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Optimal selective maintenance for multi-state systems in variable loading conditions

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ABSTRACT

This paper studies the selective maintenance problem for multi-state series systems working in variable loading conditions in the next mission. In the mission, a component's degradation depends on its current state and the load applied on it. A load-dependent degradation model is proposed for multi-state components operating in variable loading conditions. This model is inspired by the load-sharing model where many components share a common workload and the failure rate of a component depends on the state of other components. A Monte-Carlo simulation method is presented to simulate the multi-state component's degradation and to evaluate the system reliability. The final objective is to determine the best selective maintenance strategy to maximize the expected system reliability in the next mission within available resources. An illustrative example, reliability estimation results, and analysis of optimal selective maintenance scenarios for different levels of budget limitation are provided.

1. Introduction

In traditional reliability and maintenance models, the assumption that a system and its components operate under a normal and stable condition is usually made. In practice, the system and its components operate in variable operational conditions, e.g. load, environment conditions. The health of industrial devices degrades faster under a heavier loading condition and in a more severe environment.

The condition-dependent failure rate was first presented by Cox [1] in analysis of survival data in biostatistics. It was later brought to reliability and maintainability of a component in [2–8]. Lanza et al. [2] assumed that the tool's lifetime followed the Weibull Cumulative Damage Model, where the shape parameter β is the same as in Weibull distribution, i.e. load-independent, and the scale parameter η is load-dependent. You et al. [3] used the Proportional Hazard Model (PHM) to represent the failure rate of a system under variable operational conditions. Nourelfath and Yalaoui [4] suggested that the failure rate of a component depends on load following a power law in a study on production systems. Stochastic processes were also used to model the dynamic environment such as the Markov addictive process [5–7]. A preventive maintenance model was investigated in [5], where two levels of operating environment, i.e. normal and severe conditions, were considered. One state represents the normal condition, and the other represents the severe condition. The hazard rate function jumps when the environment switches from one state to the other. Dao and Zuo [8] employed the Proportional Hazard Model to model the load-dependent failure rate of a binary-state equipment working in an extended planning horizon. A sequential preventive maintenance model for the equipment operating in a given varying loading profile was investigated.

In traditional reliability theory [9], the system and its components are considered to be in two possible states: functioning or state 1 and failed or state 0. In practice, many systems and components can degrade and operate in several intermediate states varying from perfect functioning to complete failure. Such systems are called multi-state systems (MSS). The generic concepts, literature, and several examples of MSS have been developed in [10,11].

When the systems are required to work multiple missions with maintenance breaks between missions, the maintenance resources are usually restricted. There exists a case where several components in the system need to be maintained in a scheduled maintenance break, but we cannot perform all the desired maintenance actions due to limitation of resources such as cost and time. The maintenance policy to determine a sub-set of maintenance actions to maximize the system's performance in the next operating mission is called selective maintenance. Selective maintenance was first introduced in 1998 by Rice et al. [12]. A binary-integer optimization model for optimizing the reliability of series-parallel systems was proposed. At the maintenance depot, there are only two available maintenance options on a failed component: replace or do nothing. Since the first time introduced,

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selective maintenance has been a significant subject of interest among many researchers for both binary systems [13–19] and multi-state systems [20–25]. Cassady et al. [13] extended the work of Rice et al. [12] by considering components whose lifetimes follow the Weibull distribution and different maintenance actions such as replacement and minimal repair of failed components, and preventive replacement of surviving components. Maillart et al. [14] studied selective maintenance for a system with multiple identical missions in both finite and infinite planning horizons. Janjic and Popovic [15] and Zhu et al. [16] specifically considered selective maintenance models for the distribution networks and manufacturing lines respectively. Pandey et al. [17] studied selective maintenance with an imperfect repair model, in which the health of a component may be not "as good as new" and depends on the cost spending in the maintenance break. Later, Pandey et al. [18] extended the model in [17] by considering components with two types of failure modes, namely maintainable and non-maintainable failure modes. Schneider and Cassady [19] studied selective maintenance for a fleet comprised of multiple binary series-parallel systems.

Chen et al. [20] reported a preliminary work on selective maintenance for multi-state systems. A selective maintenance model for a series-parallel system with the objective of minimizing the total maintenance cost subject to reliability constraints was proposed. Pandey et al. [21] investigated selective maintenance for a system with multi-state components, where multiple intermediate repair actions are available on a component between do-nothing and replacement. Liu and Huang [22] presented a selective maintenance model for systems with multi-state corresponding to cumulative performance of N binary components and considering the imperfect maintenance that may restore the condition of the system to an intermediate state. Recently, Dao et al. [23] and Dao and Zuo [24,25] investigated the selective maintenance problems for multi-state systems considering the economic and stochastic dependence between components in the system.

It is observed that the majority of the papers on selective maintenance ignore the effect of loading conditions on the degradation of components. Chen et al. [26] performed a preliminary work on the load distribution and selective maintenance of multi-component systems. They jointly optimized the load to distribute and selective maintenance action to perform on each component in the system. The component is assigned a fixed load during the next operating mission. In practice, load on a component may change during the mission due to the change of operating demand.

One of the weaknesses of the existing models on maintenance of systems in variable operating conditions is that the condition is often divided into few levels for easy modeling of the condition-dependent failure rate. Generally, the loading condition changes several times in an operating mission. In addition, the future loading conditions are not known for certainty. For example, in many cases, we know the general load trend but not the exact load in the next operating mission. Another aspect is that the current modeling of load-dependent failure rate is limited for a binary-state component. A load-dependent degradation model for multi-state components in varying operating conditions with uncertainty is needed for MSS reliability analysis and maintenance decision making.

In this paper, we will study the selective maintenance problem for a multi-state series system, which is expected to complete a mission of durationτ in variable loading conditions. The future loading conditions in the next mission are modelled by a known baseload function and a random variation following the Normal distribution. In the mission, the component's degradation depends on its current state and the load applied on it. A load-dependent degradation model is proposed for multi-state components working in such conditions. The analysis of components' degradations and the system reliability estimation are discussed. The final objective is to determine the best selective maintenance strategy to maximize the expected system reliability in the next mission within available resources.

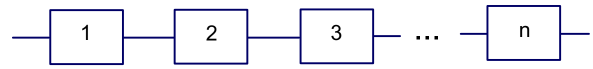

Fig. 1. A Series System.

The remaining part of this paper is organized as follows. Section 2 describes the system model and the variable loading conditions. Section 3 proposes a load-dependent degradation model for multi-state components in variable loading conditions. This model is inspired by the degradation of parallel components in load-sharing systems. A Monte-Carlo simulation-based method is presented in this section to model the component degradation and to evaluate the system reliability. A selective maintenance model to maximize the expected system reliability in the next mission is presented in Section 4. Section 5 consists of an illustrative example and discussions. Finally, a conclusion is given in Section 6.

2. The system model and the variable loading conditions

2.1. Multi-state system model

The multi-state system in this study consists of n multi-state components connected in series as in Fig. 1. Each multi-state component i, $i = 1, 2, \ldots, n$, can work in $K_i + 1$ possible states of $K_i, K_i - 1, \ldots, 1, 0$, where $K_i, K_i - 1, \ldots, 1$ are operating states and 0 is a failure state.

In this paper, the multi-state components are assumed to degrade gradually, i.e. a component, currently at state k, $k \geq 2$, will degrade to state k-1 before degrading further to state k-2. In the next mission, we assume that component i, in all operating states of $K_i, K_i - 1, \ldots, 2, 1$, can handle all the load levels from minimum to maximum load in the loading profile. This assumption is based on the degradation characteristics of a parallel load-sharing system, where the system is functioning if there is at least one component is functioning. Detailed explanations on the multi-state component's degradation and parallel load-sharing system will be presented in Section 3.

2.2. Variable loading conditions

The system is required to work in a mission of $[0, \tau]$ in variable loading conditions. An example of the variable loading conditions is given in Fig. 2.

In this paper, the future loading profile is not known with certainty. The load on the system, $L(t)$, comprises of a base-load profile,$L_0(t)$, and a random variation,ε_L, as in Eq. (1). The base-load profile is a

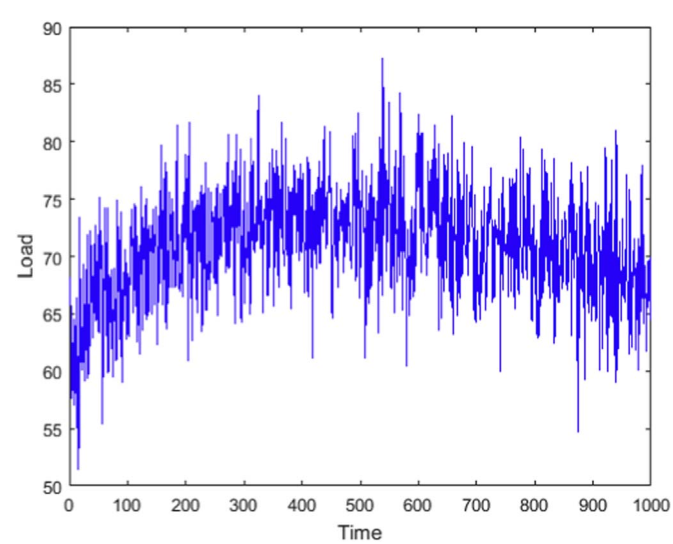

Fig. 2. Variable loading conditions.