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On a general periodic preventive maintenance policy incorporating warranty contracts and system ageing losses

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ABSTRACT

In this paper, a general periodic preventive maintenance (PM) policy for a repairable revenue-generating system is developed and studied. We define 'ageing losses' as the difference in revenues generated by an ideal system (no ageing) and a real system that ages over the same period of consideration. It is assumed that preventive maintenance slows the system deterioration process and therefore reduces ageing losses. The proposed model is general in the sense that (1) both the warranty contracts and system ageing losses are incorporated in the maintenance cost modeling and (2) the implementation of PM actions does not have to be strictly periodic. A cost model is developed for the buyer under two decision variables—the calendar time of the first PM and the degree of each PM. Numerical examples are then presented to show the effectiveness of the proposed model. Sensitivity analyses are further conducted to investigate the impact of model parameters on optimal solutions.

1. Introduction

Many industrial or service systems face inherently stochastic deteriorations that can eventually lead to failures. In order to reduce the frequency of those failures and their associated rectification cost, periodic preventive maintenance (PM) services are often implemented over the system life cycle, which requires a system to be pre-maintained at multiples of some constant intervals and be minimally repaired upon failures. Classifications on various PM strategies are given, for example, in Valdez-Flores and Feldman (1989) and Wang (2002). Furthermore, many products are sold with a warranty coverage, which provides the buyers with certain level of protection against failures during warranty. For detailed studies on various warranty policies and applications readers are referred to Blischke and Murthy (1994, 1996) and Murthy and Djamaludin (2002).

Optimization of PM strategies incorporating warranty contracts has received considerable attention in literature. From the seller's perspective, (periodic) preventive maintenance is mainly designed to minimize the expected warranty cost (over the warranty period); see Chun (1992), Jack and Dagpunar (1994), Yeh and Lo (2001), Wang (2006), and Huang and Yen (2009) for reference. In comparison, from buyer's perspective, PM efforts during both the warranty and the post-warranty period can have significant impacts on the maintenance cost after the warranty is expired and that will have to be borne by the buyer. As a result, the optimal PM strategy for the buyer should be determined under the life-cycle context. Early studies on the lifetime PM modeling can be found in Chun and Lee (1992), Jung et al. (2000), Djamaludin et al. (2001), and Jung and Park (2003). Recently, Kim et al. (2004) developed a framework for the cost analysis linking warranty and preventive maintenance (PM) under the life-cycle context. Different PM options were proposed and the optimal strategies were further selected such that the buyer's life-cycle maintenance cost was minimized. Pascual and Ortega (2006) described a periodic PM policy by allowing the buyer's negotiation on the length of warranty period. Jain and Maheshwari (2006) developed a discounted PM cost model after the expiration of renewing pro-rata warranty (RPRW). Chen and Chien (2007) considered continuous PM for a repairable system under renewing free-replacement warranty (RFRW) with two failure modes: a minor failure and a catastrophic failure. Jung et al. (2008) investigated optimal preventive replacement policies following the expiration of both renewing and non-renewing warranty.

Some other research in PM modeling related to our problem of interest is also mentioned as follows. These works however do not include warranty consideration. Pongpech and Murthy (2006) studied a periodic PM policy for the leased products. Sheu et al. (2006) studied an optimal periodic PM policy by maximizing the system availability. El-Ferik and Ben-Daya (2008) proposed a new age-based PM strategy, where the system underwent PM actions either at failure or after a pre-specified time interval whichever of them occurred first. Jackson and Pascual (2008) focused on the maintenance service negotiation between the agents and clients. More recently, Castro (2009) studied an optimal PM strategy for systems under two types of failure modes: maintainable and non-maintainable modes. Zhou et al. (2009) considered a multi-unit

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series system and investigated an opportunistic PM strategy using dynamic programming. Jin et al. (2009) described an option-based PM model under stochastic demand. Nakagawa and Mizutani (2009) presented a summary of various PM models over a finite horizon.

A common assumption for the periodic PM modeling in literature is that the calendar time of the first PM action is pre-specified. To illustrate this, let w denote the warranty period, L the length of the system life cycle ($w \le L$), τ the constant interval between consecutive PMs, and t_0 the calendar time for the first PM action. It is typically assumed that t_0 equals to either τ or $w+\tau$. The first case describes the situation that PMs are planned throughout the system lifetime; in contrast the second case implies that the PMs are only carried out during the post-warranty period. While such arrangements are easy to be implemented in practice, they do not necessarily lead to the minimization of the lifetime cost. Hence a potential improvement of the model is to consider t_0 as a decision variable to be optimized under the life-cycle context.

Another common assumption for the (periodic) PM modeling is that PM strategies are analyzed only from the aspect of maintenance cost while the benefits of PMs are seldom explicitly elaborated in the model optimization. Dekker (1996) highlighted the reason by stating that the maintenance output, in terms of contribution to company profits, is very difficult to quantify. While it is easy to measure the cost of maintenance, it is difficult to measure its benefits. Most recently, Marais and Saleh (2009) developed a framework for capturing and quantifying the value of maintenance activities on revenue-generating facilities. They argued that existing cost-centric maintenance models ignored the value of maintenance, and may lead to sub-optimal maintenance strategies. However, their valuation mechanism was applied only to perfect maintenance. For the valuation of (imperfect) preventive maintenance, new methodologies should be proposed.

In this paper, we study a general periodic preventive maintenance policy for the buyer considering both the maintenance cost and the value of maintenance. The first part of the cost model includes the preventive maintenance (PM) cost and the minimal repair cost upon system failures. We assume that PMs are carried out periodically starting from a certain time instant until the end of the system life cycle. The time to the first PM action is a decision variable chosen by the buyer. The second part of the cost model, the value of maintenance, is quantified through the reduction of ageing losses, which is defined as the total revenue losses caused by the system deterioration over its life cycle. We argue that preventive maintenance, which slows down the system deterioration, reduces ageing losses and therefore reflects its value. The optimal PM strategies for the buyer, which consider both the maintenance cost and the value of maintenance, are determined jointly by the calendar time of the first PM action and its corresponding maintenance level.

The rest of paper is organized as follows. Section 2 presents the proposed periodic preventive maintenance model in more details. Section 3 derives the total life-cycle cost model under both warranty contracts and ageing losses. A numerical case is given in Section 4, and sensitivity analysis is carried out over various model parameters. Conclusion is made in Section 5.

2. Periodic preventive maintenance model

Let L represent the system life cycle and τ represent the pre-specified PM interval. In the model, preventive maintenance (PM) is conducted at discrete time instants $y_1,y_2, \ldots, y_n$ with $y_1 = t_0$, $y_i = y_1+(i-1)\tau$ $\left(1 \le i \le n = \left\lceil \frac{L-t_0}{\tau} \right\rceil\right)$ and $y_{n+1} = L$. Here the integer n represents the number of PMs during the system life cycle. We assume that t_0 has no pre-specified value (i.e. $t_0 = \tau$ or $w+\tau$) and is a decision variable to be optimized. We further assume that the cost for performing PM actions is borne by the buyer while the warranty servicing cost is covered by the manufacturer.

For the sake of generality, we assume that the effect of each PM is imperfect (Pham and Wang, 1996) and is modeled using the virtual age method (Kijima, 1989). It defines that each PM reduces the system age by a certain amount, and therefore the system effective age or virtual age is less than its calendar age. Kim et al. (2004) modified Kijima's model by considering discrete PM levels. Such treatment was further adopted by Huang and Yen (2009) in two-dimensional warranty cost modeling under preventive maintenance. Here we further modify Kim's model by considering t_0 as a decision variable, and the system effective age right after performing the ith PM action is therefore given by

$$u_i(m,t_0) = u_{i-1}(m,t_0) + \varphi(m)(y_i - y_{i-1}) \tag{1}$$

where y_i is the calendar age of the system when the ith PM action is performed (with $y_1 = t_0$), $\varphi(m)$ the age-reduction factor, and $m(=0,1, \ldots, M)$ represents all the discrete PM levels. Note that $\varphi(m)$ is a decreasing function of m, i.e. a larger m corresponds to greater maintenance efforts and therefore a smaller $\varphi(m)$. In particular, we let $\varphi(0) = 1$ represent the case of no preventive maintenance. In our model, in addition to t_0, m is another decision variable to be selected and optimized by the buyer.

Under both m and t_0, the virtual age of the system at calendar time t – $u(t|m,t_0)$ is given by

$$u(t|m,t_0) = u_{i-1}(m,t_0) + t - y_{i-1}, \quad y_{i-1} \le t < y_i,\ i = 2,3,\ldots,n+1 \tag{2}$$

It is important to investigate the effect of the first PM action on the system effective age. Here we assume that for each PM level $m > 0$, there is a limit $K(m)$ on the reduction of system effective age, which describes the capacity of improvement under that PM level. As a result, the amount of age reduction by the first PM is simply the value of $[1-\varphi(m)]t_0$ or $K(m)$, whichever is smaller. For a general discussion, we let $K(m) = 0$. The system effective age right after the first PM action is therefore given by

$$u_1(m,t_0) = t_0 - \min\{[1-\varphi(m)]t_0, K(m)\} \tag{3}$$

Such arrangement is reasonable in the practical situation as under a fixed maintenance level, the effect of the maintenance action increases with the time span since last maintenance; however, due to the presence of physical and technical constraints, it should not exceed some finite upper limit. To further simplify the problem, we assume that $K(m) \ge [1-\varphi(m)]\tau$ for any PM level $m > 0$, or $\tau \le \min_{m \in \{1,2,\ldots,M\}}\{K(m)/(1-\varphi(m))\}$, implying that for the safety issue, the maintenance of system should not be lower than certain frequency. As a result, the amount of age reduction by the subsequent PMs will not exceed the control limit.

The modified virtual age model is summarized in the following proposition.

Proposition 1. For a repairable system subject to periodic preventive maintenance (PM), the modified virtual age $u(t|m,t_0)$ at calendar age t under both the PM level m and the calendar time of the first PM action t_0 is given by

$$u(t|m,t_0) = \begin{cases} t, & 0 \le t < y_1 = t_0 \\ t - [1-\varphi(m)](i-2)\tau - \min\{[1-\varphi(m)]t_0, K(m)\}, & y_{i-1} \le t < y_i,\ i = 2,3,\ldots,n+1 \end{cases} \tag{4}$$

Proof. When $t \le y_1 = t_0$, no PM action is carried out; therefore we have $u(t|m,t_0) = t$.