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Integrated economic and environmental models for a multi stage cold supply chain under carbon tax regulation

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ABSTRACT

The elevated level of public and organizations awareness concerning sustainability has necessitated the adoption of environmentally conscious practices in the management of supply chains. As such, classical inventory models wherein the sole measure of performance is cost minimization are no longer appropriate to handle such emerging and pressing issue. This paper assesses the impact of accounting for carbon emissions, resulting from transportation and storage activities of a cold item, in the context of a multi stage supply chain comprised of a plant/warehouse, a distribution center (DC) and a retailer. We present an operational cost minimization model, a carbon footprint minimization model and a hybrid economic and environmental minimization model where all models seek to determine the optimal lot sizing and shipping quantities, alongside the number of trucks to be used in the upstream and downstream directions of the supply chain as well as the number of freezer units utilized at the DC which is owned by a third party logistics provider. The structural properties for the optimal solution of the three models are identified and solution algorithms are also proposed. Upon conducting computational experiments, it turns out that the incorporation of carbon related costs, through carbon tax regulation, may call for adjusting the adopted operational policy which results in a minor increase in the operational cost. However, this increase is outweighed by the savings resulting from the carbon related costs. Numerical results of the sensitivity analysis on the carbon tax policy indicate that as the tax rate increases, substantial reductions in the amount of carbon footprint emitted are realized and cost savings are also achieved when adopting the lot sizing and shipping policy of the third/integrated model over the operational cost minimization model.

1. Introduction

Cold supply chain management is concerned with the cost-efficient storage and transportation of temperature sensitive products (food, vegetables, confectionaries, flowers, and medicines). According to a report by the US Department of Commerce,[1] global losses in the food industry total more than $\$750 \times 10^9$ annually due mainly to lack of proper storage facilities and improper handling procedures. In addition, nearly $\$130 \times 10^9$ of annual medical, biologic and pharmaceutical sales are dependent on cold chain logistics to maintain the quality and integrity of the products. Cold chain markets that support perishable food distribution globally are estimated to be valued at nearly $\$250 \times 10^9$. Experts also estimate that cold chain in support of healthcare industries is worth more than $\$7 \times 10^9$ and expected to reach $\$10.7 \times 10^9$ by 2017. The compound annual growth rate of cold chain markets is anticipated to reach nearly 16 percent over the next 5 years.[1] With these opportunities come great challenges to lower costs incurred in every process of the cold chain. Therefore, cold supply chain management requires effective tools, technologies and processes to efficiently manage the movement and storage of the products throughout the different stages of the chain.

Cold supply chain management is particularly vital for high ambient temperature countries, such as Middle East countries, where high temperatures are observed during most months of the year. For example, in recent years, several leading international logistics companies such as Global Shipping and Logistics and Triburg Freight Service, with state-of-the-art temperature-controlled warehouses and refrigerated transportation fleet, have been implanted in United Arab Emirates to provide storage and shipment services for cold products. Such third party logistics and

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[1] http://trade.gov/topmarkets/pdf/Cold_Chain_Top_Markets_Report.pdf.

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cold storage providers have played major roles in helping local industries to preserve the safety and quality of their perishable products in a harsh environment characterized by high temperature and humidity.

The storage of cold products is an energy intensive activity where energy costs associated with keeping the products at given temperatures account for a significant portion of the storage costs. Energy costs can be lowered using different strategies; namely, automation and efficient storage using multiple and smaller temperature monitored storage units. Indeed, several benefits can be achieved by dividing the warehouse into multiple storage units. First, only the operational storage units used will consume energy which will lower the energy cost. Second, products that require different temperature can be stored in different temperature controlled units. Third, heat loss which causes more energy consumption and energy cost can be lowered using high-density storage units (i.e. the more volume of the storage unit used the less the heat loss will be).

Incorporating sustainability in general and accounting for carbon emissions specifically have become an issue of utmost importance to all organizations nowadays. For the case of cold supply chains, this might partly be attributed to the associated high energy costs, negative environmental impacts, and pressure from the different stakeholders in the supply chain coupled with government regulations. Hence, the reduction of energy consumption costs meets the critical need to incorporate sustainability in the cold chain. From carbon emissions perspective, those emissions result from the use of electricity in refrigerator cooling and fuel in transportation between the different stages of the chain. According to James and James (2010), almost 1% of the emissions in the world are caused by the cold chain. This contribution to carbon emissions varies depending on the region where, in the United Kingdom for instance, cold chains account for 3.5% of the total emissions (Garnett and Jackson, 2007). Such concerns bring out the need to consider environmental aspects and explicitly account for carbon emissions in integrated inventory models seeking to optimize the performance of cold supply chains. Therefore, in addition to the development of efficient operational policies, cold chain management should also be concerned with the reduction of carbon emissions in the storage and transportation activities throughout the different stages of the chain which will impact the financial value positively as a result of an efficient use of energy.

The focus of this work is on optimizing the lot sizing and transportation decisions for a cold chain that consists of a single facility (plant, warehouse, farm, etc.), a single distribution center (DC), and a retailer. The distribution center is owned by a third-party logistics provider who offers storage services for cold products by renting modular temperature-controlled units. Full truckload (FTL) transportation mode is used between the warehouse and the DC, and between the DC and the retailer with similar or different capacity. Considering such cold chain structure, we first propose optimization models for the cases minimizing operational costs only, carbon emissions only, and the combined operational cost and carbon taxes. We also develop efficient solution procedures to solve the proposed models. We finally analyze the impact of integrating environmental and operational decisions on the total costs of the described cold supply chain.

The remainder of this paper is organized as follows. In the next section, the literature relevant to the problem addressed in this paper is reviewed. The third section presents the models' assumptions, the derivations of the three models as well as the solution procedures to generate optimal lot sizing and shipping decisions. The results of the computational experiments are discussed in Section 4 followed by concluding remarks and future research directions in the last section.

2. Literature review

Climate change and greenhouse effect have gained strong attention lately. With carbon dioxide (CO_2) representing 65 percent of the greenhouse gases that cause climate change,[2] different carbon emission policies were enforced. The policies can be either price based using taxes or quantity based using a cap and trade system. Under carbon tax policy, the organization is charged a constant tax rate for every ton of carbon emitted. Such a policy has shown to reduce energy consumption and encourage companies to invest in cleaner technologies. According to the quantity based carbon cap (CC) policy, however, the organization is charged only for carbon emitted above a specific level of emission set by an external regulatory party, or can be adopted as an internal management direction for the organization. The cap and trade is similar to the CC policy allowing organizations to trade their carbon credits they haven't used.

Due to the rise of important issues such as social and environmental concerns; a new trend and focus was established in inventory management literature to incorporate sustainability. Bonney and Jaber (2011) reviewed the literature and identified a range of inventory problems that are not covered appropriately by traditional inventory analysis such as the design of responsible inventory systems that reflect the needs of the environment. Several researchers have analyzed the impact of environmental aspects in the context of single stage inventory systems. Hua et al. (2011) presented an economic ordering quantity (EOQ) model under cap and trade system with emissions from logistics and warehousing activities. They examined the impact of carbon trade, carbon price, and carbon cap on order decisions, carbon emissions, and total cost. Bouchery et al. (2012) included the emission factor in the objective function of an inventory model. They proposed a multi-objective EOQ model that considers different emission regulatory policies. They proposed an interactive procedure that accounted for decision makers' preferences for non-perishable products.

Benjaafar et al. (2013) studied the multi period lot sizing problem for a single facility. They integrated carbon emission into operational decision-making with regard to procurement, production, and inventory management to show the impact of inventory policies on carbon footprint. The objective is to minimize the summation of the fixed and variable ordering costs, holding costs and backordering costs. Chen et al. (2013) included carbon footprint constraint into the EOQ model to reduce emission through modifying the ordering quantities. They considered four environmental regulations with emissions from ordering, production/purchasing and inventory holding activities. Absi et al. (2013) studied the multi-sourcing lot-sizing problems. They considered a multi-period model with deterministic demand and holding costs as well as fixed and variable production and transportation costs. They modeled the emission function as a constraint wherein four types of constraints were used: periodic carbon emission, cumulative carbon emission, global carbon emission, and rolling carbon emission.

When dealing with multi-stage inventory systems, carbon footprint can be assigned to production, storage and transportation activities (Quariguasi Frota Neto, 2010). Jaber et al. (2013) included carbon emissions into a two level (vendor-buyer) supply chain model under different emissions trading schemes including possible combinations between schemes. The goal is to minimize the inventory related and carbon emission costs when penalties for exceeding emissions limits are considered. Zanoni et al. (2014)

[2] https://www3.epa.gov/climatechange/ghgemissions/global.html.