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Non-periodic preventive maintenance with reliability thresholds for complex repairable systems

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ABSTRACT

In general, a non-periodic condition-based PM policy with different condition variables is often more effective than a periodic age-based policy for deteriorating complex repairable systems. In this study, system reliability is estimated and used as the condition variable, and three reliability-based PM models are then developed with consideration of different scenarios which can assist in evaluating the maintenance cost for each scenario. The proposed approach provides the optimal reliability thresholds and PM schedules in advance by which the system availability and quality can be ensured and the organizational resources can be well prepared and managed. The results of the sensitivity anlysis indicate that PM activities performed at a high reliability threshold can not only significantly improve the system availability but also efficiently extend the system lifetime, although such a PM strategy is more costly than that for a low reliabiltiy threshold. The optimal reliability threshold increases along with the number of PM activities to prevent future breakdowns caused by severe deterioration, and thus substantially reduces repair costs.

1. Introduction

Preventive maintenance (PM) is a schedule of planned maintenance which is carried out while a deteriorating repairable system, such as a vehicle, computer, or aircraft, is properly functioning, to reduce the likelihood of future breakdowns caused by wearout or aging. However, a PM strategy usually faces a trade-off between system reliability and maintenance costs, since frequent PM activities often result in high maintenance costs and poor system availability, while insufficient PM activities may not accomplish the goal of quality assurance. Furthermore, the determination of an optimal PM strategy involves numerous uncertainties, such as the initial status of the system, the expected system lifetime, relative maintenance costs, and the quality of maintenance procedures, which all increase the difficulty deciding on a strategy.

Ever since the early work of Barlow and Hunter [4], research has been widely conducted for dealing with system reliability and PM problems. These various PM models are often classified into two kinds of maintenance policies according to their maintenance criteria. The time-dependent PM policy, which determines a PM schedule based on the system age, might be the most common policy in the literature, in which the age may be measured by time in operation or other time related concepts (e.g., mileage driven by a motor or vehicle). In addition, as concepts of minimal repair [4] and imperfect maintenance [9,37,39] have received more attention, various generalizations of periodic age replacement models with minimal repair regarding PM have also been proposed [27,29,31,33,34,45,50] applied selective PM in a manufacturing system and constructed a PM model in which reliability can be ensure and the total cost of maintenance and failure losses can be minimized. Khojandi et al. [18] analyzed the lifetime-reward-maximizing maintenance policies under perfect and imperfect maintenance conditions, and investigated the tradeoff between the system's virtual age and the decision maker's reward rate. Shafiee et al. [40] developed a mathematical model to determine the optimal burn-in time, number of PM actions, and the corresponding maintenance degree simultaneously. The main contribution of Shafiee's model is measuring the effects of PM action when the failure rate is constant

However since many times the deterioration of a system can be effectively signified by factors other than age or time, it seems more appropriate to consider the maintenance related decision on these factors rather than age. In such a condition-based maintenance context, a maintenance activity is often carried out when a condition variable reaches or passes a specific threshold value. Since the decision of performing each maintenance activity depends on the state of the condition variable (e.g., deterioration), obtaining instantaneous information about the current condition of the system is of crucial importance. For example, the wafer etching process in the

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semiconductor industry relies on the degree of cleanliness in the clean room. The risk of contamination in wafers increases as the particle accumulation becomes worse due to the deterioration of the etching machine. Instead of conducting an experimental test to estimate the machine deterioration, the use of the in situ particle monitoring system enables a more accurate and real-time evaluation [42]. A condition variable can be a physical one [38,39], for intance, Akturk and Gurel [1] considered the wearout of a numerical cutting machine by investigating its cutting speed and feeding rate to simultaneously minimize manufacturing and PM costs under a condition-based maintenance policy. Moreover, different system performance measures are also utilized as condition varibles in the literature, such as failure rate (e.g., [17,23,25,47]) or system reliability [15], to develop an optimal condition-based maintenance strategy for complex systems. Research has utilized the homogeneous Markov model in analyzing multistate deteriorating systems. Bloch-Mercier [8] proposed an effective Markovian PM policy with a sequential checking procedure in which the deterioration degree can be measure with a finite discrete scale and failures can be detected instantly. Pandey et al. [35] developed a selective maintenance strategy for a multistate deteriorating system by using an universal generating function to determine the optimal system reliability. Eloy Ruiz-Castro [13] proposed a Markovian PM model for multistate devices which are subject to internal failures and external shocks.

With regard to the reliability assessment, Panagiotidou and Tagaras [36] discussed the relationship between statistical process control (SPC) and PM of manufacturing equipments, and argued that equipments in an out-of-control state often operate under adverse conditions and are consequently more prone to breakdown (i.e., less reliability). In fact, by continuously monitoring some physical factors (e.g., vibration degree or oil composition), SPC can provide an inexpensive solution to the measure of system reliability. For example, the reliability of a system can be continuously monitored in practice by a specific technique called the multivariate process monitoring and diagnosis (MPMD) which provides nearly perfect information about the state of the system in a real operating environment [19,20,32,41]. Liang et al. [21] also proposed a reliability assessment approach based on multi-deterioration measurement and failure analysis. Accordingly, Giorgio et al. [15] investigated the failure data of a marine diesel engine to estimate the reliability of the cylinder liner which was then utilized to develop a reliabiltiy-based PM strategy for the diesel engine. Berrade et al. [6] presented a maintenance model consisting of periodic inspections to check the state of the system, in which inspections are subject to error. Wang and Zhang [46] investigated the repair–replacement problem for repairable systems in which failures can only be detected by periodic inspections, and developed an algorithm to obtain the optimal inspection interval. Doostparast and Doostparast [11] developed an integrated approach for determining optimal types and frequencies of PM actions with consideration of maintaining a certain level of reliability for coherent systems. In their model, the possible maintenance actions can be classified into three activity-types including inspection, repair and replacement which are concurrently considered on every PM stage. Yuan and Lu [48] proposed an efficient methodology for a reliability-based optimization problem, and the methodology combines the weighted approach and a sequential approximation optimization. Beaurepaire et al. [5] proposed al model to determine the optimal maintenance schedule for mechanical components under the framework of reliability-based optimization. Valdebenito and Schuëller [43] reviewed and discussed the studies about reliability-based optimization problem in recent years. They also presented serveral techniques for solving reliability-based optimization problems which apply simulation methods for assessing reliability.

Instead of deriving the optimal PM schedule, research on condition-based maintenance strategies with continuously monitoring generally focuses either on determining the optimal time for the ultimate preventive replacement (e.g., [29]), or on obtaining the optimal condition for such a replacement (see, e.g., [7,22]) which is always worse than a given threshold of *soft failure* [30]. However, in considering that the deterioration can be modeled by an non-homogeneous Poisson Process (NHPP) and a minimal repair is carried out immediately after any breakdown, this study develops an approach to analytically determine the optimal reliability thresholds and PM schedules for cost-effectiveness consideration. The proposed reliability-based maintenance approach differs from traditional ones in allowing imperfect PM activities to be arranged in advance to reduce the number of possible breakdowns during the system lifetime, and focusing not only on when the system should be replaced but also on the time each PM activity should be carried out. By knowing the optimal reliability threshold and PM schedule in advance, the system availability and quality can be ensured and the organizational resources can be well prepared and managed. Moreover, since the system reliability can be continuously monitored, the pre-scheduled optimal PM strategy obtained by the proposed approach can be adjusted and rescheduled according to the information gained from collecting the follow-up physical data if the difference between the two reliability estimates is significant. The rule of rescheduling PM can be set up according to the domain experts' experiences. Fig. 1 illustrates that the former PM scheme may be adjusted or updated.

The remainder of this article is organized as follows: Section 2 states the fundamental assumptions for the proposed condition-based PM models. Section 3 gives the details of the model formulations and derives their corresponding optimal PM strategies. Section 4 presents a numerical example to demonstrate the usefulness of the proposed models. Sensitivity analyses are also carried out to investigate the factors which may affect the optimal PM strategies. Finally, we make some concluding remarks in Section 5.

2. Reliability-based preventive maintenance

PM activities can be performed for a deteriorating system prior to possible severe breakdowns. The optimization criterion utilized in existing optimal maintenance models often focus on minimizing the expected system maintenance cost. However, the optimal PM strategy can be based not only on cost, but also system reliability [44], which results in the optimal condition-based PM policy (or more precisely, the optimal reliability-based PM policy).

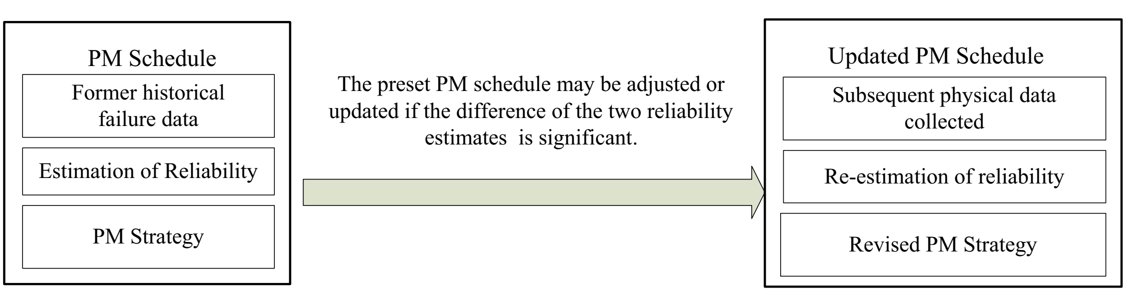

Fig. 1. Adjustment of pre-schedule optimal PM strategy.