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Cost benefits of postponing time-based maintenance under lifetime distribution uncertainty

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ABSTRACT

We consider the problem of scheduling time-based preventive maintenance under uncertainty in the lifetime distribution of a unit, with the understanding that every time a maintenance action is carried out, additional information on the lifetime distribution becomes available. Under such circumstances, typically either point estimates for the unknown parameters are used, or expected costs are minimized taking the uncertainty in the parameters into account. Both approaches, however, ignore that the uncertainty is reduced much faster if preventive maintenance actions are postponed. Although this initially leads to higher costs due to a higher risk of breakdowns, the obtained additional information can be exploited thereafter as it enables better maintenance decisions going forward. We assess the long-term benefits of initially postponing preventive maintenance, and perform a numerical study to identify under what circumstances these benefits are largest. This study is the first to recognize that the choice of a maintenance strategy influences the information that becomes available, and aims to initiate follow-up research in the area of maintenance planning.

1. Introduction

In many industries, a substantial part of the total costs and the total workforce is related to maintenance, indicating the importance of this area. 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 [33,43]. Moreover, the amount of money spent on maintaining engineering and infrastructures is continuously increasing [42].

Maintenance involves both repairing failed systems (corrective maintenance) and preventing breakdowns (preventive maintenance). Preventive maintenance is generally preferred since breakdowns occur at unexpected moments and can have severe consequences. Two types of preventive maintenance can be distinguished: time-based maintenance and condition-based maintenance. Time-based maintenance is easier to plan, while condition-based maintenance, on the other hand, leads to more effectively planned maintenance actions because it takes the condition of the maintainable unit into account. Drawbacks of the latter type are that condition monitoring needs to be technically feasible and that monitoring equipment is required. In this paper we consider time-based preventive maintenance. Other recent studies on time-based maintenance include Chang [8], Cheng et al. [9], Faccio et al. [16], Gustavsson et al. [19], and Xia et al. [45]. We refer to Ahmad and Kamaruddin [2] for an overview on condition-based maintenance.

A common assumption in many models and studies on time-based preventive maintenance planning is that the lifetime distribution, i.e. the distribution of the time until breakdown, is known. For example, the basic age-based maintenance model of Barlow and Hunter [4], which is included in many textbooks, minimizes the mean cost per unit time given a known lifetime distribution. Other examples of studies that assume a known lifetime distribution are Jiang et al. [23], Kijima et al. [25], Makis and Jardine [31], and Yeh and Lo [46].

In practice, however, it is usually not the case that the lifetime distribution is known with certainty. Reasons include incorrectly recorded or unrecorded failure codes, a lack of adequate descriptions of what was wrong and what repairs were performed [15,32], heavily right-censored data because of preventive maintenance in the past [6], and an insufficient amount of data to determine accurate estimates for model parameters [13]. In this paper, we explicitly take into account uncertainty in the lifetime distribution when studying the problem of scheduling time-based preventive maintenance.

Existing studies on this problem typically consider strategies that minimize the expected costs based on current information and update these strategies when more data becomes available [5]. For example, Gertsbakh [17] describes how the optimal maintenance age should be determined if the parameter

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Nomenclature

Roman symbols

c	normalized cost of a preventive maintenance action
k	shape parameter of the Weibull distribution
λ	scale parameter of the Weibull distribution
λ_i	scale parameter of unit type i, $i=1$ (weak), 2 (strong)
p	initial probability that the unit is 'weak'
$\hat{p}$	Bayesian estimate of the probability that the unit is 'weak'
S	length of the lifespan of a unit
$f(t;\lambda;k)$	density function of the Weibull distribution with parameters λ and k
$F(t;\lambda;k)$	distribution function of the Weibull distribution with parameters λ and k
L_j	likelihood that $\lambda=\lambda_j$, $j=1,2$
t_i	length of duration i
z_i	type of duration i, $z_i=1$ (event), $z_i=0$ (censored)
t	preventive maintenance age
$\eta(T;\lambda,k)$	cost rate as a function of t and Weibull parameters λ and k
$\eta^E(T;\hat{p})$	expected cost rate as a function of t and $\hat{p}$
T_i	optimal maintenance age if the unit is of type i, $i=1$ (weak), 2 (strong)
T^*	optimal maintenance age for the myopic policy
π	threshold level of the threshold policy
π^*	optimal threshold level

uncertainty is modelled by a discrete distribution, De Jonge et al. [14] consider the effect of uncertainty in the scale parameter of the lifetime distribution on the optimal maintenance age, and Silver and Fiechter [40] consider a unit that either fails at time 1 or time 2 with respective probabilities that are updated in a Bayesian way. They extend this setting to one with a discrete lifetime distribution, and they consider a heuristic maintenance policy that is based on the current estimated probabilities [41].

Another study using Bayesian updating is Mazzuchi [34], which determines the optimal age-based maintenance policy when the parameters of the Weibull lifetime distribution are uncertain. Juang and Anderson [24] extend this model with five possible maintenance actions and random failure costs. Moreover, Laggoune et al. [28] use the bootstrap technique to obtain distributions that model the uncertainties in the parameters of the Weibull distribution, and Coolen-Schrijner and Coolen [11,12] consider an adaptive maintenance strategy that is based on a nonparametric estimator of the lifetime distribution. This adaptive maintenance strategy determines, at the start of each maintenance cycle, a maintenance age based on the data available at that moment in time.

All the abovementioned research ignores that the choice of a maintenance age influences the information on the lifetime distribution that becomes available. That is why we propose to postpone preventive maintenance actions at the start of the lifespan of a unit. Although this will increase the expected costs during this first phase, it also leads to reduced uncertainty in the lifetime distribution for future decisions. As a consequence, preventive maintenance can be scheduled more effectively during the remaining lifespan of a unit. The aim of this paper is to investigate the potential cost benefits over the entire lifespan of a unit.

Before we investigate these potential cost benefits, we first analyze a more traditional so-called myopic policy, which determines an optimal maintenance age based on the information that is currently available. It turns out that under particular circumstances this myopic policy selects a very conservative, i.e. small, maintenance age so that little information on the lifetime distribution becomes available. Based on this observation we propose to use a threshold policy, which postpones preventive maintenance actions during the initial phase of the lifespan of a unit. Using a numerical study we show that, indeed, the benefits of postponing preventive maintenance actions can be substantial.

The remainder of this paper is organized as follows. In Section 2 we introduce the model we are considering. Next, in Section 3 we describe the myopic policy for scheduling preventive maintenance actions and we analyze its performance. In Section 4 we introduce the threshold policy and we investigate its potential cost benefits using a numerical study. We end with conclusions and directions for future research in Section 5.

2. Model formulation

We consider preventive maintenance planning for a single maintainable unit with a finite lifespan, where the lifetime distribution of the unit is not known with certainty. Instead, the unit is either 'weak' or 'strong' with corresponding lifetime distributions. When the unit breaks down, corrective maintenance has to be performed. A preventive maintenance action, on the other hand, can be scheduled at any moment in time at a lower cost. However, if preventive maintenance is performed, then the lifetime, i.e. the time until breakdown, is not observed and less information on the type of the unit is obtained. The main contribution of this paper is that we explicitly take this information aspect into account in the planning of preventive maintenance actions. In the remainder of this section the assumptions of our model are explained in more detail.

The lifetime of the unit is assumed to follow a Weibull distribution. This is the most commonly used distribution to model lifetimes of industrial machines and components and provides a good description for many types of lifetimes. The Weibull distribution has a shape parameter k and a scale parameter λ. We assume that the shape parameter k is known and that there is uncertainty in the scale parameter λ. This is a realistic assumption since the value of the shape parameter can often be estimated very accurately based on the failure mode of a unit [1]. It is, on the other hand, very likely that there is substantial uncertainty in the value of the scale parameter [48]. Other studies that consider this setting include Canavos and Tsokos [7], De Jonge et al. [14], Kwon [27], and Papadopoulos and Tsokos [37].

Because this is the first study on the benefits of postponing preventive maintenance actions, we consider a simple setting with two unit types. With probability p, the unit is 'weak' and has a scale parameter with value $\lambda=1$; and with probability $1-p$, the unit is 'strong' and has a scale parameter with value $\lambda=2$. The value of k is the same for both unit types. In practice, such a setting with two unit types occurs if components are selected from a stockpile that consists of weak and strong components [38], if a population of specific items comes from different suppliers or is produced by different manufacturing lines with varying quality [22], if a dealer sells items under his own brand label after buying them from two different manufacturers [35], or after a possible poor installation of a new component [38].

Both corrective and preventive maintenance are assumed to make the unit as-good-as-new. Furthermore, preventive maintenance is assumed to be less expensive than corrective maintenance because preventive maintenance can be planned in advance whereas breakdowns occur unexpectedly and are likely to have severe consequences. Both assumptions are also made in the