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A two-stage preventive maintenance optimization model incorporating two-dimensional extended warranty

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ABSTRACT

In practice, customers can decide whether to buy an extended warranty or not, at the time of item sale or at the end of the basic warranty. In this paper, by taking into account the moments of customers purchasing two-dimensional extended warranty, the optimization of imperfect preventive maintenance for repairable items is investigated from the manufacturer's perspective. A two-dimensional preventive maintenance strategy is proposed, under which the item is preventively maintained according to a specified age interval or usage interval, whichever occurs first. It is highlighted that when the extended warranty is purchased upon the expiration of the basic warranty, the manufacturer faces a two-stage preventive maintenance optimization problem. Moreover, in the second stage, the possibility of reducing the servicing cost over the extended warranty period is explored by classifying customers on the basis of their usage rates and then providing them with customized preventive maintenance programs. Numerical examples show that offering customized preventive maintenance programs can reduce the manufacturer's warranty cost, while a larger saving in warranty cost comes from encouraging customers to buy the extended warranty at the time of item sale.

1. Introduction

1.1. Motivation

In today's competitive market, a variety of means have been used by manufacturers to capture more market share and customers satisfaction. Offering attractive warranty policies is a common incentive. A warranty policy is a statement in connection with the sale of an item on the scheme (e.g., free repair/replacement, refund, etc.) and extent (length of period) of compensation offered by the manufacturer in the event of item failure [1]. In fact, warranty has been widely used to serve multiple purposes in consumer and commercial transactions, and extensive attention has been paid to warranty management from various disciplines [2–5].

Based on the number of variables that are used to define the policy, warranty policies can be broadly divided into two categories, i.e., one-dimensional and two-dimensional [6]. One-dimensional warranties are defined on the basis of either age or usage; while two-dimensional warranties consider both age and usage and the potential interaction between them. In practice, two-dimensional warranties have been widely applied in automobile industry. For example, a new automobile is usually sold with a two-dimensional warranty, say free repair for 3 years or 60,000 km, whichever occurs first.

Moreover, during product marketing, manufacturers usually offer customers the option of buying an extended warranty (EW) that provides protection for an additional period after the basic warranty (BW) ceases. Considering the increasing complexity of many products in both of structures and functions, the maintenance of such products becomes more complicated and costly than ever before. Thus, EW is attracting more attention from both manufacturers and customers.

However, offering any types of warranty policies to customers will incur substantial cost to manufacturers resulting from the servicing of warranty claims. One effective way to reduce warranty servicing cost is to incorporate appropriate preventive maintenance (PM) programs into the warranty policy. Different from corrective maintenance actions which are intended to restore the failed item to an operating state, PM actions are planned actions either to reduce the probability of failures or to prolong the item's lifetime while it is still in the operating state [7]. From the cost-benefit point of view, it is worthwhile for a manufacturer to adopt a PM program only when the reduction of warranty servicing cost exceeds the additional cost incurred by the PM program [8].

In recent years, the demand growth for two-dimensional EW contracts raises a challenge for manufacturers, that is, how to implement appropriate PM actions for items covered by both two-dimensional BW and EW contracts so as to reduce the warranty

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cost. However, existing approaches and models are far from sufficient for assisting the manufacturers in making such decisions. This study intends to fill this gap.

1.2. Related literature

Warranty and PM are two topics that have been separately studied by many researchers. Integrated research on both of them has gained relatively limited attention [9]. This paper focuses on the optimization of imperfect PM strategies incorporating two-dimensional BW and EW policies. Below a brief literature review is conducted to better position the novelty and contributions of this paper.

Most existing studies on warranty are related to BW policies, while studies on EW policies are comparatively limited; see [10–17] for research on one-dimensional EW policies, and [18–21] for research on two-dimensional EW policies. Among them, some references addressed the optimization of PM strategies incorporating one-dimensional EW policies; see [13–15] for example. To our knowledge, there are only two journal papers [19,21] focusing on joint consideration of PM and two-dimensional EW policies. Shahanaghi et al. [19] developed a model to determine the optimal PM decisions during the two-dimensional EW period. They assumed that imperfect PM actions were conducted during only the EW period, and no PM was scheduled during the BW period. In a recent work, Wang et al. [21] attempted to link the two-dimensional BW and EW contracts in an integrated manner, and then to identify the optimal number of PM actions during both periods.

In addition, some other studies (see [8,22–26] for instance) on PM modeling and optimization are also related to our problem of interest, although they do not take EW into consideration. Among them, Kim et al. [8] developed a framework for cost analysis linking warranty and PM policy from a life-cycle perspective. In Ref. [8], the PM actions are performed at discrete time instants, and the effect of PM is characterized by the reduction of virtual age. A variation of the modeling framework in [8] is adopted in this study to serve the research purpose.

1.3. Contributions of this work

In practice, an EW contract is usually optional for interested customers, either at the time of item sale or when the BW expires [12,20,27]. Therefore, this paper outlines a framework for the optimization of PM strategies by considering the moments of customers purchasing the two-dimensional EW contract. It is highlighted that when the EW is purchased just before the BW expires, the PM optimization problem exhibits a *two-stage* nature. To our knowledge, this is the first attempt to investigate the two-stage imperfect PM optimization problem by taking into account the moments of customers purchasing the EW contract.

Moreover, conventional PM strategies are usually age-based or usage-based. For instance, under the age- [usage-] based strategy, PM actions are scheduled according to a specified age [usage] interval, irrespective of the item's usage intensity. By now, implementing PM actions based on a two-dimensional framework, by considering age and usage intervals simultaneously, has received little attention. A new strategy, called *two-dimensional PM strategy*, is considered in this work. Under this strategy, imperfect PM actions are conducted every K units of age or L units of usage, whichever occurs first. Recently, Wang and Su [28] numerically demonstrates that the two-dimensional PM strategy is superior, or at least identical, to the age-based and usage-based strategies in terms of warranty servicing cost.

Furthermore, most existing studies on PM assume that a unified PM program is specified for all customers, regardless of their usage intensities or operating conditions. As a matter of fact, different usage intensities would result in different rates of item deterioration. Thus, it is wiser for the manufacturer to design *customized* PM programs for different customer categories. Motivated by this consideration, the manufacturer can classify customers, at the end of the BW, based on their usage rates throughout the BW period and then provide them with customized PM programs over the EW period. An illustrative example is presented to demonstrate the advantage of the customized PM policy.

In short, the settings and contributions of this paper differ from existing literature (especially [19,21]) in the following aspects: (1) a two-dimensional PM strategy is proposed; (2) a two-stage imperfect PM optimization framework is developed and investigated; (3) for the two-stage problem, the possibility of reducing servicing cost over the EW period through offering customized PM programs is demonstrated.

The remaining of this paper is structured as follows. Section 2 introduces the modeling framework, including the item failure model, the PM model and the framework of two-stage PM optimization. Then, the two-stage PM optimization problem are presented and analyzed in Section 3. In Section 4, a numerical example is provided to illustrate the applicability of the proposed model. Finally, Section 5 concludes this paper.

2. Modeling framework

2.1. Assumptions

The following assumptions are made in developing the mathematical model.

(1) The item of interest is repairable and deteriorates with both age and usage, i.e., without maintenance intervention its failure rate will increase as age and/or usage increases.
(2) The usage rate varies randomly across the customer population but is constant over time for a specific customer.
(3) An EW is optional for interested customers at the time of item sale and/or when the BW terminates. It is also supposed that the EW is provided and serviced solely by the manufacturer.
(4) During both BW and EW periods, a two-dimensional PM strategy is offered and paid by the manufacturer.
(5) Since the manufacturer bears the PM costs, the customers have to take their items into designated service centers for scheduled PM services where their average usage rates throughout the BW period can be identified.
(6) All failures under warranty are rectified minimally, which means that the item's reliability after repair is the same as that just before failure.
(7) The time to repair a faulty item, as well as to perform a PM action, is sufficiently small compared to the mean time between failures, and thus is assumed to be negligible.

Remark 1. The assumption (2) above is fundamental for the marginal approach of two-dimensional failure modeling, which will be mentioned later. Rationality of this assumption is supported by automobile warranty data analysis. For example, Gupta et al. [29] claim that the correlation coefficient between age and mileage is usually over 0.7, while the same corresponding to the age and usage rate is usually very low and sometimes even less than 0.1. It is therefore reasonable to assume that the usage rate is primarily determined by the customer's usage pattern, and independent of the age. This assumption has been widely adopted in the literature; see [30–33] for example.

Remark 2. The assumption (5) is essential for developing customized PM programs. Previous literature usually bears the