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Modeling and analysis of a product substitution strategy for a stochastic manufacturing/remanufacturing system ☆

S. Sebnem Ahiska *, Emre Kurtul

Industrial Engineering Department, Galatasaray University, Ortakoy 34349, Istanbul, Turkey

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ABSTRACT

Many original equipment manufacturers (OEMs) are implementing hybrid manufacturing/remanufacturing systems due to the economic and environmental benefits of remanufacturing such as significant reductions in resource consumption and waste disposal. We consider the periodic-review inventory control problem for such a system where manufactured and remanufactured products are considered non-identical and have separate demand streams. Product returns and demand for both products are stochastic. A remanufactured item has a perceived lower value by the customer and thus has a lower price than a manufactured item. The manufacturer considers the use of a one-way product substitution strategy. When the remanufactured item inventory is out of stock, manufactured items are sold for the remanufactured item price (i.e. lower price) to the customers who demand remanufactured items. The problem is formulated as a discrete-time Markov Decision Process in order to find the optimal inventory policies with substitution and without substitution. The behavior of the system under product substitution strategy and its profitability is investigated through a numerical study based on real data from an automobile parts manufacturer. Results show that profitability is significantly affected by the remanufactured item price (p_r) to manufacturing cost (c_m) ratio. As p_r/c_m decreases, the increased profit provided by the substitution strategy over not substituting falls at an increasing rate. However, even when p_r/c_m ratio goes below 1 (i.e. unit profit by substitution is negative), substitution may still be profitable due to savings in lost sales.

1. Introduction

Product recovery has received growing attention among manufacturers in the last couple of decades. Through product recovery, the raw materials and/or some parts of the recoverable items can be reused significantly reducing the amount of waste disposed using landfilling or incineration. It also provides resource conservation since recovered materials are used instead of virgin materials in production of new items. These reductions result in savings in disposal, raw material, energy and labor costs. Thus, product recovery activities have positive impact on both environment and economy. In several countries, environmental regulations (e.g. take-back obligations after usage) make manufacturers responsible for the entire product life cycle (Fleischmann, BloemhofRuwaard, Dekker, Van der Laan, Van Nunen, & Van Wassenhove, 1997). Expectations of consumers also put pressure on companies to consider environmentally conscious manufacturing and product recovery (Gungor & Gupta, 1999). A green image for a company has become a powerful marketing tool and provides a significant competitive advantage in the global market. These economic and environmental concerns have led many manufacturers to implement recoverable manufacturing systems (Inderfurth & Van der Laan, 2001).

Remanufacturing is usually considered as a recovery process in which a returned (recovered) item is transformed to a "like new" one that is equivalent to the original manufactured product, through several operations including disassembly, cleaning, testing, part replacement/repair, and reassembly (Naeem, Dias, Tibrewal, Chang, & Tiwari, 2013). Examples for such remanufacturable products include mostly high-value industrial products such as aircraft or automobile engines, aviation equipment, railroad locomotives and equipment, medical equipment, office furniture, and machine tools, as well as copiers, electrical and electronic equipment, toner cartridges, cellular telephones, single-use cameras, etc. (Agarwal, Barari, & Tiwari, 2012; Fleischmann et al., 1997; Guide, Jayaraman, & Srivastava, 1999; Guide & Srivastava, 1997; Jayaraman, 2006; Thierry, Salomon, Van Nunen, & Van

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* Corresponding author. Address: Galatasaray University, Ciragan Cad. No. 36, Ortakoy 34349, Istanbul, Turkey. Tel.: +90 212 2274480x436.

E-mail addresses: sahiska@gsu.edu.tr (S.S. Ahiska), ekurtul13@ku.edu.tr (E. Kurtul).

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Wassenhove, 1995; Toktay, Wein, & Zenios, 2000; United States EPA, 1997). Most studies focus on the case where the remanufactured and manufactured products are considered to have same quality specifications and thus sold for the same price to the same market. However, it is also observed in real life that the remanufacturing can cause a possible downgrading in the product. So, the remanufactured products may be perceived by consumers to have an inferior value and therefore sold at a lower price than a new item. Subramanian & Subramanyam (2012) show that market factors such as the reputation of the seller of remanufactured products and the remanufacturer identity (i.e. whether it is original equipment manufacturer, authorized factory or third party company) significantly affect the consumer's perception and thus the price differences between remanufactured and manufactured products. In this case, separate demand streams occur for those products. Examples for such products include upgraded computers, retread tires, reconditioned photocopiers, overhauled automobile engines and spare parts (Ayres, Ferrer, & van Leynseele, 1997; Ferrer, 1997a, 1997b; Van der Laan, 1997).

When there is a segmented market for manufactured and remanufactured products, the manufacturer may use a stockout-based *one-way* substitution strategy, such that the demand for remanufactured items can be satisfied by new items if the remanufactured item inventory runs out of stock and the new item inventory is positive. This is often referred to as *downward* substitution since a high-value item is substituted for a low-value item. The main reason behind applying a downward substitution strategy is to avoid lost sales and loss of customer goodwill for the remanufactured items. Clearly, the stock-out risk for remanufactured items is higher than the stock-out risk for new items since the remanufacturing capacity of a firm is mainly limited by the returns of recovered items from the field while no such limit exists for the production of new items. Hence new item inventory can also be used to meet remanufactured item demand. For example, Ayres et al. (1997) report a case where the demand for reconditioned copiers is higher than the supply, and the demand for reconditioned copiers is satisfied by the new copiers when the reconditioned copier is out of stock. Substitution of remanufactured items for new items is usually not considered since customers who demand new items prefer not to be offered an "inferior" valued item as a replacement.

In this paper, we consider the inventory control for a periodically reviewed stochastic hybrid manufacturing/remanufacturing (M/R) system with two products and downward substitution. This problem is more complicated than the classical two-product inventory problem with one-way substitution due to stochastic product returns as well as stochastic demand for the two products. We formulate this problem as a discrete-time Markov Decision Process in order to find the optimal inventory policy (i.e. optimal M/R decisions for every inventory state) and the optimal profit for the hybrid system with/without product substitution. Then, through numerical experimentation using real data from an international automobile spare parts manufacturer, we investigate the profitability of the product substitution strategy when the system is optimally controlled, and derive managerial insights from the results of the study.

2. Literature survey

In recent years, there has been a growing body of literature regarding the inventory control of hybrid M/R systems. These systems have two supply modes to fulfill customer demand: manufacturing of new items using externally supplied materials, and recovery of returned items through remanufacturing. Most studies consider a market where the remanufactured and manufactured items have the same quality, and therefore customers are indifferent to buying these products. A major classification regarding inventory models for such recoverable manufacturing systems is deterministic versus stochastic models. When demands and returns are deterministic and stationary, a widely used approach is to develop variants of the economic order quantity (EOQ) or economic production quantity (EPQ) models, which take into account return flows and a product recovery activity such as recycling or remanufacturing along with regular procurement (see e.g., Dobos & Richter, 2006; El Saadany & Jaber, 2010; Koh, Hwang, Sohn, & Ko, 2002; Mabini, Pintelon, & Gelders, 1992; Richter, 1996; Schrady, 1967; Teunter, 2004; Zanoni, Segerstedt, Tang, & Mazzoldi, 2012). For deterministic models where demand and product returns are dynamic, deterministic dynamic programming models (Naeem et al., 2013) and the variants of the Wagner/Whitin algorithm (Wagner & Whitin, 1958) have been proposed (Richter & Sombrutzki, 2000; Richter & Weber, 2001) or mathematical programming models are developed to find the optimal production plan over a multi-period planning horizon (Mahapatra, Pal, & Narasimhan, 2010).

For the stochastic version of the problem, a few studies analytically derive the structure of the optimal inventory policy for a recoverable manufacturing system with simplifying assumptions such as no setup costs and zero or identical manufacturing/remanufacturing lead times (Inderfurth, 1997; Simpson, 1978; Zhou, Tao, & Chao, 2011). However, most studies develop heuristic or exact methodologies to find the optimal or near optimal values for the parameters of a predetermined reasonable, but not necessarily optimal, inventory policy structure (Kiesmuller, 2003; Kiesmuller & Minner, 2003; Kiesmuller & Scherer, 2003; Mahadevan, Pyke, & Fleischmann, 2003; Van der Laan & Salomon, 1997; Van der Laan, Salomon, Dekker, & Van Wassenhove, 1999; Van der Laan & Teunter, 2006). More recently, Naeem et al. (2013) have proposed a stochastic dynamic programming model to find optimal manufacturing and remanufacturing amounts in a finite horizon setting. However they do not provide a characterization of the optimal policy. Ahiska & King (2010a, 2010b) present a Markov Decision Process-based analysis to find optimal or near-optimal inventory policy characterizations for a recoverable system without pre-specifying the structure of the inventory policies beforehand. All these studies analyze a recoverable system with one serviceable stock, i.e. the manufactured and remanufactured products are considered to be the same in terms of quality and they are sold for the same price to the same market.

Remanufactured items are sometimes considered to have an inferior value from customer's view point and thus have a different customer profile than for new items. When manufactured and remanufactured items have different markets, if separate production resources exist (such as production lines, storage space and labor) and one product cannot be substituted for the other, then it is clearly optimal to control the M/R processes independently from each other. Otherwise, it is necessary to use a single coordinated model (Inderfurth, 2004).

There are very few studies considering hybrid M/R systems where there are distinct demand streams for manufactured and remanufactured items, and new items can be substituted for remanufactured items in case of a stock-out for remanufactured items. Pineyro & Viera (2010) consider the economic lot-sizing problem with remanufacturing and one-way substitution for deterministic demand and returns. Li, Chen, & Cai (2006) consider a similar multi-period production planning problem with product substitution and deterministic time varying demands. In a later study, Li, Chen, & Cai (2007) extend their analysis to include capacity constraints and an emergency procurement option. Inderfurth (2004) provides some insights into the structure of the optimal policy for a single-period hybrid M/R system under product substitution with stochastic returns and demands. Bayindir, Erkip,