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Carbon emissions and energy effects on manufacturing–remanufacturing inventory models

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ABSTRACT

Reverse logistics is inevitable in today's business environment with the most common reasons being product returns, incorrect product delivery, damaged products, and product exchange programs. The use and adoption of reverse logistics has increased with the start of product recalls, but the rise of e-commerce and insight into the positive environmental impact has elevated the formal use and sophistication of reverse logistics. There are many environmental issues that may arise from the production and transportation of products. The focus of this study is to evaluate supply chain environmental implications presented in a reverse logistic setting. These environmental contributions come with associated costs that can no longer be ignored in the mathematical modeling of reverse logistics.

The model developed in this paper considers energy used for manufacturing and remanufacturing as well as greenhouse gas emissions from manufacturing, remanufacturing and transportation activities with emissions penalty tax as per The European Union Emissions Trading System. The objective of the model is to develop a total cost function that is minimized by determining the following: the manufacturing batch size per cycle, the number of manufacturing batches per cycle, the number of remanufacturing batches per cycle, and the number of times an item may be remanufactured. Numerical examples are provided.

The results show that optimizing for financial costs and all the environmental costs collectively promotes less remanufacturing to protect the environment as opposed to just focusing on solid waste disposal, which has been the focus of previous 'traditional' reverse logistics models that consider remanufacturing. In addition, the results show the need to increase the recollection of available used products that can be remanufactured. The proposed model is seen as a preliminary step into developing an environmentally responsible reverse logistics inventory model.

1. Introduction

Reverse logistics has been implemented long before the term was initially adopted, including historical roots in the military, customer service policy as early as 1872, and the automotive aftermarket as a result of material shortages during World War II (Rogers & Tibben-Lembke, 1999). The adoption of reverse logistics has increased with the start of product recalls, but the rise of e-commerce and insight into the positive environmental impact has elevated the formal use and sophistication of reverse logistics (Bei & Linyan, 2005; de Brito & Dekker, 2004; Gülsün, Bıyık, & Özgen, 2006). Reverse logistics is inevitable in today's business environment with the most common reasons being product returns, incorrect product delivery, damaged products, and product exchange programs (Fleischmann et al., 1997; Gülsün et al., 2006). It can be of higher importance in one industry over another due to production costs and the nature of remanufacturing and recycling of the products.

The purpose of reverse logistics is to recapture value from products that are returned from end customers or to, at least, appropriately dispose the returned products (Bei & Linyan, 2005; de Brito & Dekker, 2004). The collection of products from end customers, their inspection, their disassembly and eventually their distribution to product recovery facilities are all activities that direct the 'reverse flow' of products from the customer and ultimately define the term 'reverse logistics' (Bei & Linyan, 2005; Dowlatshahi, 2000; Rogers & Tibben-Lembke, 1999).

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Having an effective reverse logistics system can reduce costs, increase revenues, and moreover retain customer loyalty and protect the company's brand (Fleischmann, 2001). Furthermore, compliance with regulations to protect the environment, including reducing material resource consumption through recycling and other forms of product recovery have increased the need for reverse logistics. These economic and environmental motivations have pushed researchers to develop mathematical models to study and analyse inventory flow in reverse logistics (Bei & Linyan, 2005; Bonney & Jaber, 2011; Fleischmann et al., 1997; Gülsün et al., 2006).

There are numerous studies that analyse inventory models with return flow (Fleischmann et al., 1997; Richter, 1996; Bostel, Dejax, & Lu, 2005; Dobos & Richter, 2003, 2004; El Saadany & Jaber, 2008, 2010, 2011). The root of these models is the work of Schrady (1967) (Fleischmann et al., 1997) which, in turn, is fundamentally based on the classical economic order quantity (EOQ) model. The work of Schrady (1967) has been extended extensively as presented in the literature (Fleischmann et al., 1997). Richter (1996) considered the reality that some returned items may require disposal, and as a result presented a model that has been a building block for inventory models with return flows based on an EOQ setting (Fleischmann et al., 1997). The main assumptions considered in these models are: (1) recovered items are deemed as-good-as-new, (2) the recovery process is applicable only to the product as a whole, and (3) the recovery of returned products is indefinite (i.e., it can be recovered infinite number of times with no deterioration to product quality or material characteristics). Recent works have relaxed these assumptions; Jaber and El Saadany (2009) and Hasanov, Jaber, and Zolfaghari (2012) considered recovered items are of incompatible quality. The first study assumed that demand for remanufactured (produced) items are lost over the production (remanufacturing) segment of a cycle, while the latter assumed that unmet demand is either fully or partially backordered. El Saadany and Jaber (2011) considered in their model that subassemblies of returned items may or may not be recovered. Arguably, one of the roles of reverse logistics is to extend the useful life of a product to as much as it is technically and economically possible. The studies prior to that of El Saadany, Jaber, and Bonney (2013) assumed that a returned item is recovered for an indefinite number of times. Realistically, materials and components degrade and lose many of their characteristics when repetitively remanufactured or recycled (El Saadany et al., 2013; Matar, Jaber, & Searcy, 2014). El Saadany et al. (2013) addressed this limitation and considered an investment cost is associated with the number of times a product is recovered. This is a key consideration that has many effects on an inventory model (on the number items that are considered waste, the number of items that are required to be 'newly' manufactured) let alone other factors (design for remanufacture, design for recycling, etc.).

There are many environmental issues that unusually arise from the production and transportation of products; e.g. air emissions, solid waste disposal, declining landfill sites, biodegradability of disposed items, chemical and toxic waste disposal, water contamination, thermal pollution, energy consumption, and depletion of natural resources (Bei & Linyan, 2005; Bonney & Jaber, 2011; El Saadany, Jaber, & Bonney, 2011; Gülsün et al., 2006). These contributions come with associated costs that can no longer be ignored in the mathematical modeling of reverse logistics (Bonney & Jaber, 2011). Furthermore, environmental concerns of stakeholders and newly introduced legislation have provided additional incentives for more reverse logistics practices (Fleischmann, 2001; Sheu & Chen, 2012).

To respond to environmental pressures, mathematical modeling of reverse logistics has to account for these ignored costs. The reverse logistics models available in the literature are based on the EOQ model and only consider solid waste disposal of returned that cannot be recovered. Further, traditional inventory models (forward supply chain models), in general, have recently focused on greenhouse-gas (GHG) emissions as their environmental issue (Hua, Cheng, & Wang, 2011; Jaber, Glock, & El Saadany, 2013; Wahab, Mamun, & Ongkunaruk, 2011; Zanoni, Mazzoldi, & Jaber, 2014). There is a disparity between the EOQ-based reverse logistics models and the environmental effects the respective models should account for. This paper looks to narrow this disparity and provide a model that accounts for the impact of several environmental issues and shows how inventory policies may require adjustments to lessen their environmental impact while retaining, to the best possible, the economic benefits.

The adverse effect that GHG emissions has on the environment is discussed in Kruger and Pizer (2004), I.P.C.C. (2006), Mouzon and Yildirim (2008) and Kaygusuz (2009). In this paper, GHG emissions come from manufacturing, remanufacturing, and shipping items to and collecting used items from the market. In addition, energy consumption from manufacturing also has a significant and negative impact on the environment (Devoldere, Dewulf, Deprez, Willems, & Duflou, 2007; Dietmair & Verl, 2009; Mouzon & Yildirim, 2008). Coupled with the aforementioned solid waste disposal, which is the main environmental issue addressed in the available reverse logistics mathematical models, GHG emissions and energy used for manufacturing and remanufacturing are considered. The reverse logistics mathematical model presented in this paper accounts for these three main environmental issues.

The model assumptions and the development of the cost functions are presented in the next section. Section 3 provides numerical examples to facilitate general understanding of the inventory system. Section 4 provides additional points that extend the discussion beyond the results of this paper. Section 5 summarizes the work, highlights the main results, and provides an insight into the future work.

2. The model

In a similar approach to the available reverse logistics mathematical models that are based on the EOQ setting, the fundamental objective is to operate at minimum cost. The underlying difference between the model of this paper and the models surveyed above is that it accounts for the environmental costs of the system, which have been previously ignored.

2.1. Model concept, main assumptions and nomenclature

The model of Richter (1996) is the first EOQ based mathematical model to consider the disposal of items and can be considered a base model for this work. The main assumptions considered by Richter (1996) are that items are deemed as-good-as-new, the recovery process is applicable only to the product as a whole, and that the recovery of returned products is indefinite (i.e., it can be recovered infinite number of times with no deterioration to product quality or material characteristics). The focus of this study is to include environmental implications present in a reverse logistics model. For this reason, the consideration of a limited number of times for which an item can be recovered directly affects the number of returned items that are disposed. This consideration is presented in El Saadany et al. (2013) and for its environmental importance, which is considered in the development of the proposed model in this paper.