Journal of Cleaner Production 112 (2016) 2015–2028

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

Optimal production policy for a closed-loop hybrid system with uncertain demand and return under supply disruption

B.C. Giri*, S. Sharma

Department of Mathematics, Jadavpur University, Kolkata 700032, India

ARTICLE INFO

Article history:
Received 20 September 2014
Received in revised form
19 May 2015
Accepted 17 June 2015
Available online 18 July 2015

Keywords:
Closed-loop supply chain
Hybrid system
Manufacturing
Remanufacturing
Supply disruption
Unreliable supplier

ABSTRACT

The paper considers a closed-loop supply chain inventory system involving a single-manufacturer and a single-retailer with stochastic market demand and random return of used item. The manufacturer produces the finished product by manufacturing from raw materials as well as remanufacturing from used product obtained from a collector. Used product's yield rate is assumed to be random. The raw materials may be sourced from two suppliers. The primary supplier is cheaper but unreliable in the sense that supply from this source may disrupt, whereas the secondary supplier is perfectly reliable but more expensive. The objective of this study is to determine the optimal quantity of finished product which is to be manufactured from raw materials so as to maximize the total profit of the integrated system. Results of numerical experiments are presented and sensitivity analysis is carried out to investigate the influence of model-parameters on the optimal solution.

1. Introduction

Research on closed-loop supply chain (CLSC) has gained considerable attention in recent years. Remanufacturing which is an important part of CLSC is the process of collecting used items, extracting their useful parts and then reusing these parts for the production of new products which are comparable to newly manufactured products in terms of quality and durability (Zhou et al., 2011; Jena and Sarmah, 2014). Increasing environmental consciousness, social responsibilities, awareness of natural resource depletion, and more rigid government legislation are key factors that have driven many companies to initiate product recovery program (Rubio and Corominas, 2008; Kovacs, 2008; Shi et al., 2011a; Zeballos et al., 2012). In the last few years, a number of legislations with respect to product recovery have been introduced within the European Union. The most important among them are the Paper Recycling Directive, the End-of-Life (EOL) Vehicle Directive, and the Waste Electrical and Electronic Equipment Directive (WEEE) (Zeballos et al., 2012; Qiang et al., 2013; Govindan et al., 2015), which are intended to give manufacturers incentives to reduce environmental burden of their EOL products, while also removing the growing waste management cost from municipal governments (Toffel, 2004). Remanufacturing has both economical and environmental benefits (Mitra, 2007; Sasikumar and Kannan, 2008). For instance, in case of remanufacturing, the cost of a remanufactured part is generally 30–50% less than the cost of a new part and hence overall production cost is lower than that in case of manufacturing (Toffel, 2004). Therefore, now-a-days, remanufacturing is being successfully employed in several industries such as auto parts, electric home appliances, air-conditioning units, heavy-duty engines, tires, furniture, mobile phones, cameras, printer ink cartridges, laser toner cartridges, computers, photo copiers, pumps, aircraft parts and military vehicles (Robotis et al., 2012; Shi et al., 2011b; Gray and Charter, 2008). There are numerous leading organizations world wide where remanufacturing is practiced on a wide range of products. For example, Caterpillar Inc. remanufactures parts and components for diesel and turbine engines, construction and mining equipments, electric power generators, rail road locomotives, and rail cars in North America; Nextant Aerospace remanufactures aircraft; A.C. Electric Corporation remanufactures motors, generators, pumps and electric switch gear; Perkin Engines (now owned by Caterpillar) use remanufacturing in various products like diesel engines, naval and marine propulsion engines, generator sets, construction equipment, etc.; Milliken Carpets remanufactures carpet tiles (Gray and Charter, 2008). Several original equipment

* Corresponding author.
E-mail addresses: bibhas_pnu@yahoo.com (B.C. Giri), subhodip.math@gmail.com (S. Sharma).

http://dx.doi.org/10.1016/j.jclepro.2015.06.147
0959-6526/

manufacturers (OEMs) like Hewlett–Packard (Jorjani et al., 2004), General Electric, Boeing, Deere, Sony (Gray and Charter, 2008; Hatcher et al., 2013) and most automotive OEMs employ remanufacturing jointly with manufacturing to satisfy market demand with competitive price.

In a manufacturing-remanufacturing hybrid system, the management usually deals with two uncertainties: uncertainty with the market demand for new product and uncertainty with the quantity of returned product (Wei et al., 2011). Besides these two uncertainties, the management has to deal with uncertainty of quality of returned product as well because the used items are in general obtained through different channels from different consumers and under different circumstances. There exists an inherent variation in the condition of used product which offers one of the major challenges to the remanufacturing firms when they undertake the reusability and remanufacturing operations (Aras et al., 2006). The quality of the used product is unknown to firms in advance, and it varies from one product to another because of differences in usage patterns (Robotis et al., 2012). Many remanufacturing industries such as automobiles, cell phones and other electronic appliances face the uncertainty in the percentage of used items that can actually meet the quality criteria for remanufacturing. This percentage is usually called the remanufacturing yield (Li et al., 2015). Uncertainty in remanufacturing yield combined with uncertain quantity of used product (Guide and Wassenhove, 2001; Akcali and Cetinkaya, 2011; Zeballos et al., 2012) and uncertain market demand add new dimensions of complexity and difficulty to the management of firms having hybrid production systems.

Though considerable amount of research has been carried out on CLSC, to the best of the authors' knowledge, no attempt has been made to study the impact of supply disruptions on its performance. Many firms are exposed to the risk of supply disruption due to labor strikes, supplier bankruptcies, natural calamities, terrorism or other facts (Snyder, 2014; Fang and Shou, 2014). Supply chain disruptions are unplanned and unanticipated events that prevent the suppliers from fulfilling the orders placed with them. These risks could potentially affect or disrupt the flow of products or services that the supply chain offer to its customers (Li et al., 2010). Dual or multiple sourcing strategy (Silbermayr and Minner, 2014), contingency plans (Tomlin, 2006), product substitution, better planning and coordination of supply and demand, etc. are some effective strategies employed to cope up with unexpected supply breakdowns.

The majority of literature on CLSC mainly addresses three types of uncertainties: uncertainty in demand and returns, uncertainty in demand and quality of returns or uncertainty in quality and quantity of returns. To the best of the authors' knowledge, no work has been reported in the literature considering uncertainty in demand as well as uncertainty in quality and quantity of returns in a CLSC framework. The present study aims to consider an integrated manufacturing-remanufacturing CLSC system with random market demand and various sources of uncertainty in remanufacturing. The objective is to determine the optimal quantity of finished product obtained by manufacturing process when the system is exposed to the risk of supply disruption, and it faces uncertainty in market demand as well as uncertainty in the quantity and quality of returns.

The rest of the paper is organized as follows. Literature review of related research streams is presented in the next Section. The description of the proposed model is given in Section 3. Assumptions and notations are given in Section 4. The proposed model is formulated in Section 5. Numerical experiments together with sensitivity analysis of model-parameters are done in Section 6. Finally, the paper is concluded in Section 7 with a few suggestions for future research.

2. Literature review

In the past few decades, there has been an enormous increase in the research of remanufacturing and CLSC. Various strategic and operational aspects of CLSC were studied by different researchers such as production planning/control, forecasting, inventory management/control, network design, etc. A comprehensive review of literature discussing various aspects of CLSC can be found in Atasu et al. (2008). For the more recent developments in this field, interested readers can refer to the review article provided by Govindan et al. (2015). In the survey of literature, the authors mainly address four research streams which are relevant to this paper: hybrid production system, CLSC and reverse logistics under uncertainty, quality uncertainty and supply disruption.

When both manufacturing and remanufacturing operations are involved in a CLSC, the coordination between the two production processes offers a crucial challenge to the manufacturer. Van Der Laan et al. (1999) analyzed two control strategies: PUSH strategy and PULL strategy in the study of production planning and inventory control of a CLSC model where market demand is satisfied by producing products utilizing both manufacturing and remanufacturing processes. Inderfurth et al. (2001) addressed a production planning problem for a stochastic remanufacturing system where returned products can be reused in multiple ways yielding different serviceable products which satisfy different market demands. Inderfurth (2004) analyzed the optimal policies to control a hybrid manufacturing-remanufacturing system where brand new products can serve as perfect substitute to remanufactured products in case shortage of remanufactured products occurs.

Zhou et al. (2006) investigated a hybrid manufacturing-remanufacturing system and analyzed the dynamic performance of the hybrid system by control theory and simulation. Choi et al. (2007) presented a joint economic order quantity (EOQ) and economic production quantity (EPQ) model in which the stationary demand is satisfied by recovered products as well as by newly purchased products. Chung et al. (2008) proposed a multi-echelon CLSC with remanufacturing. The analytical results of the study show a significant increase in the joint total profit when the integrated policy is adopted.

Besides the coordination between manufacturing and remanufacturing processes, the complexity arising from uncertain demand and return further complicates the study of CLSC system and makes the optimization of CLSC model difficult. Inderfurth (2005) observed that uncertainty in returns and demand can be a considerable obstacle to following a consequently environmental-benign recovery strategy within a reverse logistics system. Fleischmann et al. (2002) presented a systematic analysis for an inventory control problem where demand and returns are assumed to be independent and poisson distributed. Shi et al. (2011b) investigated a production planning problem for a multi-product closed loop system where the manufacturer has two channels for supplying products: producing brand-new products and remanufacturing returns into as new ones. The market demand is uncertain while the return quantity of used product is assumed to be price-sensitive and uncertain. The solution approach was developed by using Lagrangian formulation method and the decision variables include the production quantity of brand-new products, the acquisition price of the used products and the quantity of the remanufactured products. Wang et al. (2011) determined the optimal production policy for a hybrid manufacturing-remanufacturing system with stochastic demand and return for a short life-cycle product like mobile phone. Wei et al. (2011) applied a robust optimization approach to tackle an inventory control and production planning problem in which the product return is integrated into the manufacturing process over a finite planning horizon, where it is assumed that the demand and returns are uncertain with only intervals being known. Kenne et al.