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Carbon emissions in a multi-echelon production-inventory model with lead time constraints

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ABSTRACT

We develop a deterministic optimization model that incorporates carbon emissions in a multi-echelon production-inventory model with lead time constraints. We impose that each customer order must be delivered within the due date fixed by the customer. The quantity that cannot be delivered on time is a lost sale. We consider a multi-echelon supply chain with different external suppliers, different manufacturing facilities, and different distribution centers. We adopt a general inventory policy. Indeed, we do not impose any constraints on the stock level that must be kept for each product in each facility in each period and on the procurement order quantities in the different facilities. Carbon emissions are associated with the decisions of manufacturing of intermediate and final products, ordering (transportation) from external and internal suppliers, and inventory positioning of the different products in the different stages of the supply chain. We first deal with the case of carbon emissions tax and then turn to the case of carbon emissions cap.

We use the model to provide a series of insights that would be of interest for firms and policy makers. Such insights would be difficult to obtain with classical production-inventory models. For instance, the integration of lead times permits to show how the amount of carbon emissions is non-monotone with the variation of customer lead time and orders frequency. Also, the consideration of a general inventory policy permits to show how some particular policies (such as the base stock and the fixed order quantity) leads to increasing emissions. In addition, we capitalize on the multi-echelon aspect of our model in order to study the effect of individual emissions caps on each facility with comparison to a global cap on the entire supply chain. For instance, we demonstrate that individual caps can achieve significant lower emissions but can paradoxically lead to increasing the per unit emissions. We also show how a share of emissions can improve per unit emissions without deteriorating total emissions.

1. Introduction

The optimization of logistics and production activities has been based on economic criteria (cost minimization or profit maximization) for a long period regardless of the negative impacts that these activities may have on environment, basically in terms of carbon emissions. In the last decade, the environmental concerns are becoming increasingly relevant for firms as governments' environmental policies become more stringent and customer awareness to the environment increases. Thus, several traditional logistics and production management problems have been revisited with environmental considerations. Most of these works focus on the environmental damages (mainly, carbon emissions) associated with the decisions of facility location, technology selection, and supplier selection in either forward or reverse supply chain as shown in many recent overviews (Seuring, 2013; Tang and Zhou, 2012; Dekker et al., 2012). However, as highlighted by Benjaafar et al. (2013), the analytical-based operations management literature tends to overlook the source of emissions driven by operational decisions and basically those relevant to production and inventory management.

Typically, the production-inventory problem deals with the decisions of manufactured quantity, order size, and inventory level. Such decisions may potentially have significant impact on carbon emissions. In this paper, we revisit the production-inventory model with carbon emissions consideration while considering the challenging context of a multi-echelon supply chain

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with lead time constraints. We impose that each customer order must be delivered within the due date fixed by the customer. We adopt a general inventory policy. Indeed, we do not impose any constraints on the stock level that must be kept for each product in each facility in each period and on the procurement order quantities in the different facilities. We consider a multi-echelon supply chain with different external suppliers, different manufacturing facilities, and different distribution centers. In addition to rethinking the classical issues on the correlation between production-inventory decisions and carbon emissions, the proposed model helps to address new research questions that arise when we consider lead times, general inventory policy, and multi-echelon supply chain.

In order to better explain the context of this research, we consider the following generic case of a multi-echelon supply chain (SC) with different manufacturing and distribution facilities owned by a single global firm. The manufacturing facilities buy raw materials from external suppliers to transform them into intermediate products which are then used to obtain a final product. The intermediate products can translate between the different facilities and the final product is shipped to end customer through a distribution center. The firm faces a deterministic demand over a planning horizon of multiple periods. For every order, the end customer requires to be delivered within a quoted customer lead time which is defined as follows: *Customer lead time = time elapsed between placing an order by the end customer and the due date of that order*. A customer order that cannot be delivered on time is partially or totally lost with corresponding lost sale cost. The delivery lead time that can be achieved by the firm for a given customer order depends on many factors: the lead times of purchasing raw materials from external suppliers, the lead times of manufacturing intermediate and final products, the lead times of procurement between facilities, and also the available inventories of the different products at the different echelons of the SC. This situation is close to many real-world cases. We give hereafter some questions that may arise in such a context and that motivate the present work.

- If the customer lead time is shorter than the delivery lead time that can be achieved by the firm then the firm is generally constrained to keep inventories of some products (input, intermediate, or final products) at the different echelons of the SC. This can have a considerable impact on the carbon emissions in inventory as highlighted by Benjaafar et al. (2013). Thus, it would be interesting to investigate whether a shorter customer lead time leads to higher emissions level.
- Tight customer lead times might also favor small production runs and frequent deliveries (from suppliers to facilities and between facilities) as the system might not have enough time to aggregate manufacturing and delivery orders. This confirms that we need to study the impact of lead times on emissions.
- If we increase the frequency of end customer orders (i.e., we increase the number of orders while keeping constant the total demand) then this might increase the transportation emissions while decreasing the inventory emissions. Overall, according to the conventional wisdom, the higher is the frequency the larger the amount of emissions becomes. However, it would be difficult to capture the impact of frequency on emissions when we implicitly assume that the system is able to deliver all orders on time (i.e., when we ignore lead time constraints). Indeed, a higher frequency might make difficult the satisfaction of customer lead time which might have effect on operational decisions and, consequently, on emissions. Therefore, it would be of interest to examine the effect of frequency on emissions under lead time constraints.
- Unlike the case of some particular and relatively simple structures of SC, the optimal inventory policy in a general multi-echelon SC like the one considered in this paper is not known, especially when environmental concerns are incorporated. A valuable effort has been made in the literature to revisit the classical EOQ model with carbon emission considerations (see e.g., Bouchery et al., 2012). However, the comparison of different inventory policies in terms of emissions in the context of multi-echelon SC has not yet received adequate attention. Our model permits to investigate this question since some classical inventory policies (such as the base stock and the fixed order quantity) can be considered as particular cases of the general inventory policy adopted in this paper.
- If environmental legislations impose an emissions cap per period of time then the SC might be constrained to adjust its production rate in order to meet the emissions target. As shown by Chen and Monahan (2010), such legislations may also push companies to keep stocks in a given period in order to be able to reduce the production level in a subsequent period and, consequently, reduce emissions without losing demand. It would be interesting to investigate how such adjustments of operational decisions occur in a multi-echelon SC with lead time constraints. In addition, the context of a multi-echelon SC raises the question of individual emissions caps (on each facility) vs a global emissions cap (on the entire SC).

Clearly, the above research questions cannot be addressed if one ignores lead time constraints, adopt a specific inventory policy, or/and consider a simple SC structure. The problem of integrating lead time constraints in the context of multi-echelon SC leads to challenging optimization models as explained in Hammami and Frein (2014). We developed two versions of this problem. The first version focuses on inventory placement with the objective of minimizing the total inventory cost while incorporating a fine approach of lead time calculation by considering the interactions of procurement and manufacturing orders between time periods (Hammami and Frein, 2014). This first model does not consider environmental concerns. The second version, which is the purpose of this paper, is motivated by the above questions and focuses on the integration of environmental concerns in the management of production-inventory systems. Two environmental legislations are alternatively considered: carbon tax and emissions cap. The objective is to minimize the total system's cost. In order to make advances in the experiments and analysis of environmental aspects, we add some constraints in the modeling of lead times with comparison to Hammami and Frein (2014). In particular, we impose that procurement and manufacturing orders launched in a given period must be accomplished within this same period.

The impacts of production-inventory decisions on environment have been addressed in some pioneer papers by Hua et al. (2011), Wahab et al. (2011), Bouchery et al. (2012), and recently Benjaafar et al. (2013). While there is clearly value in such efforts, they ignore the impacts of lead time constraints on emissions. In addition, most of these works consider a simple SC structure and deal only with the emissions associated with the final product (raw materials and intermediate products are not considered). There is clearly a need to address environmental considerations in more realistic production-inventory models in order to consolidate the insights derived so far in the literature and to investigate new insights relative to real-world complexities. The present work is a step forward in this direction.

In addition to the proposed optimization model, a major contribution in this paper is a set of insights relative to the carbon emissions in production-inventory systems, some of which would be difficult to obtain without the support of the model developed here. The following is a highlight of some results.