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Preventive maintenance modeling for multi-component systems with considering stochastic failures and disassembly sequence

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ABSTRACT

The existed PM (preventive maintenance) efforts on multi-component systems usually ignore the PM opportunities at the component failure moments and the structure dependence among the system components. In this paper, a time window based PM model is proposed for multi-component systems with the stochastic failures and the disassembly sequence involved. Whenever one of the system components stochastically fails or reaches its reliability threshold, PM opportunities arise for other system components. A Monte-Carlo based algorithm is built up to simulate the stochastic failures and then to calculate the cumulative maintenance cost of the system. The optimal PM practice is obtained by minimizing the cumulative maintenance cost throughout the given time horizon. Finally, a numerical example is given to illustrate the calculation process and the availability of the proposed PM model.

1. Introduction

PM (preventive maintenance) modeling for multi-component systems is a popular issue to the researchers. Because of the complexity of the system level maintenance modeling, the research results on the PM modeling for multi-component systems are much less than that for a single unit [1]. However, with the growing demand for industry, PM modeling efforts are increasingly being focused on multi-component systems, and a variety of PM models have been intensively developed [2,3].

There are two types of PM policies for the PM modeling of the multi-component systems. One is the group maintenance, which is usually used to deal with the systems where parallel components exit and the components are economically dependent. Under this policy, the system components are preventively maintained in group once the time interval or the number of the failed components reaches a predetermined threshold [4,5]. The other is the opportunistic maintenance. The basic assumption for opportunistic maintenance is that for most of the multi-component systems, a single failure usually results in the stop of the whole system. Therefore combining PM activities can decrease the number of system stops and then save the total set-up cost (i.e. system downtime cost) of the system [6]. That implies whenever one of the system components fails or is preventively maintained, which usually indicates a stop of the whole system, PM opportunities will arise for other system components because of the possible saving of the total set-up cost.

In recent decades, opportunistic maintenance has become much more popular for its adaptability in application. Different opportunistic maintenance models have been developed to decide which of the system components will be preventively maintained together. Tian [7] proposes a condition based PM model for a multi-component system based on proportional hazards model, where economic dependency, such as the cost for sending a maintenance team to the site which will only occur once if multiple components are replaced at the same time, exists among different components subject to condition monitoring. Zhou [8] gives a dynamic opportunistic PM scheduling algorithm for a multi-component series system based on short-term optimization. Whenever one of the components reaches its reliability threshold, a PM action will be performed on the component and at that moment PM opportunities will arise for other system components. Economic and failure dependencies, including the number of system stops, are the main concern of this effort. Kamran [9] proposes a multi-objective optimization model to determine the optimal PM and replacement schedules in a repairable and maintainable multi-component system. The planning horizon is divided into discrete and equally-sized periods in which three possible actions are planned for each component, namely maintenance, replacement, or do nothing. The issue of this effort is how to decrease the fixed downtime cost of the whole system. Other similar research results on opportunistic maintenance can be found in [10–14]. These research efforts are

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playing great roles in improving system reliability, preventing system failures and reducing maintenance cost for multi-component systems.

However, there are still two issues that need to be addressed. First, all of the above research efforts always assume that the opportunistic maintenance occurs only when one of the system components is preventively maintained or replaced. In fact, failures are obviously inevitable within the PM interval and corrective repair is an effective way to restore the failed component to its operational status. Whenever corrective repair happens, the system also has to stop and therefore PM opportunities will still arise for other system components. This circumstance is usually ignored in the existed research efforts. The main reason for ignoring the maintenance opportunities at the failure moments is that the component failures are usually stochastic and subsequently the arising of the PM opportunities becomes stochastic too. This makes the PM modeling much more complex. Second, economic dependency or failure dependency is the main concern in these research efforts. Therefore combing PM activities usually implies a saving of this kind of fixed set-up cost (i.e. the cost for system stop, the cost for sending a team to the site). However, this is just one kind of set-up cost. Another kind of set-up cost, which results from the structural dependency, is also important for the PM modeling of the multi-component systems. For example, because of the constraint of the system structure, there usually exists a disassembly sequence for the system components. Especially for a complex disassembled system, combing the PM activities of different components can decrease the number of system disassembly and subsequently save part of the disassembly cost if there exists an intersection among the disassembly sequences of the target disassembling components. Currently, few of the above research efforts consider the structural dependency in the PM modeling although the technique of disassembly sequence planning has already widely studied [15–17]. There are a few research results on disassembly sequence planning which are oriented to product maintenance [18,19]. However, the main concern of these research efforts is how to optimize the disassembly sequence to obtain a lower disassembly cost, and they paid little attention on the opportunistic maintenance modeling for multi-component systems under the constraint of disassembly sequence.

This paper proposes an opportunistic maintenance policy for multi-component systems. The main concern of this policy is the PM opportunities at the component failure moments and the effect of the disassembly sequence. The opportunistic maintenance model is established based on the time window theory under which all the system components whose original PM moments are within the time window will be preventively maintained together [20]. The rest of the paper is arranged as follows. Section 2 gives the PM policy for multi-component systems. An opportunistic maintenance model is given in Section 3 and Section 4, and the PM modeling is divided into two levels which are the component level and the system level. Section 5 illustrates a numerical example to show how the proposed PM model works.

2. Problem definition

Consider a multi-component system (i.e. a machine tool) whose disassembly for maintenance is costly. Whenever one of the system components fails or reaches its predetermined reliability threshold, proper minimal repair or PM needs to be applied on this component. Usually this leads to the stop of the whole system. For example, the multi-component machine tool usually needs to be powered off when repair or maintenance happens. At that moment, PM opportunities arise for other system components since combining PM activities can decrease the number of system stops and system disassembly. Assume minimal repair is applied on the failed component, and it just restores the function of the component and does not change the hazard status of the component. PM is considered for the component that reaches the reliability threshold or has the PM opportunities, and it restores the status of the component to be as good as new.

Based on the above assumptions and strategies, the procedure for the PM modeling of the multi-component system is defined as follows.

(1) Maintenance modeling for component level. The reliability threshold and the optimal PM interval for each system component can be determined based on this model, which are the basic inputs for the system PM model.
(2) Maintenance modeling for system level. As mentioned above, PM opportunities will arise at the failure moments or the PM moments. Therefore, first, an opportunistic maintenance model is established to determine the total maintenance cost for the components that have PM opportunities at that moment. These components are obtained based on the time window theory (see Section 4.1). Second, the cumulative maintenance cost of the system throughout the given time horizon is modeled and calculated. The optimal time window is deduced by minimizing this cumulative maintenance cost.

Since the failures are stochastic, the PM opportunities accompanied with the failures are obviously stochastic too. In such an instance, a Monte Carlo based algorithm is considered to simulate the stochastic failures during the calculation of the system maintenance cost.

3. PM modeling for component level

Since PM can restore the status of the system component to be as good as new, a periodic PM policy is considered for component level modeling. Usually, the reliability threshold R_j for component j can be defined as

$$R_j = \exp\left[-\int_0^{T_j} h_j(t)dt\right] \tag{1}$$

where $h_j(t)$ is the hazard rate function for component j and T_j is the optimal PM interval for component j. $\int_0^{T_j} h_j(t)dt$ represents the number of the stochastic failures for component j in each PM cycle. With the assumption that all the failures occurring within the PM intervals are minimally repaired, the total maintenance cost per unit time for component j in every PM cycle can be evaluated as

$$c_j = \frac{c_j^m \tau_j^m \int_0^{T_j} h_j(t)dt + c_j^p \tau_j^p + c^d \tau_{j0}^d \left[\int_0^{T_j} h_j(t)dt + 1\right] + c^s \tau_j^s}{T_j + \tau_j^m \int_0^{T_j} h_j(t)dt + \tau_j^p + \tau_{j0}^d \left[\int_0^{T_j} h_j(t)dt + 1\right]} \tag{2}$$

where c_j^m, c_j^p are the minimal repair cost per unit time and the PM cost per unit time for component j, respectively. c^d is the disassembly cost per unit time and it is assumed that this cost is same for all the components. c^s is the downtime cost per unit time for the system, with the consideration that the maintenance of one system component always means the stop of the whole system. $\int_0^{T_j} h_j(t)dt + 1$ represents the number of the disassembly for component j within a PM cycle based on the assumption that the disassembly happens not only at the failure moment but also at the PM moment. τ_j^m, τ_j^p are the duration for a single minimal repair and the duration for a single PM for component j, respectively. τ_{j0}^d is the total duration to disassemble component j, and it is defined as

$$\tau_{j0}^d = \tau_j^d + \tau_j^{dp} \tag{3}$$