

where, $R_S(t)$ represents the system mission reliability; T_{total} represents the total maintenance time; T_{mi} represents the maintenance time of the i-th component; T_C represents the maintenance window time; x is the quantity of personnel engaged concurrently in maintenance activities; p_i indicates the maintenance priority ranking of the i-th component.

4. Case Study

A steam turbine feedwater system is taken as a case study to perform selective maintenance decision-making at the end of a mission phase. By considering the system's operational status in the subsequent mission phase and relevant constraint conditions, the feasibility and efficacy of the proposed method are verified.

Based on the current operational conditions of the system, the duration of the subsequent mission phase is 6 months, and the maintenance window time is 24 hours allocated for this period. The segmentation of the system's mission phases, along with the reliability block diagram corresponding to the upcoming mission phase, is illustrated in Fig.3. System mission reliability is calculated as shown in Eq. (17).

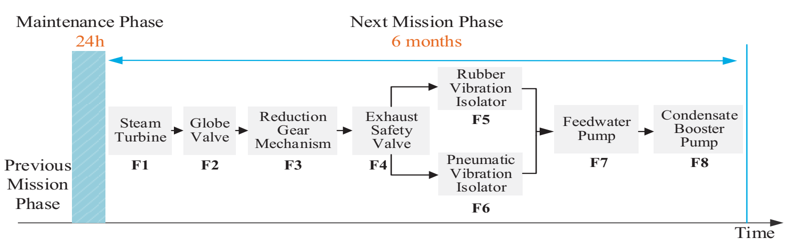

Fig. 3. Schematic Diagram of the Mission Phase of the Feedwater System

$$R_S(t)=R_{C1}(t)\times R_{C2}(t)\times R_{C3}(t)\times R_{C4}(t)\times\left[1-\left(1-R_{C5}(t)\right)\left(1-R_{C6}(t)\right)\right]\times R_{C7}(t)\times R_{C8}(t) \quad (17)$$

4.1. Failure Consequence Severity Indicators

Based on the actual operational data of the feedwater system and the results of FMECA, failure models are developed, and the relevant quantitative parameters for failure consequence quantification are presented in Table 2

Subsequently, the failure consequence severity index of each fault mode is calculated according to these parameters, and the maintenance priority ranking is performed based on the entropy weight method. (refer to Table 3) .

4.2. Selective Maintenance Decision Model

In this case, a selective maintenance decision model is developed, incorporating constraints including the mission cycle, maintenance window, resource limitations, and maintenance priority ranking. (refer to Table 4).

Table 2. Quantitative Parameters of the Failure Consequence

Component	Failure	S	Q	D	OM	R(t)	α			$R_C(t)$	C_i	C_t	C_m
Steam Turbine	F1	0.9	1	0.2	1	0.01	Ra	F3	0.52	0.437	4000	9600	1856.02
								F5	0.30	0.623			
								F6	0.27	0.676			
Globe Valve	F2	0	1	0.4	1.3	0.01	-	-	-	-	600	2000	0
Reduction Gear Mechanism	F3	0.3	0.09	0.2	1	0.91	Ra	F7	0.41	0.896	3500	9600	695.84
								F8	0.34	0.92			
Exhaust Safety Valve	F4	0.7	1	0.6	1.8	0.01	Ca	F3	0.12	0.801	1000	4800	700
Rubber Vibration Isolator	F5	0	0.11	0.4	1	0.89	Ra	F3	0.65	0.845	500	1200	1446.85
								F7	0.61	0.868			
								F8	0.59	0.907			
Pneumatic Vibration Isolator	F6	0	0.186	0.4	1	0.814	Ra	F3	0.56	0.741	800	1200	2654
								F7	0.54	0.757			
								F8	0.54	0.789			
Feedwater Pump	F7	0.1	0.07	0.3	1.5	0.93	Ca	F8	0.48	0.680	3600	7200	1280
Condensate Booster Pump	F8	0.2	0.03	0.3	1.5	0.97	-	-	-	-	4000	7200	0

Table 3. Failure Consequence Severity Indicator and Maintenance Time

Component	Failure	SC	E_nC	UC	E_cC	Severity	Maintenance Priority	T_p
Steam Turbine	F1	0.18	0	1.66	15456.02	0.7215	1	48h
Globe Valve	F2	0	0.3	5.95	2600.00	0.3864	3	12h
Reduction Gear Mechanism	F3	0.0054	0	5.43	1804.57	0.1879	7	48h
Exhaust Safety Valve	F4	0.42	0.5	5.24	6500.00	0.4528	2	24h
Rubber Vibration Isolator	F5	0	0	4.82	346.16	0.2014	6	18h
Pneumatic Vibration Isolator	F6	0	0	3.21	865.64	0.3107	4	18h
Feedwater Pump	F7	0.0021	0.3	4.17	845.60	0.2982	5	36h
Condensate Booster Pump	F8	0.0018	0.3	5.95	336.00	0.1246	8	36h

Table 4. Parameters of the Selective Maintenance Decision Model

Constraint Conditions	Mission Cycle	Maintenance Window	Maintenance Personnel	Maintenance Level			Maintenance Priority
				No	Imperfect	Perfect	
Value	4320h	24h	3	0%	30%, 50% and 80%	100%	See Table 3

According to the selective maintenance decision model, a total of 425 selective maintenance strategies and their corresponding operational reliability are calculated, as shown in Fig.4.

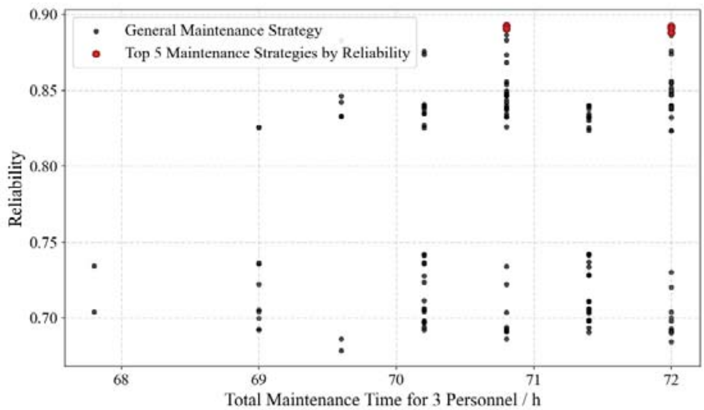

Fig. 4. Schematic Diagram of Selective Maintenance Strategy Combination

Table 5. Top 5 Maintenance Strategies

No.	Maintenance Strategy	$R_S(t)$	Maintenance Time
1	F1: 30%, F2: 80%, F3: 30%, F4: 30%, F5: 30%, F6: 50%, F7: 30%	0.8925	70.8h
2	F1: 30%, F2: 80%, F3: 30%, F4: 50%, F5: 30%, F6: 30%, F7: 30%	0.8921	72h
3	F1: 30%, F2: 30%, F3: 30%, F4: 30%, F5: 30%, F6: 30%, F7: 30%, F8: 30%	0.8911	72h
4	F1: 30%, F2: 80%, F3: 30%, F4: 30%, F5: 50%, F6: 30%, F7: 30%	0.8906	70.8h
5	F1: 30%, F2: 50%, F3: 30%, F4: 50%, F5: 30%, F6: 50%, F7: 30%	0.8880	72h

Taking the water supply system as the research object, a case analysis on the optimization of maintenance strategy is performed based on the parameters of the selective maintenance decision-making model. Through quantitative calculation, the top 5 maintenance decision combinations with the optimal system reliability are screened out (refer to Table 5), which verifies the practical application effect of the selective maintenance decision-making method proposed in this study in improving system reliability. The case results show that the water supply system achieves the maximum reliability of 0.8925 with a corresponding total maintenance time of 70.8 h, when the steam turbine, exhaust safety valve, feed water pump, rubber vibration isolator and reduction gear mechanism are subjected to 30% state recovery maintenance, the globe valve is subjected to 80% state recovery maintenance, and the air-spring vibration isolator is subjected to 50% state recovery maintenance. A reference is provided for the formulation of maintenance decisions in the practical operation and maintenance of water supply systems.

5.Conclusions

Addressing the limitation of traditional selective maintenance approaches that inadequately account for the comprehensive consequences of failures, this study proposes a selective maintenance decision method for PMSs that explicitly incorporates failure consequences. The method categorizes failure consequences into four distinct types: safety, environmental, usability, and economic impacts, and develops corresponding quantitative assessment approaches for each category. Building upon this framework, maintenance priorities are established, an optimized selective maintenance decision model is formulated, and maintenance strategies are devised, thereby enhancing the scientific rigor and rationality of maintenance decision-making processes.

To demonstrate the applicability of the proposed method, a case study involving a feedwater system is conducted. Severity indicators for failure consequences are computed for each failure mode to inform maintenance prioritization. Subsequently, a selective maintenance decision model is constructed with the objective of maximizing the reliability of the subsequent mission, guiding the formulation of maintenance strategies. The results validate the scientific soundness and practical feasibility of the proposed method.

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