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Optimization of closed-loop supply chain of multi-items with returned subassemblies

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ABSTRACT

The importance of reverse logistics is increasing for several environmental, societal and governmental reasons. The number of studies available in the literature on reverse logistics is a good indicator of its significance. Almost all of the available studies deal with a single product that is collected and recovered as a whole unit. In reality, manufacturing firms produce multiple products and spare parts. When a product reaches its end-of-life, the product and the spare parts produced to service it over its operational life are collected and then returned to the manufacturer for possible recovery (e.g., reuse, remanufacturing, and repairing). In most cases, returned items are disassembled to recover useful components that could be reused in producing new items or remanufactured ones, after which are introduced into the market as-good-as new.

This paper develops a mathematical model for a system where a product (new or remanufactured) and its spare parts are returned and disassembled, where applicable, for recovery. The demand for the product and spare parts are met from production, remanufacturing and inspection/disassembly center. This paper identifies which strategy (pure remanufacturing, pure production or mixed) is more viable. Numerical examples are provided to illustrate the behavior of the model and to draw some insights.

1. Introduction

Environmental concerns from solid waste and pollution that many manufacturing firms generate are growing by the day. Government legislation and the public have been pushing manufacturers to reduce waste disposal, which led many firms to invest in product (including spare parts) recovery programs (e.g., remanufacturing, reuse, recycle, etc.) and reverse logistics (RL). Besides the environmental, social and legal reasons, RL helps companies meet customers' demand and increase their satisfaction (Richter, 1996). The productivity and efficiency of a recovery program and its RL processes determine its economic success or failure (Cruz-Rivera and Ertel, 2009). RL has become a fundamental part of 'Green' Supply Chain Management, where making good operational decisions, developing models for forward and reverse flows, should be studied or analyzed simultaneously (Ramezani et al., 2013). This paper is motivated by the growing concern of extending the useful life of a product (e.g., cars, electronics) and its spare parts or components by making recovery programs economically viable (Farzipoor Saen, 2009). This is important since the relationship between customers and manufacturers does not end with the purchase of products, but continues through the service programs that the manufacturers or their representatives provide during warranty periods and beyond.

RL involves many activities. It collects items from customers through designated points, inspect them, and return them to the manufacturer or to a third party for disassembly. The components of disassembled items are tested and checked before reuse. Non-functioning or damaged items are repaired and then reused. Recovered raw material can be reused, if suitable, or recycled. The latter is used by other processes with the objective of minimizing disposal into landfill sites. The purpose of RL is to keep recovering value from an item for as many times as possible (El Saadany et al., 2013). This reduces the extraction of virgin material and dumping solid waste into the environment (Bonney and Jaber, 2011; Matar et al., 2014).

Although the literature on inventory management for repairable items dates back to the 1960s (see Schrady, 1967), the interest of business and research in the collection of used items for the purpose of recovery is relatively recent (Srivastava, 2008).

RL has been studied from different aspects (e.g., El Saadany and Jaber, 2010, 2011; Jaber and El Saadany, 2009, 2011; Hasanov et al., 2012; Jaber et al., 2014; Bazan et al., 2015). RL deals with the

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traditional forward flow of raw material, components and finished products. It is also concerned with reusing, recycling and remanufacturing of these products, their components and the raw material used in manufacturing them (El Saadany and Jaber, 2008). When RL is considered, material management has to be modified accordingly. This challenging problem enticed several researchers to develop models for controlling inventories when the rate at which items are returned for recovery is stochastic (Fleischmann et al., 2002). Other researchers investigated different situations and developed models that best describe them.

It is not possible to review the entire literature here, so we provide the readers with a brief review of the review papers on RL. Fleischmann et al. (1997) reviewed the literature from 1967–1997 and classified the papers into: reverse distribution, inventory control with return flows and production planning with reuse of parts and materials, Rubio et al. (2008) reviewed articles published on RL in the period 1995–2005 to identify the methodology and the techniques of analysis used in each article. The 186 articles were classified into: literature review (~3%), survey (~5%), wholly technical (~5%), case study (~22%) and mathematical models (~65%). The majority of the mathematical models covered production planning, inventory management and supply chain management issues in RL. Pokharel and Mutha (2009) provided a concise review of the developments in the research and practice of RL. They found that the articles and books they reviewed covered all aspects of reverse logistics: RL inputs (new or used products or parts, or recycled materials) and the collection of used items, RL structure (strategic planning, inspection and consolidation, integrating manufacturing and remanufacturing and product modularity), RL processes (disassembly, coordination, supply chain, inventory, repair and after-sales) and RL outputs (product pricing and competition, customer relation). Finally, Ilgin and Gupta (2010) provided a state-of-the-art review of the articles on environmentally conscious manufacturing and product recovery. They categorized the articles they surveyed as: environmentally conscious product design (design for X, Life cycle analysis, material selection), reverse and closed-loop supply chains (Network design, Simultaneous consideration of network and product design issues, optimization of transportation of goods, selection of used products, selection and evaluation of suppliers, performance measurement, marketing-related issues, EOL alternative selection, product acquisition management), remanufacturing (forecasting, production planning and scheduling, capacity planning, inventory management and effect of uncertainty) and disassembly (scheduling, sequencing, line balancing, disassembly to order systems, automation).

Although there are numerous papers related to RL in the literature, the above review papers and those papers published after (until 2011) have not considered disassembling of returned items in a production, remanufacturing and waste disposal context, with the fundamental studies being those of Richter (1996) and Teunter (2001). They implicitly assumed that a returned item is recovered as a whole unit, El Saadany and Jaber (2011) touched on this issue. They considered a single product that is returned, disassembled into components and classified into subassemblies with nonconforming components disposed at a cost. The subassemblies are managed independently from one another. The recovered components are used in producing new or remanufactured items. The new items are considered hybrid in the sense that they are built from new and used components. The mathematical model was investigated for three strategies: (1) manufacture all, (2) produce all and (3) mixed. The third was found to be the most economical. This finding is contrary to that of a bang–bang strategy of either remanufacture or produce all (e.g., Richter (1996), Teunter (2001) and Dobos and Richter (2004)). For example, automotive companies manufacture spare parts for their end products, where after a while inferior spare parts are returned from customers as well as used products. In this regard, this paper addresses a similar system to that of El Saadany and Jaber (2011), but a more complex one as it considers a second market for spare parts and additional system processes. The demand for these items is met from production, remanufacturing and inspection/disassembly center. A detailed description of the proposed system is provided in a later section along with a table that clearly differentiates the model of this paper from that of El Saadany and Jaber (2011). The remainder of this paper is organized as follows. Section 2 lists the assumptions and notations, provides a description of the system. Section 3 is for developing the mathematical models. Section 4 provides numerical examples and discusses their results. Finally, Section 5 is for summary and conclusions.

2. Assumptions and notations

This section presents the assumptions and notations needed in developing the model.

2.1. Assumptions

1. Demand rates of the product and its spare parts are known and constant.
2. Return rates of the item and spare parts are continuous and constant.
3. Remanufactured items are considered as-good-as-new.
4. Multi-production of items is considered.
5. Lead time is assumed to be zero.
6. Planning horizon is infinite.
7. Unlimited storage capacity is available.

2.2. Notations

Input parameters

D_m	demand rate of produced items (units/unit of time).
D_s	demand rate of spare parts (units/unit of time).
D	total demand (D_m+D_s).
h_n	holding of a disassembled item (\$/unit/unit of time).
h_r	holding cost for a recovered item (\$/unit/unit of time).
h_p	holding cost for a produced item (\$/unit/unit of time).
k_j	number of components for subassembly j of the end product, where $j=1,2,3..,u$.
r_{ij}	percentage of return for subassembly j of D_m and D_s, where $i=1,2,3$ (remanufacture, recycle, repair).
S_p	set up cost for production.
S_r	set up cost for remanufacturing.
q	acceptance quality level of returned items
c_{pij}	ordering cost for a batch of $(1-q)r_{ij}D$ units of subassembly j, where $i=1,2,3$ (remanufacture, recycle, repair)
c_{rij}	unit remanufacturing cost for a batch of $qr_{ij}D$ of subassembly j, where $i=1,2,3$ (recovery, recycle, repair)
c_{sc}	unit collection cost for βD_s units
c_{mc}	unit collection cost for αD_m units
c_{ts}	fixed cost per shipment for spare parts
c_{tm}	fixed cost per shipment for produced and remanufactured items
n_s	number of trucks to transport for spare parts
n_m	number of trucks of capacity to transport for produced and remanufactured items
w	wholesale price
ϕ	is a positive parameter