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On inventory control of product recovery systems subject to environmental mechanisms

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ABSTRACT

The aim of this paper is to study the impact of inventory control in reducing the carbon footprint of an organization. Through a stochastic inventory model, our research extends the traditional minimization cost problem by incorporating environmental legislation. We consider a finite-horizon closed-loop system whereby decisions are subject to an emissions trading scheme and to random demand and returns. Demand can be satisfied by two sources. The primary source is environmentally friendly but expensive, whereas the second is cost effective but with negative environmental consequences. The problem is formulated as a stochastic dynamic problem, where replenishment and carbon management decisions must be made at each period. The objective is to describe how replenishment and carbon management strategies are affected by environmental constraints. In particular, considering the computation restriction of dynamic programming, in order to extend the results, we propose a genetic algorithm to find near-optimal solutions for larger instances. A sensitivity analysis is performed to identify the impact of carbon allowance prices, emission-cap and other environmental factors in the decision-making process. The results indicate that environmental strategies and their factors have an impact on replenishment decisions. There is an emission-cap from which a company must focus on strategic decisions rather than on tactical and operational decisions. In addition, if the carbon allowance price is such that the environmental benefit absorbs the cost of less polluting technology, a change in the inventory policy must be made.

1. Introduction

In view of environmental legislation and the increasing costs of resources, environmental performance has become a major concern for many companies. In such context, production, transportation and sourcing decisions play a key role in reducing an organization's negative environmental impact (Benjaafar et al., 2013). Therefore, decision-making models should be improved in order to develop appropriate planning methods which balance environmental performance against costs. There exists a range of possibilities for a model integrating environmental concerns and logistics. End-of-life product recovery and greenhouse-gas (GHG) reduction are two main approaches studied by researchers.

Motivations for product recovery include reduction of waste, minimization of raw material, and reduction of life cycle cost, among others. Caterpillar is an example of a pioneer company in product recovery; it has already made a business priority the practice of returning end-of-life products to like-new conditions. Meanwhile, GHG reduction is mainly motivated by altruism, climate programs, and economic benefits (Veen and Venugopal, 2014). Examples of these programs include the European Union Emissions Trading Scheme (EU ETS), the Western Climate Initiative (WCI) and the Regional Greenhouse Gas Initiative (RGGI). Those initiatives seek to reduce GHG emissions by implementing a cap-and-trade mechanism, where the industries must respect an emission-quota and may trade carbon allowances. Multiple countries as the United States, Canada and those in the European Union are implementing these programs.

Several authors have studied inventory control of product recovery systems. In van der Laan et al. (2004), the optimal inventory policy for a hybrid manufacturing/remanufacturing system is derived. Later in Ahiska and King (2010), setup costs were included. In parallel, GHG reduction policies such as (1) emission-tax, (2) direct-cap, and (3) cap-and-trade have also been the subject of various studies. The Economic Order Quantity (EOQ) has been reformulated in Bouchery et al. (2012) to include the sustainable objectives. Liu et al. (2013) compute the optimal order quantity for retailers when a cap-and-trade mechanism is considered. For their part, Toptal and Konur (2014) presented an

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extension of the EOQ model to include alternative environmental policies. Ultimately, García-Alvarado et al. (2014) have been shown that the inventory policy is affected when emissions are considered in an infinite-horizon closed-loop system.

As each year, the emission-cap and environmental legislation are adjusted according to the sector and the environmental standards of the year, a finite-horizon approach may be more appropriate to simulate the dynamics of the environmental legislation. Although numerous researchers have studied recovery systems, to our knowledge, no author has studied a finite-horizon recovery system subject to environmental constraints. This raises the question whether environmental policies affect replenishment and carbon management strategies in a finite-horizon product recovery system. Thus, the aim of the paper is threefold: (1) to present a stochastic inventory model incorporating environmental constraints, (2) to present a solution method to overcome the solution difficulties, and (3) to provide a set of managerial insights on the knowledge of joint inventory control and carbon footprint reduction. The rest of this paper is organized as follows: the following section surveys the recently emerged research on product recovery and environmental inventory systems. Section 3 presents the inventory model. Section 4 introduce a dynamic programming solution approach. Section 5 presents a genetic algorithm for extending our results. Numerical results are carried out in Section 6. Section 7 summarizes the results and suggests some directions for future research.

2. Literature review

Throughout this work, we are interested in two streams: (1) inventory control of product recovery systems and (2) inventory control subject to environmental constraints.

Simpson (1978) and Inderfurth (1997) conducted initial research of recovery systems. They characterized the optimal inventory policy for a product recovery system with single-period lead-times and random demand and returns. The inventory policy is characterized by three parameters: (1) the manufacturing-up-to-level ($S_{p,t}$), (2) the remanufacturing-up-to-level ($S_{r,t}$) and (3) the disposal-down-to-level (U_t). Each parameter denotes the trigger to produce, remanufacture, and dispose, respectively. van der Laan et al. (2004) extended the model presented by Inderfurth (1997). A hybrid system (S_p, S_r, U) under finite-horizon with different lead-times, demand, and returns were introduced. Bayindir et al. (2006) explored a recovery system under alternative inventory control policies. They determined the desired level of recovery given a probability of failure at the recovery operation. Recent literature such as Ahiska and King (2010) extended the model in Inderfurth (1997). The authors considered setup costs and different lead-time structures over an infinite-horizon. Modeling the system as a discrete-time Markovian Decision Process (MDP), the authors were able to characterize the optimal policy. Hence, for the given scenario, the optimal policy comprises four parameters: (1) the reorder level for manufacturing (s_p), (2) the manufacturing-up-to-level (S_p), (3) the reorder level for remanufacturing (s_r) and (4) the minimal quantity to remanufacture (q_r). Later on, Naeem et al. (2013) studied the lot sizing problem with remanufacturing options for a finite-horizon stochastic scenario. Finally, the work presented by Feng et al. (2013) analyzed a continuous-time recovery system for perishable products.

The studies by Dobos (2005, 2007) gave the first insights in the integration of the environmental effects into inventory models. Using the Arrow–Karlin model, the author analyzed the effects of emission trading on the production–inventory strategy of the firm. Through numerical examples the author proved an increase in inventory levels, and a smoother behavior of production rate. Later on, the study by Li and Gu (2012) extended the work of Dobos (2005, 2007) and explored the introduction of banking carbon allowances. The authors proved that allowance banking causes higher inventory levels and a smoother behavior on production rate. Besides the latter works, studies dealing with inventory and environmental constraints have mainly extended the EOQ-model in several directions. Bonney and Jaber (2011) present an extension of the EOQ model entitled the "Enviro-EOQ." In addition to traditional costs, they considered disposal and emission costs from transport. The authors concluded that when the environmental costs are introduced, the lot size is greater than the one provided by the traditional EOQ model. The work of Arslan and Turkay (2013) also extended the EOQ model, towards the integration of the sustainable concept. In their work, they presented five environmental management methods: (1) direct accounting, (2) carbon tax, (3) direct cap, (4) cap-and-trade and (5) carbon offsets. However, under approaches 1 and 2, the EOQ model does not change. The study of Hua et al. (2011) included an environmental damage cost in their model. Using a deterministic approach, they carried out an extension of the EOQ model. The authors determined the effect of the economic lot size, the carbon price, emissions and legislation on the total cost. Chen et al. (2013) also focused on the EOQ model. Their study is based on the traditional objective function, subject to an emission-cap. The authors proved that a cap is effective only when it is small enough to trigger a change in the quantity to order. Bouchery et al. (2012) presented an extension of the EOQ model named "the Sustainable Order Quantity" (SOQ) model. A multi-objective formulation coupled with an iterative method which allows interaction with decision makers is presented. The work of Chen and Monahan (2010) presented an analysis of the impact of environmental policies on inventory levels. Based on a stochastic model with random demand and environmental impacts over a finite-horizon, the authors determined the optimal inventory policies. Ultimately, the authors proved that when organizations are working under a mandatory scheme, they tend to increase their inventory levels, causing significant environmental effects. Finally, in Toptal and Konur (2014), the EOQ-model is extended by including three carbon regulation policies: (1) direct cap, (2) cap-and-trade and (3) carbon tax. The authors derive and compare the solution approach for a retailer's joint inventory control. They show that for any given policy, there is a cap-and-trade policy that will lower cost and emissions.

The stochastic scenario has been studied by Song et al. (2012). The authors investigated the newsvendor problem under a carbon emission-tax, a direct-cap and emission trading scheme. For each approach, the optimal production quantity and the expected profit is given. Using the same approach, the study by Hoen et al. (2012) incorporates multiple emission reduction policies into inventory control. The authors seek to reduce carbon emissions by selecting transport modes. A recent work on green inventory presented by Rosiî¡ and Jammernegg (2013) explores companies' decisions considering transport carbon emission. Based on the newsvendor framework, the author presents a basic dual outsourcing model. The work of Zhang and Xu (2013) also extended the newsvendor problem. The authors studied the multi-item production planning under a cap-and-trade scheme. Liu et al. (2013) derive the optimal order quantity for retailers facing random demand and subject to a cap-and-trade scheme. Their analysis concluded that the order quantity is determined by carbon prices rather than by the emission-cap. Recently, García-Alvarado et al. (2014) dealt with an infinite-horizon product recovery problem subject to a cap-and-trade scheme. The authors characterize the inventory policy and describe some of the effects of environmental factors on the structure. Nevertheless, given the curse of the dimensionality the authors were not able to extend their results to larger instances. In this paper, we extend the work of García-Alvarado et al. (2014) to a finite-horizon.