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Optimal acquisition and production policy in a hybrid manufacturing/remanufacturing system with core acquisition at different quality levels

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ABSTRACT

We study the acquisition and production planning problem for a hybrid manufacturing/remanufacturing system with core acquisition at two (high and low) quality conditions. We model the problem as a stochastic dynamic programming, derive the optimal dynamic acquisition pricing and production policy, and analyze the influences of system parameters on the acquisition prices and production quantities. The production cost differences among remanufacturing high- and low-quality cores and manufacturing new products are found to be critical for the optimal production and acquisition pricing policy: the acquisition price of high-quality cores is increasing in manufacturing and remanufacturing cost differences, while the acquisition price of low-quality cores is decreasing in the remanufacturing cost difference between high- and low-quality cores and increasing in manufacturing and remanufacturing cost differences; the optimal remanufacturing/manufacturing policy follows a base-on-stock pattern, which is characterized by some crucial parameters dependent on these cost differences.

1. Introduction

The manufacturing industry is witnessing a growing practice of firms acquiring and remanufacturing used products returned from end-users, which are usually called cores, to obtain economical benefits and establish social images. Successful examples include the remanufacturing systems of Mercedes-Benz, IBM, DEC and Xerox (Atasu et al., 2008). One of the most important characteristics in such manufacturing/remanufacturing systems is the uncertainty of returns, including the uncertainty in return quantity, quality and timing. To better cope with such uncertainty, a market-driven acquisition channel can be adopted in which an acquisition price is offered to the end-users or core suppliers. With a higher acquisition price, the acquisition quantity for the firm can be larger and the quality of the cores can also be raised. Moreover, a grading procedure can be adopted to classify the cores with different quality conditions. For example, ReCellular, Inc., who is a leading remanufacturer of cellular phones, adopts the grading and pricing scheme in Table 1.

In this paper, we consider a hybrid manufacturing/remanufacturing system with core acquisition subject to different quality conditions. The cores are classified into high and low quality levels. In each period, the quality-dependent acquisition prices are set to replenish the inventories of high- and low-quality cores; the stochastic demand is satisfied with the serviceable inventory fulfilled by manufacturing new products and/or remanufacturing the units from the cores inventory; the leftover inventories are carried over to the next period and the shortage is backordered. The incurred costs include the acquisition costs, the remanufacturing and manufacturing costs, and the backordering cost for unsatisfied demand if any. We develop a stochastic dynamic programming to formulate this dynamic acquisition pricing and production planning problem, to minimize the total discounted cost over a finite number of time periods. The optimal production policy is characterized by three parameters, referred to as *remanufacture-up-to-level-of-high-quality*(RUTL-HQ), *remanufacture-up-to-level-of-low-quality*(RUTL-LQ), and *manufacture-up-to-level*(MUTL); the optimal acquisition pricing policy is highly dependent on the cost differences among manufacturing new products and remanufacturing high- and low-quality cores.

In what follows, we briefly relate our paper to the literature, including the studies on inventory management of hybrid manufacturing/remanufacturing systems, and on core acquisition management in remanufacturing systems.

Numerous researchers have studied inventory management of hybrid manufacturing/remanufacturing systems. Simpson (1978) first studies a hybrid system with serviceable inventory and repairable inventory in which the demands and returns can be dependent and stochastic, and provides the optimality of a

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Table 1
Quality grading and acquisition prices of ReCellular in 2011.

Quality grades	iPhone (3GS 16G)	Description
Totally Broken/ Heavy Wear	$20	Phone might work or mostly works, has heavy scratches, something broken or water damage
Normal Wear/Tear	$167	Phone works well and looks pretty good despite having survived a few drops (some scuffs and scratches)
Light Wear/Looks New	$184	Phone is in really good shape, everything works and looks almost brand new or better

three-parameter inventory policy. Kelle and Edward (1989) consider a different model of independent demand and return processes with all returned products remanufactured. Inderfurth (1997) shows that the policy derived in Simpson (1978) is still optimal in the case of fixed costs and identical leadtimes for remanufacturing and procurement activities. Van Der Laan et al. (1999) analyze push and pull control strategies in a hybrid system, and compare them with the traditional systems without remanufacturing. Teunter et al. (2004) explore the superior inventory strategies for hybrid manufacturing/remanufacturing systems with a long leadtime for manufacturing and a short leadtime for remanufacturing. DeCroix and Zipkin (2005) and DeCroix (2006) extend the problems into the multi-echelon inventory setting. Denizel et al. (2010) consider the quality uncertainty of the cores for remanufacturing. Zhou et al. (2011) explore a periodic-review hybrid system with inventories of multiple quality classes of cores, and show that the optimal inventory policy has a simple linear structure when manufacturing and remanufacturing leadtimes are identical. All the above papers assume that the product returns are exogenous and uncontrolled, while our paper focuses on the decisions of acquisition price which are related to the acquisition quantity and quality of the cores.

Although the research on hybrid systems is vast, only a few papers consider a market-driven acquisition channel which uses acquisition price to control the quantity and quality of the cores. Guide et al. (2003) is the first to build a quantitative model to analyze acquisition pricing problem for a remanufacturing system with returned products of different qualities. Bakal and Akcali (2006) extend the model to a remanufacturing system with a random yield, and Karakayali et al. (2007) study the problem in a decentralized supply chain environment, with remanufacturer-driven and collector-driven channels, respectively. Galbreth and Blackburn (2006) study the optimal acquisition and sorting policies in the presence of cores condition variability. Then, Galbreth and Blackburn (2010) extend the model to consider optimal acquisition quantity for remanufacturing and scraping in the presence of quality uncertainty. Li et al. (2012) consider the uncertainty in both acquisition quantity and remanufacturing yield. All the above papers consider a pure remanufacturing system under a single-period setting, while our paper studies the acquisition and production planning problem for a hybrid system under a multi-period setting. Moreover, Kaya (2010) investigates the joint decisions of the acquisition price with the remanufacturing and manufacturing quantities under both perfect and partial demand substitution. Zhou and Yu (2011) develop a periodic-review single-product hybrid system with price-dependent customer demand and acquisition effort dependent returns. The optimal production–remanufacturing–disposal policy in the case of exogenous selling price is shown to be simply characterized by three state-independent parameters. The above two papers assume that the quality conditions of acquired cores are homogeneous, while we consider the cases in which the cores can be classified into two quality levels and highlight the role of the remanufacturing cost difference between the quality levels. To the best of our knowledge, this paper is the first to integrate the production planning with the acquisition pricing decisions for the cores of different quality levels in a hybrid manufacturing/remanufacturing system.

The rest of the paper is organized as follows. In Section 2, we develop a stochastic dynamic programming model for our problem. Section 3 derives the optimal policy of the acquisition prices and the remanufacturing/manufacturing quantities. Section 4 provides numerical experiments to examine the analytical results and generates more insights. Section 5 concludes the paper with future research directions.

2. Model description and formulation

We consider a hybrid manufacturing/remanufacturing system (shown in Fig. 1) with a serviceable inventory and two core inventories: the inventory for high- and low-quality cores, respectively. The system is operated under a planning horizon of T periods. Demand $D(t)$ in each period is satisfied by the serviceable inventory, which is periodically replenished by newly manufacturing and/or remanufacturing the units from the two cores inventories. At the beginning of each period t, the system first reviews the initial levels of the serviceable inventory $I(t)$, the high-quality cores inventory $J_H(t)$ and the low-quality cores inventory $J_L(t)$. Then the following decision variables are determined, including: the acquisition prices $r_H(t)$ and $r_L(t)$ for the high- and low-quality cores, the remanufacturing quantities $w_H(t)$ and $w_L(t)$ for the high- and low-quality cores, and the manufacturing quantity $z(t)$ of the new products. We assume that the acquisition quantities deterministically depend on the acquisition prices, and the leadtimes of cores acquisition, remanufacturing and manufacturing processes are neglected. Hence, all the decisions in period t are made simultaneously before demand $D(t)$ is realized. After the realization of demand $D(t)$, the shortage is backordered and the leftovers are carried over to next period $t+1$.

This problem can be formulated as a Markov decision process (MDP) over T time periods. We introduce the elements of this MDP as follows:

- *State* at the beginning of period t is denoted by $(I(t), J_H(t), J_L(t))$, which stands for the initial levels of the serviceable inventory and the high- and low-quality cores inventories, respectively.
- *Decision variables* are
  – $(r_H(t), r_L(t))$, the acquisition prices of high- and low-quality cores.
  – $(w_H(t), w_L(t), z(t))$, the remanufacturing quantities of high- and low-quality cores, and the manufacturing quantity.

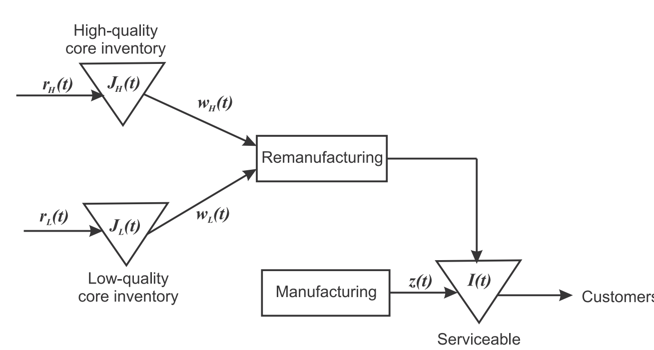

Fig. 1. A hybrid manufacturing/remanufacturing system with the cores of two quality levels.