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Inventory management in a two-echelon closed-loop supply chain with correlated demands and returns ☆

Subrata Mitra *

Indian Institute of Management Calcutta, Diamond Harbour Road, Joka, Kolkata 700 104, India

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ABSTRACT

Reverse logistics or closed-loop supply chains where product returns are integrated with traditional forward supply chains have been one of the major topics of research since about the last one and a half decades. In this paper, we address the inventory management issue in closed-loop supply chains, and develop deterministic and stochastic models for a two-echelon system with correlated demands and returns under generalized cost structures. In particular, we address the following questions – Do closed-loop supply chains cost more than traditional forward supply chains? Does a higher rate of return always translate into lower demand variability and hence lower expected costs? What is the relationship between expected costs and correlations between demands and returns? Models developed and numerical examples shown in the paper reveal that although a higher rate of return and a higher correlation between demand and return reduce the variability of net demand, it may not necessarily lead to cost savings; rather the movement of costs will depend on the values of system parameters. We also quantify the cost savings in case the actual demand and return information is available at the time of decision-making. We conclude the paper by providing managerial implications and directions for future research.

1. Introduction

Recently, since about the last one and a half decades, a lot of research interest has been shown in reverse logistics (Alamri, 2011; Chan, Yin, & Chan, 2010; Dowlatshahi, 2010a, 2010b; El-Sayed, Afia, & El-Kharbotly, 2010; Fleischmann et al., 1997; Kim, Song, Kim, & Jeong, 2006; Lee, Gen, & Rhee, 2009; Mutha & Pokharel, 2009; Ravi, Shankar, & Tiwari, 2005, 2008; Rubio, Chamorro, & Miranda, 2008; Tsai & Hung, 2009; Weeks, Gao, Alidaeec, & Rana, 2010), closed-loop supply chains (Guide & Van Wassenhove, 2009; Huang, Yan, & Qiu, 2009; Kannan, Haq, & Devika, 2009; Min, Ko, & Ko, 2006; Morana & Seuring, 2007; Neto, Walther, Bloemhof, Van Nunen, & Spengler, 2010), sustainable supply chains (Field & Sroufe, 2007; Geldermann, Treitz, & Rentz, 2007; Linton, Klassen, & Vaidyanathan, 2007; Vachon & Klassen, 2007), and sustainable product design/manufacturing/operations (El Saadany & Jaber, 2010, 2011; Gungor & Gupta, 1999; Jaber & El Saadany, 2009, 2011; Jaber & Rosen, 2008; Jayaraman, 2006; Kleindorfer, Singhal, & Van Wassenhove, 2005; Konstantaras, Skouri, & Jaber, 2010; Nagel & Meyer, 1999; Rubio & Corominas, 2008; Tseng, Divinagracia, & Divinagracia, 2009; Yan, Chen, & Chang, 2009). There has been a recent review of the quantitative models for inventory and production planning in closed-loop supply chains (Akcali & Cetinkaya, 2011). The literature on production, manufacture and waste disposal models assumes that an item can be recovered for an indefinite number of times. This is not true, in general. See, for example, El Saadany, Jaber, and Bonney (in press), who address this limitation. A number of edited books have been published on these subjects (Dekker, Fleischmann, Inderfurth, & Van Wassenhove, 2004; Dyckhoff, Lackes, & Reese, 2003; Flapper, Van Nunen, & Van Wassenhove, 2005; Guide & Van Wassenhove, 2003). Also, many special issues of journals have been devoted to these topics (Interfaces (30 (3), 2000, 33 (6), 2003); California Management Review 46 (2), 2004; Production and Operations Management 15 (3 and 4), 2006; Journal of Operations Management 25 (6), 2007; Computers & Operations Research 34 (2), 2007; International Journal of Production Research 45 (18 and 19), 2007; International Journal of Production Economics 111, 2008). Although known by different names, the basic idea behind all these is to integrate product returns with the traditional forward supply chain, which may involve from collection of returns and design of reverse logistics networks to disposal, product recovery, production scheduling and inventory management with returns, new product design and remarketing of recovered products (Guide & Van Wassenhove, 2002). Handling end-of-use or end-of-life product returns by manufacturers has been made obligatory by many developed countries in North America and Europe to prevent wastage and pollution. Therefore, it has become

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* Tel.: +91 33 24678300; fax: +91 33 24678307.
E-mail address: subrata@iimcal.ac.in

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imperative for manufacturers to design products with recyclable components as much as possible so that they can extract the maximum economic value from product returns. The appropriate recovery operation will, however, depend on the quality of returns. Thierry, Salomon, Van Nunen, and Van Wassenhove (1995) classify product recovery operations into five categories – repair, refurbishing, remanufacturing, cannibalization and recycling – based on the quality and degree of disassembly of returns. Among these, the most prominent recovery operation is remanufacturing, which is particularly useful for products with long technological cycles such as automobile engines, machine tools and photocopiers. The size of the remanufacturing industry in the US is estimated between $40 and $53 billion. The cost of remanufacturing is generally 40–60% (sometimes as low as 20%) of the cost of manufacturing a new product. However, a remanufactured product is considered to be 'as good as new' and sold often with the same warranty but at discounted (as low as 50%) prices either through the same channel as a manufactured product or through a separate channel (Souza, 2009; Thierry et al., 1995). This provides manufacturers with an opportunity to turn in profits from returns and simultaneously build corporate image by projecting "green" and environment-friendly supply chains.

Inventory management in closed-loop supply chains is much more complicated than in traditional forward supply chains since returns are more uncertain than demands in terms of quantity, quality and timing (Guide, Jayaraman, Srivastava, & Benton, 2000), and also valuation and setting inventory holding costs of returns are not straightforward (Teunter, Van der Laan, & Inderfurth, 2000). In addition, correlation between demands and returns adds another dimension of complexity to such systems. It may vary from a perfect positive correlation for reparable items to a fair degree of correlation for short life-cycle products such as reusable containers (Kelle & Silver, 1989) and single-use cameras (Toktay, Wein, & Zenios, 2000) to almost no correlation for long life-cycle products such as durables (e.g. electrical and electronic equipment). In the literature, it is usually assumed that demands and returns are independent (Fleischmann & Kuik, 2003; Fleischmann et al., 1997; Mahadevan, Pyke, & Fleischmann, 2003). The extension of single-echelon closed-loop supply chains to multi-echelons involving multiple levels of inventory locations further complicates such systems. Recently, Yuan and Gao (2010) has developed an inventory-control model for a closed-loop supply chain with a retailer, a manufacturer, a supplier and a collector for deterministic demand and return rates allowing no shortages. Only a handful of references that deal with stochastic multi-echelon closed-loop supply chains are available in the literature (DeCroix, 2006; Korugan & Gupta, 1998; Minner, 2001; Muckstadt & Isaac, 1981; Savaskan, Bhattacharya, & Van Wassenhove, 2004). Although these papers make valuable contributions to the literature, they make a number of assumptions, including the independence between demands and returns and the non-existence or non-relevance of some of the costs – set-up, inventory holding and shortage – at some or all of the stocking points, for the purpose of tractability. Mitra (2009) does address the above cost issue; however, independence between demands and returns is assumed in the paper.

The present paper considers a two-echelon closed-loop supply chain with set-up and inventory holding costs at all the stages and shortage costs at the stages stocking serviceable inventory. Also, demands and returns may be correlated (for optimal models using genetic algorithms for two-echelon inventory systems with correlated demands, readers may refer to Xiong and Sun (2010)). We develop deterministic and stochastic models for such a system. For the stochastic model, we assume that the system is under periodic review. In particular, we address the following questions in the paper:

- Do closed-loop supply chains cost more than traditional forward supply chains? In other words, does the incorporation of returns into the forward supply chain increase the cost of the supply chain?
- Does a higher rate of return translate into lower demand variability? Does it mean lower expected costs of the systems under every situation?
- What is the relationship between the expected costs of the system and correlations between demands and returns? Do higher correlations necessarily mean lower expected costs?
- Given that the availability of information reduces expected costs (Ketzenberg, Van der Laan, & Teunter, 2006), how can the savings, in case the actual demand and return information is available, be quantified so that the savings can be traded off against the cost of acquisition of information?

The paper is organized as follows. Sections 2 and 3 present the problem description and model formulations, both deterministic and stochastic, respectively. Section 4 provides numerical examples and sensitivity analyses. The case when the actual demand and return information is available is presented in Section 5. Finally, Sections 6 and 7 present the managerial implications and directions for future research, respectively.

2. Problem description

In this paper, we consider a two-echelon inventory system with returns. Returns are remanufactured, which are 'as good as new' after recovery (100% recovery rate is assumed) and are interchangeable with new items that are procured from an outside supplier to meet customer demand from the serviceable stock. It is assumed that a remanufactured item and a new item are of the same value, and as such they have the same inventory holding costs. It is also assumed that a returned item awaiting recovery is of lower value than an item in the serviceable stock, and hence has a lower inventory holding cost. The time to remanufacture a batch of returns is assumed to be insignificant compared to the time to procure new items from the outside supplier at the corresponding stage. As such, the remanufacturing order is initiated and realized at the same instant as replenishments from the outside supplier are realized at the corresponding stage. The simultaneous replenishment of remanufactured and new items is an assumption in the problem, which leads to the same cycle length at the corresponding stages. However, in general, the cycle lengths need not be the same in case of alternate replenishments of remanufactured and new items, which, of course, is beyond the scope of the system under consideration in the paper.

We consider set-up costs and inventory holding costs at all the stages and shortage costs at the stages containing serviceable stock, and develop deterministic and stochastic models for the system. It may be noted here that in a closed-loop supply chain, there exist many other components of cost such as collection, transportation, inspection, sorting, recovery, disposal and remarketing. However, in this paper, we have analyzed the cost structure of the system from the inventory management point of view, and restricted to set-up, inventory holding and shortage costs (for stochastic models only). The objective is to determine the values of the inventory policy variables (order quantities in case of the deterministic model, and review periods and order-up-to levels in case of the stochastic model) at all the stages that minimize the (expected) total costs of the system. In the stochastic model, it is further assumed that while demands and returns – both Normally distributed – in different periods are i.i.d., demand and return in a given period may be correlated. Also, every return is