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Optimal preventive maintenance strategy for repairable items under two-dimensional warranty

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ABSTRACT

For repairable items under the two-dimensional warranty, the manufacturer expenses warranty costs for rectifying the failures occurring over the warranty coverage. Preventive maintenance actions reduce the occurrence intensity of item failures, and hence the warranty cost resulted from corrective maintenance, but bring additional preventive maintenance cost. In this paper, we investigate a periodic and imperfect preventive maintenance strategy for an item covered by a fixed and combined base warranty and extended warranty region from the manufacturer's perspective. After the base warranty expires, the buyer purchases an extended warranty service contract from the same manufacturer for extra protection. Over the whole warranty coverage, the item failures are minimally repaired by the manufacturer at no cost to the buyer. The effect of preventive maintenance action is characterized by reducing the item's failure intensity proportionally to the maintenance degree at each preventive maintenance action. Then a mathematical model is proposed to derive the optimal preventive maintenance strategy so as to minimize the total expected warranty servicing cost to the manufacturer. A numerical example is presented to illustrate the application of the proposed model and evaluate the impact of different model parameters on the optimal solutions and the corresponding warranty servicing costs.

1. Introduction

Due to the rapid technological development and fierce competition in the marketplace, new products are becoming more complex, and less easily evaluated by consumers, who face a degree of uncertainty with regard to perceive product performance directly when making purchase decisions. In such situation, warranty is a good indicator of product reliability and an effective tool to promote sales and compete with other manufacturers. A warranty is a contractual agreement between the product manufacturer and the consumer. It specifies the manufacturer's obligation in the event that the product is unable to perform satisfactorily when properly used. A new product is often bundled with a *base warranty* (BW) [15], which is free of charge and integrated into the product sale. The manufacturer provides, in addition, an option of *extended warranty* (EW) [14] for consumers in case of BW expiration. In contrast to the BW, the EW is a separate warranty service contract which the consumer can purchase for further protection beyond the BW coverage. For the manufacturer, the EW provides an additional source of revenue, and a potential to keep a solid relationship with buyers [11,16].

A warranty policy states the extent of the warranty coverage and the type of compensation provided to the customers in the case of failures. The compensation may be specified as a free/pro-rata repair or replacement, lump sum payment and so on. Depending on the number of variables used to define the limits of warranty coverage, a warranty policy can be either one- or two- (or more) dimensional [1]. A one-dimensional warranty policy is usually characterized by a calendar time interval on the age of the item, called warranty period. In contrast, a two-dimensional warranty policy is characterized by a two-dimensional region, with one axis representing item age and the other one representing item usage. For example, a typical warranty for an automobile can be expressed as a free repair warranty for a maximum of 2 years or 60,000 miles, whichever comes first.

Given any type of warranty policy, the manufacturer incurs additional warranty cost due to warranty claims servicing. According to the 2013 General Motors annual report, the firm had total revenue of US$155.4 billion and the warranty servicing cost on sold cars was estimated to be US$3.2 billion—about 2.1% of the revenue. Within the warranty coverage, two types of maintenance are commonly carried out for warranty service, which are

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corrective maintenance (CM) and *preventive maintenance* (PM) [5]. A CM action in the type of repair or replacement, is usually unscheduled to restore a failed item back to its operational state. The repair could be minimal which restores the failed item to the same state as it was before failure, or imperfect which brings the failed item back to a state between “as good as new” and “as bad as old”. A replacement is equivalent to a perfect repair by restoring the item to the level as if it were new. Compared to a CM action, a PM action is commonly scheduled and performed before the item fails, aiming to control the degradation and reduce the likelihood of failures. A PM action, the degree of which being determined and controlled by the manufacturer, can also be either perfect or imperfect. Performing PMs reduces the warranty servicing cost by improving the reliability of the product, but at the expense of additional PM costs on the other hand. This is worthwhile only if the reduction in the warranty servicing cost exceeds the cost of PM actions [5,12]. An effective PM strategy has therefore a significant impact on the warranty servicing cost to the manufacturer.

There has been lots of attention paid to the integrated research on product warranty and maintenance. The literature with details on mathematical model of warranty servicing cost involves the role of effective servicing strategy on the warranty cost reduction. The related work can be classified into the following three main categories [16]: (a) warranty servicing with only CM actions; (b) warranty servicing with both CM and PM actions; and (c) maintenance during the post-warranty coverage. In this paper, we confine our scope to the category (b), which deals with the use of PMs to achieve a trade-off between the reduction in the expected warranty cost and the additional PM cost. The related research is reflected in the available publications where the vast majority treat problems under one-dimensional warranty policy [2–5,10,13,12,21,24]. In contrast, the research on servicing strategies for the two-dimensional case is still limited. Iskandar et al.[7–9] have studied several repair–replace strategies for items sold with two-dimensional failure free warranty. Considering both fixed and random degrees of repair, Varnosafaderani and Chukova [20] have studied a two-dimensional warranty servicing strategy involving minimal repair and imperfect repair to find the minimum expected warranty cost. Su and Shen [19], Shahanaghi and Noorossana [18] have proposed several warranty cost models to determine the optimal setting of PM program implemented the two-dimensional EW coverage.

The above researches focus on the optimal warranty servicing strategy design without incorporating the BW and EW in an integrated manner, expect that of Wu and Longhurst [23], which focus on finding the optimal opportunity-based age replacement policy and EW length to minimize the expected life cycle cost from a consumer's perspective. Such a separation may result in different selections for the optimum PM strategy. The ideal strategy under either BW or EW coverage may be not the best one for the manufacturer when considering both warranty policies. From the manufacturer's perspective, it is necessary to link the BW and EW contracts, estimate the total expected warranty servicing cost to the manufacturer, so as to derive the optimal PM strategy within the whole warranty region. In this paper, we look at a periodical and imperfect PM strategy for repairable items under two-dimensional warranty. The objectives are to (i) connect the BW and EW from the manufacturer's perspective, (ii) identify the optimal PM strategy including the number of PM actions performed in both BW and EW coverages, and (iii) explore the effect of different model parameters on the optimal PM strategy and the associated warranty servicing costs.

The rest of the paper is organized as follows. The modeling assumptions and notations are listed in Section 2. In Section 3, the mathematical model analysis is illustrated to estimate the expected warranty servicing cost under the PM scheme. In Section 4, we present a numerical example to evaluate the performance of the proposed PM strategy. Finally, the concluding remarks are given in Section 5.

2. Model assumptions and notations

In this section, the model assumptions and notations used in the paper are presented.

2.1. Model assumptions

Before developing the mathematical model, several assumptions are listed as follows:

- All the item failures during the warranty coverage are statistically independent and minimally repaired.
- Each failure affects the item's performance and results in a warranty claim.
- All warranty claims are valid, and the following-up warranty services offered by the manufacturer are necessary.
- After the BW ceases, the buyer purchases an EW contract from the same manufacturer for further protection.
- The manufacturer implements a periodical PM program, and the time required for performing each PM action is negligible.
- No PM action is taken at the time of sale of the product, and the last PM action is assumed to be performed at the end of warranty coverage.
- After each PM, all the subsequent item failures are minimally repaired by the manufacturer till the next PM occurs.

Table 1
Mathematical notations and description.

Notation	Description
W_0,U_0	Age and usage limits of the BW coverage
W_1,U_1	Age and usage limits of the EW coverage
x, u	Actual age and usage of the item
R	Usage rate of the item
$g(r)$, $G(r)$	Density function and cumulative distribution function of R
n, m	Expected number of PM actions in the BW and EW regions, respectively
$\lambda_0(x\|r)$	Conditional failure intensity of the item with no PM actions
$\lambda_k(x\|r)$	Conditional failure intensity after the kth PM action, $1 \le k \le n+m$
τ_0, τ_1	Expected PM time intervals in the BW and EW regions, respectively
δ	Preventive maintenance degree
T_k	Time instant for performing the kth PM, $k=1,\ldots,n+m$
C_m	Expected cost of each minimal repair
$C_p(\delta)$	Expected cost of each PM action with the PM degree δ