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Impact of transportation lead-time variability on the economic and environmental performance of inventory systems

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ABSTRACT

Storage and transportation of goods within global supply chains is a major cause of environmental damage in modern value added processes. Thus, in the past, theory and practice developed several approaches in order to decrease these negative environmental impacts that frequently counteract the traditional efficiency-oriented ambitions. However, in many cases the economic and environmental performance can be improved at the same time. As many activities in logistics and inventory management are related to the treatment of potential uncertainties in the system by establishing redundancies, the reduction of uncertainty has equally a positive impact on both performance measures. To investigate the interrelation between uncertainty and the economic and environmental performance of supply chains, a serial inventory system consisting of a manufacturer who works with overseas suppliers and a carrier is considered, whereas the carrier is able to reduce lead time uncertainty. The relationships between uncertainties and the economic and environmental performance of the considered inventory system are highlighted by a simulation study based on empirical data from an international container shipping supply chain.

1. Introduction

In recent years we have seen the necessity of including environmental considerations in business operations, in particular for emission intensive activities such as global transportation of goods. Although we should be willing to undertake some cost for reducing the environmental impact, identifying opportunities which have positive environmental effect without deteriorating economic performance has become very important. Such efforts would lead to sustainability on both dimensions. As mentioned by Wu and Dunn (1995) and McKinnon (2010) preserving the environment while maintaining economic growth is a priority for many countries and therefore developing and implementing practical and cost-effective carbon mitigation strategies for the logistics sector is a major challenge. Several activities through the supply chain contribute to these challenges.

Goods storage and transportation is a major cause of CO_2 emissions and is cited as the single largest source of environmental hazard in the logistics chain (Wu and Dunn, 1995). It is estimated that 2800 mega-tones of the overall greenhouse gas emissions, which is equivalent to 5.5% of the total emissions, are caused by the logistics and transport sector (WEF, 2009). In 2004 transport activities were responsible for 23% of the energy related greenhouse gas emissions and freight transport was responsible for around 8% (Kahn Ribeiro, 2007). Lengthening of supply lines and the increase in freight transport intensity coupled with high usage of carbon-intensive transport modes are the main drivers of transport related carbon emissions in global supply chains (McKinnon, 2010). In addition, carbon emissions related to warehousing is a significant factor because of the considerable energy requirements for heating, cooling, materials handling equipment, etc. (Dhooma and Baker, 2012), which is a result of the increasing warehouse capacities due to rising buffers caused by longer lead times in global supply chains as well as due to growing product portfolios.

In order to decrease the negative environmental impact of goods storage and transportation, different entities of the logistics chain can take on actions with immediate implications on the transportation system. Manufacturers and retailers can use more environmentally friendly transportation modes, or reduce the need for transportation by buying from on-shore suppliers as well as centralizing warehouses. On the other hand, logistics providers can work on reducing the carbon intensity of the energy they use and increase the energy efficiency of their operations by freight consolidation or by improving the technical features and the

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maintenance of their vehicles (McKinnon, 2010). Additionally, there are actions which can help improve the system through the interaction of the overall operations. One example is coordinating production schedules among suppliers to allow joint shipments which results in better vehicle utilization and hence fewer emissions (Bonney and Jaber, 2011).

Similarly, in this paper we analyze the economic and environmental implications of a serial inventory system through such an interaction effect: the indirect effect of transport lead time variability through the replenishment policy on economic and environmental performance of supply chains. In order to develop sustainable operations we need to understand the effect of system parameters on environmental performance. In this study we are interested in the impact of a system parameter, transport lead-time variability, on carbon emissions.

As Fransoo and Lee (2012) put it, although 'containerized ocean transport has become the lifeline of almost any global supply chain', there appears to be little or no attention to end-to-end supply chain focus. Similarly, in a recent review, Tang and Zhou (2012) conclude that there is a need to develop and analyze end-to-end supply chain models that incorporate the issue of sustainable operations. Although we do not consider a complete end-to-end supply chain, we still consider the interactions of different parts of the supply chain.

When we consider global supply chains with overseas transportation, air freight and containerized ocean transportation are the two relevant modes of transportation. Decreasing lead-time variability is an operational improvement which can indirectly affect the carbon emissions on the whole supply chain by triggering actions and policies from shippers that lead to lower carbon emissions. It is commonly acknowledged that unanticipated variability in demand and/or lead-time is the major reason for stock-outs or excess inventories in supply chains. As the ocean carrier is able to reduce the lead-time variability under certain conditions, the need for both emergency shipments by air freight as well as safety stocks will decrease, which will also have significant impacts on the environmental performance of the supply chain.

Economic implications of lead-time variability have been studied extensively. Song (1994), He and Kim (2005), and Song et al. (2010) analyze the effect of lead-time variability on optimal inventory control policies and the resulting total costs under standard inventory control policies. With a simulation study of a multi echelon supply chain Chaharsooghi and Heydari (2010) show the significant impact of lead-time variability on performance measures such as inventory levels, product availability and the bullwhip effect.

The time factor is a critical component in ocean transportation. Shipping lines have developed a strong focus on designing liner services with high frequencies, short transit times, combined with a high degree of schedule reliability. Variability in transportation time and the resulting delays not only decrease the reliability of the liner services, but can also incur additional costs (Notteboom, 2006).

Delays have negative impact not only on economic performance but also on environmental objectives. McKinnon (2007) presents a framework where seven sustainability ratios link supply chain activities with the carbon emissions of freight transport operations. Sanchez-Rodrigues et al. (2010) study the negative impact of operational uncertainty on the seven key ratios. They present the perceived economic and environmental risks of transport uncertainty based on focus groups and surveys from different industries including manufacturers, retailers, and logistics providers. Delays are identified as the main source of transport uncertainty which has the highest economic and environmental risk.

Recently, several models and policies have been developed which consider an environmental objective or constraint in addition to the economic objectives. Generally, environmental considerations are included in the models as they are imposed by regulations: either as limits on carbon emissions or as costs derived from carbon taxes or carbon trading.

Benjaafar et al. (2010) study how classical operational models can be modified to include carbon emission concerns in order to address the role of operational decisions on carbon reduction. In a following study, Chen et al. (2011) analyze the classical EOQ model with a carbon constraint and extend the results to the newsvendor model and facility location problems. They provide conditions under which carbon reductions can be achieved without significantly increasing cost using only operational adjustments. Similarly, Hua et al. (2011) and Song and Leng (2012) analyze EOQ and newsvendor models respectively under carbon cap-and-trade mechanism and show that under some conditions it is possible to reduce carbon emissions and decrease cost or increase profit at the same time. Jaber et al. (2012) model a two-echelon supply chain considering emissions trading. Using an EOQ type formulation they consider different legislative systems such as carbon tax, emissions penalty, and a combination of a carbon tax and penalty.

In addition to identifying optimal policies for companies, these studies provide insight about the effectiveness of different regulations on emission reductions. However, this implies that most of the research on operations including carbon emissions ignores market forces including competitors and consumers (Tang and Zhou, 2012). An exception is El Saadany et al. (2011) who study a two-level supply chain under cost optimization objective where demand is assumed to be a function of several product features including its environmental performance. Bouchery et al. (2012) state that the regulation based models poses a restriction with respect to their relevance and applicability. They study a multi-objective model in order to avoid this problem and apply their model for the EOQ problem. They identify the efficient frontier between total cost and total amount of carbon emissions resulting from the inventory system, and further use this to analyze the effectiveness of different regulations.

Hugo and Pistikopoulos (2005) and Frota Neto et al. (2008) address the supply chain network design problem using multi-objective models with environmental and economic criteria. They identify settings where significant improvements in one criterion can be achieved with marginal compromise in the other one. Similarly, Chaabane et al. (2012) show how to achieve environmental objectives in a cost efficient way while designing supply chains under carbon regulations. On the other hand, Harris et al. (2011) present a network design problem with a classical economic objective of cost minimization in order to study the impact of this approach on environmental performance. They analyze the relation between total logistics cost and their environmental impact in terms of carbon emissions from transportation and warehousing. They highlight that the cost-optimal solution is not necessarily the same as the solution which minimizes environmental impact.

The remainder of the paper is organized as follows: Section 2 presents our model and the modeling assumptions. We present the findings from our model based on a simulation study in Sections 3 and 4 finally concludes the article.

2. Problem description

This paper studies a serial inventory system consisting of a shipper, i.e. a manufacturer or a retailer, who works with overseas suppliers and has to decide on replenishments in the presence of uncertain customer demands as well as uncertain