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A general modeling method for opportunistic maintenance modeling of multi-unit systems

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ABSTRACT

This paper presents a deterioration state space partition method for opportunistic maintenance modeling of multi-unit systems. The method represents common characteristics of opportunistic maintenance models based on different maintenance strategies. All possible maintenance groups of general multi-unit systems with a known number of non-identical units at each maintenance decision time and their corresponding probabilities are deduced using the presented approach. Further, a general representation of the stationary law of the system deterioration and its numerical solution is developed. Numerical experiments verify the correctness and validity of the state space partition method and the numerical solution of the stationary probability density. The proposed method is applicable to both single-unit and multi-unit systems, and it provides a new generalized modeling method for maintenance optimization of multi-unit systems.

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1. Introduction

Many of today's technological systems, such as aircrafts, nuclear power plants, military installations, advanced industrial and medical equipments, etc., involve high level of complexity in their maintenance and operation and require high level of availability and reliability. Preventive maintenance activities are typically planned to help prevent system deterioration and failures while in service, especially when such an event can be hazardous and expensive, thereby reducing maintenance costs and improving the production effectiveness of the system. However, excessive preventive maintenance can itself be expensive and time-consuming. Therefore, it is important to perform appropriate and effective preventive maintenance practices to balance maintenance activities and cost.

Since the minimal repair model proposed by Barlow and Hunter in 1960 [1], various maintenance models have been extensively studied and widely applied in practice. Most of these models focus on preventive maintenance of single-unit system; however most of the systems in reality are multi-unit systems [2]. Moreover, the multi-unit maintenance problem cannot be reduced to a single-unit maintenance problem, unless all units are independent of one another [3]. Many researchers and practitioners have realized that interactions between the units in a system must be taken into account in maintenance decisions. A number of review articles [4–9] show that there has been growing interest recently in the modeling and optimization of maintenance of systems consisting of multiple units. In recently years, more realistic multi-unit systems were studied by researches with new maintenance policies and analytical methods [10–16].

The common planning approaches for multi-unit systems include block, group and opportunistic maintenance polices [9]. Under a block maintenance policy, all of units are preventively replaced by new ones at periodic intervals regardless of the actual states of individuals. Such a policy is rather wasteful, since sometimes almost new units are replaced. If there exists any dependence between units (economic/stochastic/structural) to optimize maintenance decisions, it is advisable to use group and opportunistic maintenance policies [9]. Both of them combine maintenance activities on several units under a certain condition based on time and/or cost at the same time, in order to reduce the common downtime and costs for the system, due to economic dependence. The analyzed problems are likely the same either for opportunity maintenance models or for group maintenance models [9]. However, in the group maintenance policy, a group maintenance is performed either when a fixed time interval is expired or when a fixed number of units are failed, whichever comes first [9]. Its maintenance groups can be fixed or not corresponding to various applications and policies. Under an opportunistic maintenance policy, maintenance is performed at the time when an opportunity arrives, like scheduled downtime, planned shutdown of the machines, or failure of a system in close proximity to the item of interest [9]. It leads to dynamic grouping, in which group maintenance will be carried out only for the non-failed components that are in the opportunistic zone

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[16]. Opportunistic task aims at avoiding (or at least reducing) future failure, and then consequently reducing the induced downtime and cost. Although the original goal of opportunistic maintenance is to reduce maintenance costs, it may also impact the system availability. If maintenance of a unit implies system shutdown, then system availability can be better served by combining maintenance activities on several units [16]. Therefore, there has been a growing interest in using opportunistic maintenance model for optimizing multi-unit systems maintenance problem, such as literatures [2,10–12,16,17].

All the studies referenced above use simplified assumptions, or dealt with particular systems, in order to formulate the decision problem of multi-unit systems with less mathematical difficulty [11]. Because the complexity of the mathematical model grows exponentially when the number of units in a multi-unit system increases, most of the previously proposed approaches are restricted to small systems with two or three-unit systems. However, no models that investigate the common characteristics of the general multi-unit systems is established for them.

In the optimization maintenance model, all possible maintenance activities and their corresponding probabilities play a key role in modeling. For multi-unit systems using opportunistic maintenance model, maintenance activities can be dynamic groups with different combination of the system units, even with different maintenance actions for these units. Enumeration can be regarded as a good method to list all maintenance activities of a simple system, but it will be very complicated and time-consuming in a system with a great number of units. For these systems, it needs to find a more efficient method to analyze the maintenance groups and deduce their corresponding probabilities.

Furthermore, if dependences between units are considered, the optimal maintenance decision on the whole system should depend on the deterioration state of the system at that time rather than the deterioration state of individual units. Therefore, a general representation of the system deterioration should be analyzed for a general multi-unit system to characterize the deterioration of the whole system.

The goal of this study is to establish a common analysis model for multi-unit systems opportunistic maintenance. Instead of giving an objective-specific optimization model (such as for only for reliability or availability or cost rate), we present a deterioration state space partition method for opportunistic maintenance modeling of multi-unit systems by investigating the common characteristics of the model based on different maintenance strategies. With a known number (n) of non-identical units system, we derived a common representation of all possible maintenance groups at each maintenance decision time and the corresponding probability of each group according to the presented approach. Further, a general representation of the stationary law of the system deterioration and a numerical solution is developed.

The rest of the paper is organized as follows. Section 2 describes the deterioration state space partition method. Section 3 presents the derivation of the common representation of maintenance groups and the corresponding probabilities according to the presented approach. In Section 4, a general formulation of the stationary law of the system deterioration is deduced and its numerical solution approach is developed in Section 5. Section 6 provides numerical experiments to verify the correctness and validity of the state space partition method and the numerical solution of the stationary probability density. Finally, Section 7 draws conclusion of the research with summary and remarks.

2. Deterioration state space partition methods

2.1. Research motivations

For multi-unit systems, interactions between units complicate the modeling and optimization of maintenance. Interactions also offer the opportunity of group maintenance which may reduce the downtime and save costs. In the 1960's, few researchers investigated the opportunistic replacement policy for multi-unit systems with ‘economies of scale’, or economic dependency, in the components' replacement [18–20]. Since then, many extensions of opportunistic maintenance have been introduced and studied [21,22]. In subsequent research, the opportunistic maintenance policy was gradually used in various multi-unit systems maintenance modeling based on different maintenance strategies such as: (1) age-based maintenance (ABM) strategy; (2) failure-rate-tolerance-based maintenance (FBM) strategy; (3) control limit strategy of condition-based maintenance (CBM); and (4) CBM strategy based on proportional hazards model (PHM).

2.1.1. ABM strategy

Radner and Jorgenson [20] first introduced the (n_i, N) policy. It is an opportunistic replacement of a single uninspected part considered in the presence of several monitored parts. According to this policy, the uninspected part is replaced on its failure or the arrival of its preventive replacement age N, and replaced opportunistically with a failed part i, if its age has reached a critical age $n_i (n_i \le N)$. This approach was extended by Van der Duyn Schouten and Vanneste [23] for a two-component series system, by taking the possibility of (n, N) strategies application into account.

Gertsbakh [24] develops an optimal group preventive maintenance model for a system of n identical units with age control limit (t, T). In this model, if a unit fails within time interval $[0, t]$, it will be correctively replaced individually. If it fails within time interval $(t, T]$, it will be correctively replaced and the other units will be preventively replaced. And if no failure occurs before time T, the whole system is replaced. Pham and Wang [25] extended (t, T) opportunistic maintenance policies for k-out-of-n systems.

2.1.2. FBM strategy

Zheng and Fard [26,27] examined a failure-rate-tolerance-based opportunistic replacement policy $(L-u, L)$, for a system with k different types of units. A unit is replaced at failure [27] or is replaced preventively when its failure rate exceeds limit L [26,27], whichever occurs first. As a unit is replaced, all other units with their failure rates falling in $[L-u, L)$ limits are replaced jointly.

2.1.3. Control limit strategy of CBM

Wijnmalen and Hontelez [28] adopted a complex scheme of the actual degree of deterioration control limits of the equipment to allow taking discounts from coordinating repair actions. In the model presented in this paper, an upper limit value is considered to induce a mandatory repair action independent of other components (but not ruling out the possibility of coordination). Several lower limit values are also introduced allowing a repair to be made earlier if it can be combined with a mandatory repair of one or more remaining components, if this coordination yields a cost reduction larger than the cost of advancing the repair. This is the exact lower limit value which depends on the amount of discount offered. Barbera et al. [29] discussed a condition-based maintenance model with exponential failures and fixed inspection intervals for a two-unit system in series. Latterly, Castanier et al. [3] considered a condition-based maintenance policy for a two-unit deteriorating system, which is an extension to the multi-threshold maintenance policy proposed by Grall et al. [30–32] for mono-component systems. In this model, a critical level and sequential decision threshold values for the preventive maintenance of component i are denoted $L^{(i)}$ and $\xi_k^{(i)} (k = 0, 1, \dots, n)$ respectively. Another threshold ς_i is added for each component i which defines a zone of ‘opportunistic replacement’. At time t_k, if the observed deterioration level of component i, denoted by x_i, belongs to the

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