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Remanufacturing and pricing decisions with random yield and random demand

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ABSTRACT

Remanufacturing is creating considerable benefit to industry and community, but the uncertainties in both supply and demand sides bring significant difficulty to the production and marketing management of remanufactured products. This paper considers the remanufacturing and pricing decisions when both the remanufacturing yield and the demand for remanufactured products are random. Two typical sequential decision strategies are explored: First-Remanufacturing-Then-Pricing (FRTP) and First-Pricing-Then-Remanufacturing (FPTR). The optimal remanufacturing quantity and selling price of the remanufactured product are developed for each strategy, under negligible salvage value and shortage penalty. We also conduct a numerical study to investigate the scenario where the salvage value and shortage penalty are non-negligible, and explore the parameter sensitivity of the systems. We find that FRTP strategy is more preferable for low remanufacturing cost, market-price sensitivity, and variance of demand randomness, and for high shortage penalty, salvage value, and variance of remanufacturing yield; while FRTP strategy is more preferable for the complementary situation.

1. Introduction

As a sound way to deal with products after customer usage, remanufacturing represents great opportunities for improving productivity, saving resources, and establishing good image for enterprizes. Therefore, many businesses have emerged to exploit potential profitable remanufacturing opportunities. It is reported that the size of the remanufacturing sector in the U.S. has reached 53 billion, involving over 70,000 firms and 480,000 employees [12]. The remanufacturing industries in Europe and Asia are also developing fast.

However, a major challenge for remanufacturing firms is the inherent variation in the condition of used products. For example, the uncertainty lies in many remanufacturing industries, such as automobiles, cell phones and other electronic appliances, regarding the percentage of used products that can actually meet the quality criteria to be remanufactured. This percentage is usually called as remanufacturing yield. The uncertainty in the remanufacturing yield combined with the uncertainty in market demand for the remanufactured product adds difficulty into the management for the remanufacturing firm, who has to carefully choose appropriate remanufacturing and marketing strategies to maximize his profit.

This paper explores the remanufacturing and pricing decisions in such uncertain circumstances. Specifically, we capture the remanufacturing yield as a random variable to model the uncertainty in the remanufacturing process which stems from the used product quality variation, and assume that the market demand is also random and price-sensitive. We consider two remanufacturing-pricing strategies: First-Remanufacturing-Then-Pricing (FRTP) and First-Pricing-Then-Remanufacturing (FPTR). Under FRTP strategy, the firm first determines the remanufacturing quantity of the used products and after the realization of the remanufacturing yield, the firm determines the selling price of the remanufactured products and finally realizes the demand. In contrast, the firm adopting FPTR strategy first determines the selling price and realizes the demand for the remanufactured products, and then chooses the remanufacturing quantity with consideration of the realized demand and the knowledge of random yield distribution. Both strategies are commonly adopted in real industry. In fact, FRTP is more preferable in the second-hand market for remanufactured cellphones and cars as the selling price can be adjusted according to the quantity and quality of collected cores, while FPTR exists usually in combination with the make-to-order production policy when electronic products are remanufactured and sold via an online store, *e.g.*, Dell, Apple, or Gateway Computers, as the case in Vorasayan and Ryan [28] indicates. Under each strategy, we utilize a two-step stochastic dynamic programming to solve the problem, and obtain closed-form solutions of the optimal selling price and remanufacturing quantity under negligible salvage value for leftover remanufactured products and shortage penalty for unmet

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demand. Although it is difficult to analytically solve the problems under non-negligible salvage value and shortage penalty, we conduct a numerical study which shows the uniqueness of the optimal solutions, and more importantly, reveals the answers to the following questions: what are the effects of the main parameters to the decisions and system performances, such as the remanufacturing cost, the salvage value, the shortage penalty, and the variances of yield randomness and demand randomness? When should the firm adopt FRTP strategy or FPTR strategy?

In what follows, we briefly relate our paper to the literature, including the study on remanufacturing and pricing strategies in the remanufacturing systems.

There has been substantial research into the remanufacturing planning and inventory management in remanufacturing systems, *e.g.*, Langella [18], Qu and Williams [26], and Shi et al. [27], etc. For a comprehensive review in this aspect, we refer the reader to Dekker et al. [5], Guide and Van Wassenhove [11], and Ilgin and Gupta [14]. Our study is particularly related to those considering remanufacturing quantity decision with a random remanufacturing yield under the single-period framework, which are similar to the setting of this paper. Ferrer [7] provides optimal lot-size policies for remanufacturing processes subject to random yield and examine the value of information and how it changes with the time of its acquisition in the remanufacturing site. Ketzenberg et al. [16] also investigate the value of yield information in determining the optimal configuration of a mixed assembly–disassembly line. Ketzenberg et al. [17] explore the value of information in the context of a firm that faces uncertainties with respect to demand, product return, and product remanufacturing yield. Bakal and Akcali [2] study the problem of determining the optimal acquisition price for the end-of-life products and the selling price for remanufactured parts under a random remanufacturing yield. Zikopoulos and Tagaras [32] investigate the acquisition and production problems in a reverse supply chain consisting of two collection sites and a refurbishing site, and examine how the profitability of reuse activities is affected by the uncertainty of the random yield representing the quality variation of returned products. Mukhopadhyay and Ma [24] investigate a hybrid system where both used and new parts can serve as an input in the production process to satisfy demand in which the quality variation of returned product parts is modeled through a random yield. Li et al. [21] address the joint decision problems of manufacturing, remanufacturing, and acquisition price in a market-driven channel, where both remanufacturing yield and used product acquisition are random. In contrast to the above researches that only focus on the remanufacturing planning, this paper explores the joint decisions of the remanufacturing quantity and the selling price of the remanufactured products.

Compared to the vast literature on the production planning, only a few papers consider the pricing decision of the remanufactured products. Guide et al. [9] develop a quantitative model to determine the optimal acquisition price of used products and the selling price of remanufactured products by assuming that the quantity of return items can be fully controlled by the acquisition price. Karakayali et al. [15] extend the problem of determining the optimal acquisition price of the end-of-life products and the selling price of the remanufactured parts under centralized as well as decentralized remanufacturer-driven and collector-driven decentralized channels. Some other literatures on pricing remanufactured products are mainly involved in the market competition between new and remanufactured products. For example, Majumder and Groenevelt [22] describe a two-period model on pricing both the new and remanufactured products under the assumption of indistinguishable quality between remanufactured and new product, but distinguishable brand between the competing OEM and remanufacturer. Ferrer and Swaminathan [8] extend Majumder and Groenevelt [22] into a multi-period setting where the brand competition is carried on in the second and subsequent periods. Ferguson and Toktay [6] adopt a similar two-period model focusing on the strategic role of OEM remanufacturing as an entry deterrent to the local remanufacturer. Other related papers include Debo et al. [4], Heese et al. [13], Atasu et al. [1]. Note that the above papers deal with deterministic models, while this paper considers both random demand and random remanufacturing yield. The exceptions that focus on pricing remanufactured products under stochastic environment are Vorasayan and Ryan [28] and Li et al. [20]. The former models the sale, return, refurbishment and resale processes in an open queueing network, which differs from our paper in both the model (ours is a single-period lot-sizing and pricing model) and the methodology (ours is a discrete stochastic dynamic programming). The latter shares some similarity with this paper on the stochastic demand and yield modeling. But the main point of that paper is to study the influence of risk-preference to the system under a mean-variance framework while this paper assumes risk neutrality and compares two alternative strategies: FPTR and FRTP. The acquisition/production models are also different. Hence, there are fundamental differences between these two papers in the motivation, scope, problem modeling and managerial results.

The rest of paper is organized as follows. In Section 2 we present the model description and assumptions. In Section 3 we establish a two-step stochastic dynamic programming to analyze the system with FRTP strategy and derive the optimal solutions for the remanufacturing quantity and the selling price under negligible salvage value and shortage penalty. In Section 4 we use the similar approach to analyze the system with FPTR strategy. Section 5 provides a numerical study to show the parameter sensitivity and to illustrate when to choose FRTP or FPTR strategy. Section 6 concludes the paper.

2. Model description

Consider that a firm acquires and remanufactures a lot size of used products to satisfy a stochastic demand for the remanufactured products. Due to the quality uncertainty of the acquired used products, there is a random yield ξ in the remanufacturing process. In other words, there is only a percentage ξ of the used products that meet the quality limits and are recovered into the remanufactured products. We suppose ξ is a random variable on the support $[A_1, B_1] \in [0,1]$ with pdf $f_\xi(x)$ and cdf $F_\xi(x)$, and its mean is $\mu < 1$. Define the generalized failure rate of ξ as $g_\xi(x) = x f_\xi(x)/\overline{F_\xi}(x)$. We assume an increasing generalized failure rate (IGFR) of ξ, *i.e.*, $g_\xi(x)$ is increasing in $[A_1, B_1]$. This is a very mild condition that is satisfied by many distributions such as truncated normal, uniform, and also the gamma and Weibull families, subject to parameter restrictions (see [19,23], and the references therein).

The market demand for the remanufactured products is stochastic and sensitive to the selling price p. We assume the demand as the following multiplicative form:

$$D(p) = ap^{-k} \cdot \varepsilon, \tag{1}$$

where $a > 0$ and $k > 1$ are constants representing the market scale and the price-elasticity index, respectively, while ε is a random variable representing the market fluctuation. We suppose that ε has a finite support $[A_2, B_2]$ and normalize $E[\varepsilon] = 1$. Moreover, ε is independent of ξ, and ε also has an increasing generalized failure rate (IGFR). In the literature, both multiplicative and additive forms are commonly used in modeling demand randomness. We choose the multiplicative form in this paper for its convenience in obtaining analytical results, which is adopted in Wang et al. [30], Wang [29], and Cai et al. [3], etc.