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Numerical study of inventory management under various maintenance policies

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ABSTRACT

Capital assets, such as manufacturing equipment, require maintenance to remain functioning. Maintenance can be performed when a component breaks down and needs replacement (i.e., corrective maintenance), or the maintenance and part replacement can be performed preventively. Preventive maintenance can be planned on a periodic basis (periodic maintenance), or it can be triggered by a certain monitored condition (condition-based maintenance). Preventive maintenance policies are gaining traction in the business world, but for many companies it is unclear what their impact is on the resulting inventory requirements for the spare parts that are used for the maintenance interventions. We study the impact of the maintenance policy on the inventory requirements and the corresponding costs for a setting that is realistic at an OEM in the compressed air industry. Preventive policies increase the total demand for spare parts compared to corrective maintenance, since the former do not exploit the entire useful life of the components. This leads to higher inventory requirements. At the same time, the preventive policies inhibit advance demand information, as the interventions, and correspondingly the spare parts demands, are planned in advance. Using a simulation study, we show that by using this advance demand information in managing the spare part inventory, the increase in inventory requirements of preventive maintenance policies can to a large extent be offset; for condition-based maintenance, we find that inventories can even be lower compared to corrective maintenance, provided that the advance demand information is used correctly when managing inventories. Our analysis sheds light on the behaviour of the inventory related costs under various maintenance policies.

1. Introduction

Modern society depends to a large extent on the functioning of capital assets, which are expensive systems having a long life time. Examples are the trains and railroads that are used to transport people and freight, the equipment that is used in the process industry, and the machines that are used to manufacture the goods that we use daily. These assets require a lot of maintenance throughout their life cycle. Van Dongen [30] gives various examples of systems incurring more maintenance costs throughout their life cycles than their initial acquisition costs; e.g., for rolling stock and the joint strike fighter this is about twice as much.

Some users maintain their assets themselves. Examples are most national railway operators and defence organisations. Others outsource all or some maintenance to the original equipment manufacturers or system integrators (we will refer to both as OEMs) or to third parties. One reason to do so is that assets are often so complex that it is hard for users to maintain them: they lack the specific knowledge and skills that are required to perform the more complicated maintenance tasks. For the OEMs, it is in their interest to take over the maintenance, and to deliver other services, since these after sales activities generate a more steady revenue stream with profit margins that are often more rewarding than the sales of the assets themselves. This trend is called servitisation. In its extreme form, users are not even acquiring the asset anymore; they only buy the use of it ('power by the hour'). We refer to Basten and Van Houtum [2] and the references therein for a further discussion of the different types of users and the reasons to outsource maintenance. In the remainder of this paper, we will take the perspective of an OEM, who is in charge of the maintenance of the installed base of machines at its customers' premises. The reason is that our work is motivated by, and validated at an OEM in the compressed air, generator and pump industry. The OEM deploys a preventive maintenance strategy on the majority of its components and started to implement condition-based

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maintenance on a selected number of components. However, the findings are also useful for users maintaining their own assets.

To be able to perform maintenance, various resources are required: spare parts, trained personnel, facilities, tools, and test equipment [15]. If these resources are not available, maintenance cannot be performed. We focus in this paper on the relation between the maintenance policy and the spare parts inventory control policy. The maintenance policies that we will use throughout this paper and that are most frequently encountered, both in academia and in practice, are: *corrective* maintenance (CM), *periodic* maintenance (PM), and *condition-based* maintenance (CBM), with the latter two being *preventive* maintenance policies. (We come back to these policies in Sections 3 and 4). If corrective maintenance is applied, with maintenance being performed upon failure, then the demand for spare parts depends on the failure behaviour of the assets only. This is different if maintenance is performed preventively. For instance, in case of periodic maintenance, it is a combination of a deterministic demand stream of spare parts for the PM interventions, and some random demands in case a component breaks down prior to the preventive maintenance. The stochastic nature of the degradation behaviour, the maintenance policy that is applied, and the resulting degree of advance demand information determine the requirements for the inventory control policy.

Still, in practice, it often happens that if some demands for spare parts are planned, while others are unplanned, they are all treated as being the same, i.e., unpredictable without taking into account the maintenance policy. In other words, the advance demand information generated by the maintenance policy is not used to manage inventories. We noticed this at several OEMs with whom we collaborate, but it is also noticed by others (see e.g., [8]). Therefore, our first contribution is that we show how the standard inventory control policies that are used in practice can be improved, by leveraging the advance demand information generated by the maintenance policy. In other words, we show the inventory cost reductions that can be obtained by not simply treating all demands as being random and unplanned.

Our second contribution is that we compare the inventory costs of the three mentioned maintenance policies combined with their inventory control policies. This results in a more thorough comparison in which not only maintenance and downtime costs, but also the inventory costs for spare parts are included. To the best of our knowledge, such a comparison has not been performed in the literature; we come back to the existing comparison studies in Section 2.

We achieve these contributions using a numerical simulation study. We focus on the maintenance policy and spare parts for one component, and we assume that this component is critical, so that failure of the component causes the machine to stop. We analyse the inventory performance of the different maintenance policies under a variety of settings, e.g., failure behaviour of components and size of the installed base. We focus especially on CBM, since that policy is getting more popular in practice and in the literature (see e.g., [34] and the references therein). One reason for its popularity is that monitoring and storing data becomes cheaper and big data technology allows for better analyses. Another reason is that when looking at the maintenance and downtime costs only, this policy is typically the most cost-effective one (see e.g., [22]).

The remainder of this paper is organised as follows. Section 2 reviews the related literature. In Section 3 we discuss the maintenance policies that we consider in our numerical study. In Section 4 we introduce our model, the assumptions that we make, and the notation that we use. In this section we also address how the inventory policy can be adapted based on the maintenance policy in use. We present our extensive numerical study in Section 5. Section 6 concludes.

2. Related literature

We first discuss some literature related to the degradation and failure behaviour of components. We then discuss literature related to the maintenance policies considered in this paper and their related spare parts inventory control, with specific focus on the use of advance demand information. We conclude with some comparison studies that are related to ours.

When components are in use, they degrade, resulting at some point in a failure. There are many ways in which degradation behaviour and thus failure behaviour can be modelled. We discuss a few well known examples. The delay time model (DTM) was introduced by Christer [5] and Christer and Waller [6] and is discussed more recently, for example, by Wang [36]. In the model, it is assumed that a component can be in three states: good, defect and failed. The time that the component remains good, the time-to-defect, has a certain distribution, while the time that the component remains in the defect state, the delay time, has another distribution. This model is especially useful when the degradation behaviour is monitored using inspections, and the goal is typically to optimise the inspection interval. The time-to-failure of the component is the convolution of the time-to-defect and the delay time. A somewhat related model that can be used to model degradation behaviour is the Markov chain, in which there can be any number of states and a component remains in a state an exponentially distributed amount of time. If the sojourn time in each state is equal, the time-to-failure is Erlang distributed. If there is only one state that can be distinguished, the time-to-failure is exponentially distributed. This is often assumed for electronic components.

The degradation can also in some cases be tracked on a continuous scale. In that case, the Gamma process can be used to model the degradation behaviour. It is a process with independent gamma distributed increments, which means that degradation can only increase. Van Noortwijk [33] gives an excellent review of the Gamma process applied to maintenance. We use a special case of the random coefficient model. In this model, degradation follows a certain function with known and unknown parameters, or coefficients. If all parameters are known, the degradation path is deterministic. The original application of random coefficient models is to estimate the time-to-failure distribution based on degradation data [19]. The special case that we consider is linear with one unknown parameter. This parameter itself is Weibull distributed, which means that the time to failure is also Weibull distributed. It allows us to focus on the interesting insights, without using too complicated models.

Given the degradation and failure behaviour of a component, it can be determined when to perform maintenance. This means that it should be decided which maintenance policy to use, and how to set its parameters. We consider three different maintenance policies, which we discuss in more detail in Section 3. One of them is the policy of corrective maintenance, which means that maintenance is performed upon failure. The other two policies are periodic maintenance and condition-based maintenance, which are both preventive maintenance policies. This means that maintenance is planned some time in advance, in order to prevent failures. This results in so-called *advance demand information* (ADI; see e.g., [9,12]). There are many overviews of maintenance policies, for instance, Wang [35], Tinga [27,28], Van Horenbeek et al. [34], or Goossens and Basten [11].

A maintenance intervention may mean various things, but we assume that it means a replacement of a failed component by a spare part. For extensive treatments on spare parts inventory control, typically not considering the maintenance policy, we refer to the books by Sherbrooke [24], Muckstadt [20], Van Houtum and Kranenburg [32], or the review paper by Basten and Van Houtum [2]. The literature is extensive, and we do include an exhaustive list. Different assumptions are made in the literature, for example on who owns the spare parts and performs maintenance (as discussed in Section 1). If an OEM owns spare parts to service many customers, there are pooling effects that lower the total required number of spare parts compared with the situation that each customer owns its own spare parts. There exist also situations where customers join forces and pool their spare parts, which is modelled, for example, in [16]. From a modelling point of view, there is often no real difference