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Theory and methodology on the global optimal solution to a General Reverse Logistics Inventory Model for deteriorating items and time-varying rates ☆

Adel A. Alamri *

Royal Saudi Air Force, Riyadh Air Base, Operations Support Wing, P.O. Box 92571, Riyadh 11653, Saudi Arabia

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ABSTRACT

In this paper, we present a unified general inventory model for integrated production of new items and remanufacturing of returned items for an infinite planning horizon. Our model considers a production environment that consists of three shops. The first shop is for remanufacturing returned items, the second shop is for manufacturing new items, while the third shop is for collecting returned items to be remanufactured in the first shop. The system is subject to joint production and remanufacturing options, the first one is to produce new items while the second one is to reproduce/recycle the returned items "as-good-as new". Items deteriorate while they are in storage, and production, remanufacturing, demand, return, and deterioration rates are arbitrary functions of time. A closed form for the total relevant costs as well as a rigorous mathematical proof, which shows the global optimality of the solution to the underlying inventory system are introduced. Illustrative examples, which explain the application of the theoretical results as well as their numerical verifications, are also given.

1. Introduction

One of the main topics in supply chain is the management of the flow of products in reverse logistics (e.g., recycling, remanufacturing, repairing, etc.), which extends the classical forward process to manage the used and reusable parts and products return from the customers, i.e., to extend their useable lives and to reduce waste and conserve natural resources. Moreover, factors such as economical incentives and environmental consciousness forces manufacturers to initiate such product recovery systems. Remanufacturing is the process that collects and remanufactures used products to achieve quality standards that are "as-good-as those of new products". In such systems, the assessment of joint lot-sizing decisions for remanufacturing and manufacturing increases the problem of inventory control in magnitude and complexity, i.e., the manufacturer has to coordinate joint manufacturing and remanufacturing options.

Inventory management in reverse logistics that incorporate joint manufacturing and remanufacturing options has been receiving increasing attention in recent years. Rogers and Tibben-Lembke (2001) defined reverse logistics as the process of planning, implementing, and controlling the efficient and cost effective flow of raw materials, in-process inventory, finished goods, and related information from the point of consumption to the point of origin for the purpose of recapturing value or proper disposal. Fleischmann et al. (1997) subdivided reverse logistics into three main areas, these are: distribution planning, inventory control, and production planning. They have provided a survey, which addressing the logistics of industrial reuse of products and materials from an Operational Research perspective.

Although reverse logistics is relatively a new term, the earliest approach in the area of joint determination of production and remanufacturing lot sizes was made by Schrady (1967). He analyzed the problem in the traditional Economic Order Quantity (EOQ) model for repairable items which assumes that the manufacturing and recovery (repair) rates are instantaneous with no disposal cost. Nahmias and Rivera (1979) have generalized Schrady's model to allow for the case of finite recycling/repair rate. A multi-product extension of these models was investigated by Mabini, Pintelon, and Gelders (1992). These authors have not investigated the optimal use and return rates. In these models all returned items are reusable. Richter (1996a, 1996b, 1997), Richter and Dobos (1999) and Dobos and Richter (1999, 2000) have investigated a waste disposal model, where the return rate is a decision variable. They have given the optimal number of remanufacturing and production batches depending on the return rate. Richter (1997) in his paper has examined the optimal inventory holding policy, if the waste disposal (return) rate is a decision variable. The result of this paper is that the optimal policy has a pure (bang–bang) policy of either no waste disposal (total repair) or

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* Tel.: +966 1 2212007; fax: +966 1 4792204.
E-mail address: adel_nlp@msn.com

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no repair (total waste disposal) dominates a mixed strategy of waste disposal and repair. It is worth noting that the pure policy means either to buyback all used/returned items for remanufacture/recycle with no production option, or produce new items with no buyback or remanufacturing/recycling option. Richter and Dobos (1999) further examined the (bang–bang) policy where they showed that the properties of the minimal cost function and the optimal solution known for the continuous EOQ repair and waste disposal problem (Richter, 1996a, 1996b, 1997) could be extended to the more realistic integer problem. Teunter (1998) has offered a model, where not all items can be remanufactured, i.e., the decision maker decides the reuse of returned items for known return rate. He assumed that the inventory holding cost parameter for manufactured items is higher than that for the remanufactured products because the remanufacturing costs are lower than the manufacturing costs. Vörös (2002) presented demand as a decreasing and increasing exponential functions of price and quality. He integrated these functions into one function that describes the forward flow of a product, i.e., from the inventory system to the market, where demand increases as selling price (quality) decreases (increases). Vörös's demand function describes a general and known behavior that is well documented in the literature (e.g., Kalish, 1983; Teng & Thompson, 1996). Dobos and Richter (2003) investigated a production/recycling system with constant demand that is satisfied by non-instantaneous production and recycling with a single repair and a single production cycles per time interval. In a subsequent paper, Dobos and Richter (2004) generalized their earlier model (Dobos & Richter, 2003) to the case of multiple repair and production cycles. Dobos and Richter (2006) extended their previous work and assumed that the quality of collected used/returned items is not always suitable for further recycling, i.e., not all used/returned items can be reused.

Next to the analysis of the basic model context, other researchers have developed models that relax some of the assumptions made so far. Examples of these works, including, but not limited to, are those of Bloemhof-Ruwaard, van Beek, Hordijk, and Van Wassenhove (1995), Smith, Small, Dodds, Amagai, and Strong (1996), Richter (1996a, 1996b, 1997), Reimer, Sodhi, and Knight (2000), Teunter (2001, 2004), Blackburn, Guide, Souza, and Van Wassenhove (2004), Inderfurth, Lindner, and Rachaniotis (2005), Grubbström and Tang (2006), Konstantaras and Papachristos (2006), Jaber and Rosen (2008), El Saadany and Jaber (2008), Jaber and El Saadany (2009, in press), Behret and Korugan (2009), Liu, Kim, and Hwang (2009). The above cited contributions assumed a constant return rate and ignored the factors that govern this rate. Recently, and along the same line of research, Omar and Yeo (2009) presented a production system that satisfies a continuous time-varying demand for a finished product over a known and finite planning horizon by supplying either new products or repaired used products. They assumed that there is no further collection of used products during the period when they are being repaired or shipped. Konstantaras and Skouri (2010) generalized the model of Teunter (2004) by considering a general cycle pattern in which a variable number of remanufacturing lots of equal size are followed by a variable number of manufacturing lots of equal size. Sufficient conditions are given in this paper, based on the closed form formulae for the total cost function of the system. They also have studied the case where shortages are allowed in each manufacturing and remanufacturing cycle and similar sufficient conditions, as the non-shortages case, are given. El Saadany and Jaber (2010) extended the models developed in Dobos and Richter (2003, 2004) by assuming that the collection rate of used/returned items is dependent on the purchasing price and the acceptance quality level of these returns. That is, the flow of used/returned items increases as the purchasing price increases, and decreases as the corresponding acceptance quality level increases. They developed two mathematical models by incorporating a price–quality demand function, adopted from Vörös (2002), to model the collection rate of returned items. The first assumed a single remanufacturing cycle and a single production cycle, with the second being a generalized version of the first assuming multiple remanufacturing and production cycles. Numerical results showed that when considering the return rate of used items to be dependent on the purchasing price and acceptance quality level of these returns, a pure (bang–bang) policy of either no waste disposal (total repair) or no repair (total waste disposal) as advocated in Dobos and Richter (2003, 2004) is not optimal. The limitation considered in Dobos and Richter (2006) that a pure strategy recycling should be more cost effective than pure strategy production was addressed. Results showed that a mixed (production + remanufacturing) strategy is optimal, when compared to either a pure strategy recycling (pure remanufacturing) or a pure strategy production.

The motivations associated with this work reflect some reality issues. As we know from a product life cycle, the constant demand rate is usually valid in the mature stage of the life cycle of the product. In the growth and/or ending stage of the product life cycle demand rate can be well approximated by a linear demand function. Also, in conventional inventory models, one implicit assumption is that the stored items can retain the same utility forever, i.e., they do not lose their value of characteristics as time goes on. Furthermore, the assumptions that all used/returned items that are collected in the returned stock facility can be remanufactured, and that newly produced and/or remanufactured items are perfect are nearly unattainable. In fact, the variation of demand and/or product deterioration with time (and may be with some other factors) is a quite natural phenomenon. For instance, seasonal variations, occasions (e.g., Christmases, new years, festivals) may cause an increase or a decrease in the demand of a certain commodity. Also, the increase of time storage as well as the changes in the environments of storage may also result in an increase or a decrease in the deterioration rate of certain items. Therefore, it is necessary to consider the variation of production, remanufacturing, demand, return, and product deterioration with time, which may enhance this line of research. The generality of our model adopts different options (e.g., fixed or varying rates, defective items, dependent costs, quality level of returned items, etc.), therefore, it may help managers in determining the optimum production and remanufacturing quantities and the acceptable returned amount that are collected for recovery purposes and that minimizes the total system cost. In recent years, some researchers provided clearer definitions to the terms repair, reconditioning, remanufacturing, and recycling. For example, De Brito and Dekker (2004) differentiated between the terms repair and remanufacturing by industry. They suggested that if only a part of the product deteriorates, then recovery options like repair or part replacement or retrieval are considered. King, Burgess, Ijomah, and McMahon (2006) defined the term repair as the correction of specified faults in a product, where the quality of repaired products is inferior to those of remanufactured and reconditioned. The term "remanufacturing" adopted herein refers to repairing, reconditioning, recycling, refurbishing or remanufacturing.

In this paper a unified General Reverse Logistics Inventory Model (GRLIM) for integrated production of new items and remanufacturing of returned items is presented for an infinite planning horizon. Items deteriorate while they are in storage, and production, remanufacturing, demand, return, and deterioration rates are arbitrary functions of time. The model developed in this paper coordinates joint production and remanufacturing options by producing new items of a product as well as by remanufacturing collected used/returned items to quality standards that are "as-good-as those of new products" with a single remanufacturing and a single production cycles per time interval. Items are subject