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Flexible decision models for a two-dimensional warranty policy with periodic preventive maintenance☆

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ABSTRACT

We study the consumer's and the manufacturer's optimal strategies for items sold with periodic preventive maintenance (PM) under a two-dimensional warranty policy. The cooperative and non-cooperative interactions between the manufacturer and the consumer are investigated for both the base warranty (BW) period and the extended warranty (EW) period. Under the BW, we propose a new upgrade model where the cost of PM is shared by two sides. In the EW period, consumers are assumed to have the option to either accept or reject PM at each time based on his utility. Two upgrade models are built and the revenue functions are analyzed. Profit maximization and cost minimization for both sides are analyzed by a game-theoretic approach. It is shown that the manufacturer's and the consumer's decisions are different, so the induced hazard rate functions are also different. In static and dynamic scenarios, we derive the equilibrium number of PM, the equilibrium value of acceptance probability and the equilibrium upgrade level for both the BW and the EW cases. Numerical examples are discussed to demonstrate the applicability of the methodologies. The results about the optimal solutions of the expected profit functions for the consumers and the manufacturer are provided.

1. Introduction

Product warranty and maintenance service are crucial to new product marketing and sales. Nowadays, many new products (e.g., medical systems, manufacturing systems and defense systems) become more complex and multi-functional and the maintenance of these products turns out to be more difficult and costly. The manufacturers of these new products have transformed their business strategies from a pure product-oriented strategy to a strategy with a stronger focus on after-sales services, including warranty contracts, preventive maintenance services, spare parts sales, etc. [13]. For instance, Jaguar and Hyundai in the automobile market, Panasonic, Samsung and Sears in the home electronics market [36], the Templer Systems in the test and measurement equipment market [50], highlight their attractive product warranties for sales purposes. A study conducted by Accenture [14] shows that, in 2003, after sales services constitute on average 25% of the total revenues across all manufacturing companies (in North America, Europe, and Asia), and they are responsible for 40–50% of the profit.

Traditionally, many products are sold with a base warranty (BW) period in which the manufacturers or retailers offer free maintenance services when the product fails. Once the BW period expires, the manufacturers will charge the consumer for providing spare parts, maintenance, and other services to keep the availability of the systems. This may lead to higher service costs and lower system availabilities than a consumer anticipated when buying the system. Extended warranties (EWs) are thus required by consumers to avoid this undesired situation. Many firms (e.g., Sears, Apple, GM, etc) [33] provide extended warranties in order to obtain competitive advantage, increase the market share and improve the quality of after-sales services. As an optional purchase of service contract for the consumer, the EW provides additional coverage for an item after the expiry of the BW. This flexible policy can also cater to customer behavior variations such as heterogeneous customer risk preferences [48], heterogeneous customer use rates [39], and both of these two factors [47].

Since the extended warranty provides consumers a flexible manu for use, based on different use rates [25,26,33,51] and risk preferences [15,16], consumers need to find a good tradeoff between the EW cost and its effects on the products. In this regard, Chien [8] and [10] considered the effect of pro-rata warranty on the age replacement policy and preventive maintenance (PM) strategy. Wu and Huang [49] used a Bayesian approach to determine the optimal warranty lengths.

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Nomenclature

K, T	Parameters of the two-dimensional warranty policy
L	Upgrade level
C_0	Setup cost of the upgrade action per time in upgrade model 1 in EW
C'_0	Fixed cost of the upgrade action per time in upgrade model 2 in EW
C_1, C_2, C_3	an adjustment coefficient of L, T and K
Ω_i	Two-dimensional warranty region
T_B, K_B	Base warranty restriction
T_E,K_E	Extended warranty restriction
τ_1,τ_2	PM period for light users
l_1	Upgrade level under BW
δ	Upgrade level under EW
β_1, β_2	A relative increase of cost required by the manufacturer
τ'_1, τ'_2	PM period for heavy users
r_0	Normal usage rate
r	Usage-rate
$G(r)$	The distribution function of r
$g(r)$	The intensity function of r
$g(r\|r \in [r_s, r_0])$	The conditional intensity function of r in light case
$g(r\|r \in [r_0, r_b])$	The conditional intensity function of r in heavy case
m,n	Number of PMs in base and extended warranty
α	Probability of accepting the service
$h(t\|r)$	Failure intensity function under usage rate r
E_{cB}	Profit of a consumer in BW
E_{dB}	Cost of the manufacturer in BW
E_{cE}	Profit of a consumer in EW
E_{dE}	Profit of the manufacturer in EW
W_1	PM profit in BW
W_2	PM profit in EW
W_0	EW fee
$\mathcal{A}$, $\mathcal{B}$, $\mathcal{C}$, $\mathcal{D}$	Solution sets

Blischke and Murthy [1–3], Chien [10], Murthy and Jack [30] and Shafiee and Chukova [39] summarized a variety of warranty policies and the cost analysis associated with these policies. However, only a few works have been carried out in the literature on the EW policy that provides flexible options open to consumers. Lam [24] proposed an extended warranty model with options open to consumers following a free replacement warranty, and Wu and Longhurst [48] analyzed the life cycle cost of equipment protected by both base and extended warranty policies from a consumer's perspective, assuming that the equipment has non-renewing free replacement warranty. Su and Shen [41] analyzed the extended warranty policy with different repair options. Bouguerra et al. [4] addressed the problem related to the adoption of an extended warranty period for failed products sold under free minimal repair warranty. Jung et al. [22] studied an extended warranty model under which the customer was offered an additional warranty period after the original two-phase warranty expired. They determined the optimal length of maintenance period after the extended warranty expired from the consumer's perspective. Interested readers are referred to Murthy and Jack [30] for recent advances.

In the warranty periods, the repair strategies are essential for maintaining and upgrading the failed products. The commonly used repair strategies include complete repair, imperfect repair and minimal repair (see Pham and Wang [38]). For example, in the context of automobile repairs [38], a typical example of minimal repair would be changing the tires, rectifying the ignition or wiring system, or any repair of the engine that does not change the car's overall performance. Whereas a typical complete repair would be a transmission replacement or an engine replacement. Engine tune-up is an example of imperfect maintenance because an engine is not as good as new but its performance might be greatly improved. Many papers have studied optimal maintenance strategies. Chukova and Johnston [11] considered when and how to carry out minimal repairs and complete repairs. Park et al. [35] presented a warranty cost model when an age replacement policy is adopted in conjunction with the renewal of a minimal repair-replacement warranty. For Markov deteriorating systems, Pan and Thomas [34] optimized the sequential decisions of minimal repair versus replacement over time. Yun and Kang [53] obtained the optimal imperfect repair strategies under two-dimensional warranty. Kim et al. [23] studied the optimal maintenance level for second-hand product and obtain the optimal maintenance level. Chien [7] and [9] studied the effects of a renewing free-replacement warranty (complete repair and imperfect replacement) on the age-replacement policy. Bram [5] investigated the effect of parameter uncertainty on the optimal age-based maintenance strategy. Lin [28] undertook a general reliability study using both classical and Bayesian semi-parametric degradation approaches.

In this paper we are mainly interested in developing the optimal maintenance strategy and optimal choice of PM for a two-dimensional warranty policy from the manufacturer's and the customer's perspective respectively. In principle, there are two types of warranty policies provided by manufacturers or sellers: one- and two-dimensional (2-D). The former is characterized by an interval called the warranty period, and the latter usually uses a product's usage and age for two dimensions. A good example for 2-D warranty policy is the vehicle warranty policy using age and product usage. Different characteristics for 2-D warranty can be found in Park and Pham [36] and [37], in which the authors considered failure times and repair times as two dimensions for warranty policy. One of the main concerns that arises from the warranty policy is to obtain the optimal warranty period and the corresponding warranty cost. Many works intended to find the optimal maintenance strategy to minimize the total cost in the two-dimensional warranty, e.g., Hu et al. [17], Huang et al. [20], Jack et al. [21], Huang and Yen [19], Varnosafaderani and Chukova [44], Chang and Lin [6], Wang et al. [45], Huang et al. [18], among others. Recently, Ye and Murthy [50] investigated the design of a flexible two-dimensional warranty policy that contains a number of rectangular regions. Wang and Su [46] proposed a new PM strategy called 2-D PM strategy in the 2-D warranty. They used the marginal approach to describe the effect of age and usage on item reliability by treating usage as a random function of age. Su and Wang [42] studied the optimal upgrade policy for used products sold with two-dimensional warranty. Su and Wang [43] investigated the optimization of imperfect preventive maintenance from the manufacturer's perspective considering the moments of consumers purchasing two-dimensional extended warranty.

In most of these papers mentioned above, however, the interaction between consumers and manufacturers in real scenarios is overlooked somehow. For instance, to balance the maintenance cost and profit maximization, it is essential for manufacturer to take PM action periodically on the product to improve the system reliability. On the other hand, based on the consumers' justification of the products' status, more flexible policy should be rendered to consumers by allowing them to select separately each time when the periodic PM action is scheduled to perform.

The main objective of this paper is to find an optimal periodic PM schedule for the products in the BW period, and to find a hybrid periodic PM policy in the EW period based on the interactions between the manufacturer and consumers by virtue of game theory. To the best of our knowledge, such an optimal hybrid PM strategy has not been