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The influence of practical factors on the benefits of condition-based maintenance over time-based maintenance

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ABSTRACT

Recent developments in condition monitoring technology have led to an ongoing shift from time-based maintenance (TBM) to condition-based maintenance (CBM). Although CBM allows for more effectively planned maintenance actions, its relative performance strongly depends on the behavior of the deterioration process, the severity of failures, the required setup time, the accuracy of the condition measurements, and the amount of randomness in the deterioration level at which failure occurs. The contribution of this paper is twofold. First, we review studies that compare CBM with TBM, and studies that consider the above factors in combination with a CBM model. Second, whereas existing studies confine themselves to a few examples, we perform a numerical investigation to derive insights on the effects of the various characteristics on the relative benefit of CBM. The results can be used by companies to decide what factors are most important when considering to implement CBM, and to assess whether the benefit of CBM during the operational phase outweighs the additional costs during the life cycle of equipment. This study allows for follow-up research to quantify and generalize the insights obtained, and to analyze interaction effects.

1. Introduction

Due to ongoing automation of production processes and increasing reliance on expensive production equipment, the importance of effectively planned and performed maintenance activities is growing, and both the portion of employees working in maintenance and the maintenance costs are increasing [78]. As an illustration, over a quarter of the total workforce in the process industry, and up to 30% in the chemical industry, deal with maintenance operations [71]. In refineries, the maintenance and operations departments are usually the largest [17]. Furthermore, maintenance costs typically account for 15–70% of the total value of the end product [8,44], the amount of money spent on maintenance of engineering structures and infrastructures is increasing continuously [68], and medical equipment maintenance nowadays demands large sums from hospital budgets [14].

Many firms still apply ‘traditional’ time-based maintenance (TBM) strategies, which are easy to implement as only the time that a unit is in service has to be recorded. However, substantial remaining useful life is wasted if the machine is still in reasonable condition when preventive maintenance is performed, and a breakdown might occur if it happens to deteriorate faster than expected. Due to the increasing technical possibilities to monitor, store, and analyze conditions, condition-based maintenance (CBM) strategies are gaining popularity [10,18,28,59,64]. Condition-based maintenance generally results in more effectively scheduled preventive maintenance, and, in the ideal case, preventive maintenance that is performed just before failure.

The relative benefit of CBM, however, strongly depends on the behavior of the deterioration process and the severity of failures. Furthermore, it is affected by various practical factors that are often present in practice, viz., required planning time, imperfect condition monitoring, and variation in the deterioration level at which failure occurs. CBM should only be applied if this relative benefit outweighs the efforts and costs during the entire life cycle that are required to apply CBM [22,50,60,69]. The requisites to switch from time-based to condition-based maintenance include condition monitoring equipment and software to store, analyze, and initiate maintenance actions [3,59]. Companies that are interested in implementing condition-based maintenance must also consider the risks related to the lack of experience [78]. Furthermore, they should realize that CBM requires a dynamic scheduling of maintenance activities, whereas they might not have the capability for such flexible planning.

The first contribution of this paper is to review studies that compare

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condition-based and time-based maintenance, as well as studies that consider the above practicals factor in a CBM model. Although both CBM and TBM have received ample attention in the scientific literature, few studies compare them. Moreover, existing comparative studies confine themselves to a few examples. Insights on how the various characteristics influence the performance of condition-based and time-based maintenance are lacking. Therefore, our second contribution is to derive insights on the effects of the various characteristics on the relative benefit of CBM from a numerical investigation. We start with the effects of the behavior of the deterioration process and the severity of failures. Thereafter, we extend our model and analyze the effects of the practical factors on the relative performance of CBM. The obtained insights are useful in practice to decide what factors are most important when considering to switch from TBM to CBM, and for avoiding the risk of switching from TBM to CBM in situations where benefits do not outweigh costs.

The remainder of this paper is organized as follows. In Section 2 we review existing studies that compare condition-based maintenance with time-based maintenance, and studies that consider planning time, accuracy of condition measurements, and predictability of the failure deterioration level. The approach that we use to compare the two maintenance strategies is discussed in Section 3. This section also contains formal definitions of the condition-based maintenance and the time-based maintenance strategy that we adopt. In Section 4 we consider the effect of the behavior of the deterioration process and of the severity of failures on the relative performance of CBM. In Section 5 we point out how this performance is influenced by required planning time, imperfect condition information, and predictability of the deterioration level at which failure occurs. We end with conclusions and suggestions for future research in Section 6.

2. Literature review

We start this section with a review of studies that compare condition-based maintenance with time-based maintenance. Thereafter, in Section 2.2, we review studies that consider various practical factors that influence the relative performance of condition-based maintenance.

2.1. Comparative studies

In this section we review studies that compare time-based maintenance with condition-based maintenance.

The most simple models are those that consider a small number of deterioration states. McKone and Weiss [42] consider the integration of condition-based maintenance with traditional periodic preventive maintenance. The available condition information is limited to a signal of a potential failure that might be received before the actual failure. The probability that this signal is received depends on the prediction accuracy, and the time between the signal and the failure depends on the prediction precision. The performance of the condition-based maintenance strategy depends on the prediction accuracy and precision. In some situations, periodic preventive maintenance or a combination of condition-based and periodic preventive maintenance is preferred. Paté-Cornell et al. [55] use a Markov chain with four states to model the deterioration process of a production system. Time-based maintenance and three types of condition-based maintenance are considered. The latter are based on inspections of the product, signals of the machine, and signals provided by the use of the product. Zhang et al. [77] develop an adaptive discrete-state model based on Bayesian Belief Network theory. Both Paté-Cornell et al. [55] and Zhang et al. [77] consider a single illustrative example, and no attempt is made to generalize the results.

Other studies consider deterioration processes with a continuous state space. Pandey et al. [53] use gamma deterioration processes and linear deterioration processes with a random (but fixed) rate. Xiang et al. [75] also adopt linear processes, but consider a rate that depends on the environment in which the system operates. This environment is represented by a continuous-time Markov chain with three states. Crowder and Lawless [13] consider gamma and Wiener processes, and Zio and Compare [78] adopt the randomized Paris-Erdogan fatigue crack growth model. For the main part of their analysis, Pandey et al. [53] consider the threshold deterioration level that triggers preventive maintenance as fixed. Only a limited investigation also includes the threshold deterioration level as a decision variable. Condition-based maintenance turns out to be preferred over time-based maintenance only if the coefficient of variation of the lifetime exceeds a certain level. Crowder and Lawless [13] and Zio and Compare [78] compare the optimal condition-based maintenance policy with the optimal time-based maintenance policy, but they only do so for a single specification of the parameters. In both studies, the performance of condition-based maintenance turns out to be much better than that of time-based maintenance for the considered parameter settings, but general insights are lacking. Xiang et al. [75] include randomness in the deterioration level at which failure occurs, and show that there is potential cost saving through implementing a condition-based maintenance policy as opposed to time-based maintenance. No insights are presented on the effect of changes in the other model parameters on these cost savings.

More sophisticated models are considered by Huynh et al. [26] and by Bouvard et al. [9]. The former combine failures due to deterioration with failures due to shock events. Because failures are not self-announcing but should be identified by inspections, a cost is introduced for system inactivity. A condition-based strategy with periodic inspections is compared with a purely time-based block replacement strategy. A clear effect of the type of condition deterioration is lacking, as only two deterioration processes are considered (high and low variance). The influence of the values of the cost parameters is studied in more detail and the relative benefit of the condition-based strategy turns out to increase in the preventive replacement cost. Bouvard et al. [9] develop a maintenance model that dynamically optimizes the maintenance decisions for a multi-component system at each periodic inspection time. Maintenance actions are grouped to reduce maintenance costs. A system with three components is considered as an example and it is shown that the use of condition information leads to lower costs compared with the case that this information is not used. Cost savings are most significant for short times between inspections and moderate variances of the underlying gamma processes that are used to model deterioration of the components.

Summarizing, we conclude that only a few general insights on the benefits of condition-based maintenance compared with time-based maintenance are provided by the current literature.

2.2. Practical factors influencing the benefits of CBM

We continue with a review of studies that include various practical factors that influence the relative benefit of CBM. These factors are required planning time, imperfect condition monitoring, and uncertainty in the deterioration level at which failure occurs.

2.2.1. Planning time

In many practical situations, repairmen are not continuously available [27,34], and spare parts may not be on stock and have to be ordered [19,38,51]. If so, a certain planning time (in the literature also called lead time or delay time) is required between initiating and performing a maintenance action. We remark that joint optimization of maintenance and spare parts inventories has been considered by a number of authors. This is beyond the scope of our study; we refer to Van Horenbeek et al. [66] for a recent review.

A required planning time to perform preventive maintenance in combination with a continuously monitored unit that deteriorates according to a gamma process is considered by various authors. They