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Managing carbon footprints in inventory management ☆

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A B S T R A C T

There is a broad consensus that mankind must reduce carbon emissions to mitigate global warming. It is generally accepted that carbon emission trading is one of the most effective market-based mechanisms to curb the amount of carbon emissions. This paper investigates how firms manage carbon footprints in inventory management under the carbon emission trading mechanism. We derive the optimal order quantity, and analytically and numerically examine the impacts of carbon trade, carbon price, and carbon cap on order decisions, carbon emissions, and total cost. We make interesting observations from the numerical examples and provide managerial insights from the analytical results.

1. Introduction

The Intergovernmental Panel on Climate Change (IPCC) reports that global warming poses a grave threat to the world's ecological system and the human race, and it is very likely caused by increasing concentrations of carbon emissions, which mainly results from such human activities as fossil fuel burning and deforestation (IPCC, 2007). In order to alleviate global warming, the United Nations (UN), the European Union (EU), and many countries have enacted legislation or designed mechanisms to curb the total amount of carbon emissions. These include the Kyoto Protocol (UNFCCC, 1997) and the European Union Emission Trading System (EU-ETS), which implements a mandatory "cap and trade" system in the 27 EU (2009) member countries. Among these legislation and mechanisms, carbon emission trading is generally accepted as one of the most effective market-based mechanisms, which has been broadly adopted by UN, EU, and many governments. There are now more than 20 platforms for trading carbon in the world. Australia, Canada, Japan, and the USA are also paving the way for domestic carbon emission markets. The global carbon market is expected to reach US$2 trillion by 2025. The EU carbon market is estimated to be worth US$131 billion a year (Bothra, 2010), while that in the USA will reach US$60 billion in 2012 (Environmentalleader, 2009).

To respond to the regulations on carbon emissions, firms tend to adopt more energy efficient equipment, facilities, or vehicles. On the other hand, they can also optimize their operations decisions in production, transportation, and inventory to reduce carbon emissions. This approach may reduce more carbon emissions with less or no cost than adopting low-energy-consumption technologies (Benjaafar et al., 2010). However, industry and academia seem to have largely ignored this approach to environmental protection. According to a survey by Accenture, only 10% of companies actively model their supply chain carbon footprints and have implemented successful sustainability initiatives. More than one-third (37%) of supply chain executives have no awareness of the levels of supply chain emissions in their supply chain networks (Accenture, 2009).

The literature on carbon footprint management in supply chain is also very sparse. Some studies focus on the measurement method of carbon emissions in supply chains. Carbontrust (2006) develops a methodology to determine the carbon footprints of different products by analyzing the carbon emissions generated by the energy used across the supply chain. Cholette and Venkat (2009) calculate the energy and carbon emissions associated with each transportation link and storage echelon in a wine supply chain. They find that different supply chain configurations can result in vastly different energy consumption and carbon emissions. Mtalaa et al. (2009) review the current measurement and calculation models that compute CO_2 emissions from truck transportation. Sundarakani et al. (2009) present an analytical model that measures carbon emissions from both stationary and non-stationary supply chain processes. Chaabane et al. (2010) introduced a mixed-integer linear programming based framework for sustainable supply chain design, their model demonstrated that efficient carbon management strategies will help decision makers to achieve sustainability objectives in a cost-effective manner.

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There are few studies on the operations decisions under carbon emission regulations. Penkuhn et al. (1997) present a nonlinear programming model for joint production planning problems by integrating emission taxes. Letmathe and Balakrishnan (2005) present two models for firms to determine their optimal product mix and production quantities in the presence of different types of environmental constraints. Rosič et al. (2009) examine a single-period dual model that incorporates the carbon emission cost. Kim et al. (2009) examine the relationship between the freight transport costs and CO_2 emissions in given intermodal and truck-only freight networks by multi-objective optimization. Cachon (2009) discusses how the new objective of reducing carbon footprints is likely to affect supply chain operations and structures. Hoen et al. (2010) examine the effects of two regulation mechanisms (emission cost vs. emission constraint) on the transport mode selection decision and suggest that policy-makers impose a constraint on freight transportation emissions. Benjaafar et al. (2010) introduce a series of simply models to illustrate how carbon footprint considerations could be incorporated into operations decisions. Pan et al. (2010) examined the environmental impact of pooling of supply chains, they found the supply network pooling is an efficient approach in reducing CO_2 emissions. Harris et al. (2011) investigated the relationship between total logistics costs and the environmental impact in terms of CO_2 emissions from transportation and electricity usage in depots when using a traditional cost-based optimization approach. Bonney and Jaber (2010) examined the importance of inventory planning to the environment and the possibility of using models to perform analyses.

This paper mainly examines the operations decisions in inventory management with a view to managing a firm's carbon footprints under the carbon emission trading mechanism, where a carbon footprint measures the total greenhouse gas emissions caused directly and indirectly by a person, organization, event, or product in tonnes (or kg) of CO_2 equivalent (Carbontrust, 2009). We found that Benjaafar et al. (2010) also presented a relatively simple inventory model incorporating cap-and-trade mechanism, but their model is so general that they cannot present an algorithm for their model and any theoretical analysis except for some observations. Based on the EOQ model, we introduce an environmental inventory model under the cap-and-trade system, derive the optimal order quantity, compare our model with the classical EOQ model, and analytically and numerically examine the impacts of carbon emission trading, carbon price, and carbon cap on order decisions, carbon emissions, and total cost. We make interesting observations and provide managerial insights from the research findings.

The rest of this paper is organized as follows: In Section 2 we formulate the carbon footprint management problem, derive the optimal order quantity, and examine analytically and numerically the impacts of carbon trading, carbon price, and carbon cap on order decisions, carbon emissions, and total cost. In Section 3 we provide some numerical examples to gain practical insights from the analytical results derived in Section 2. Finally we conclude the paper and suggest topics for future research in Section 4.

2. Optimal order quantity with carbon emission trading

In this section we consider the single-product replenishment problem with carbon trading based on the EOQ model. Carbon trading is also known as cap and trade. A firm is allocated a limit or cap on carbon emissions. If its amount of carbon emissions exceeds the carbon cap, it can buy the right to emit extra carbon from the carbon trading market. Otherwise, it can sell its surplus carbon credit. Obviously, this market mechanism can unify environmental objective and economic objective. We derive the optimal order quantity and examine the impacts of carbon trading on the optimal order policy, carbon emissions, and total order cost.

2.1. The model

We suppose that the product demand is known and deterministic, the retail price is exogenous, and the retailer decides only the order size. The processes of delivering and storing products consume significant amounts of energy, resulting in the creation of large amounts of carbon emissions from the transportation and warehouse operations (Penman and Stock, 1994; Stock, 2008; Stock et al., 2010). Therefore, we focus on the carbon emissions caused by logistics and warehousing activities. The level of carbon emissions from logistics depends on the mode of transportation, choice of fuel used, and distance travelled (Sundarakani et al., 2010). In this paper we assume that the retailer continues to use his current supplier and vehicles after the implementation of the cap-and-trade system. In other words, we only focus on operations decisions. Since linear cost functions are widely used in literature, to simplify the problem, we suppose the carbon emissions from logistics per order is linear in the order quantity and the carbon emissions from warehouse is linear in the inventory. The carbon price is only affected by the carbon cap of a country, a region, or the world, and is not affected by the carbon cap allocated to a single retailer.

First, we introduce the notation used in the paper as follows:

- K, fixed ordering cost per order;
- D, annual demand or demand rate;
- h, annual holding cost per unit;
- Q, order size in units (a decision variable);
- Q^0, optimal order size in the classical EOQ model;
- Q^*, optimal order size with cap and trade;
- $\hat{Q}$, optimal order size when carbon emissions reach the minimum;
- α, carbon emission quotas per unit time;
- C, carbon price per unit (ton);
- $e+e_0Q$, the amount of carbon emissions in executing an order of Q units, where e is the carbon emissions when the truck is empty, and e_0 is the variable emission factor;
- g_0+gQ, the amount of carbon emissions in holding Q units product, where g_0 is the fixed carbon emissions, and g is the variable emission factor in warehouse;
- X, transfer quantity of carbon emissions (a decision variable);
- $TC(Q,X)$, total cost per unit time if the order size is Q units and transfer quantity of carbon emission is X.

We choose the classical EOQ model as the benchmark, of which the formulation, the optimal order quantity, and the total cost are known as follows:

$$\min TC(Q) = K\frac{D}{Q} + \frac{hQ}{2}, \quad Q^0 = \sqrt{\frac{2KD}{h}},$$

and

$$TC_0 \triangleq TC(Q^0) = \sqrt{2KDh}.$$

Under the cap-and-trade system, the retailer's objective function is

$$TC(Q,X) = K\frac{D}{Q} + \frac{hQ}{2} - CX.$$

According to the assumptions, the carbon footprints per unit time from logistics and warehouse are $(e+e_0Q)/(Q/D) = e_0D + eD/Q$ (which is in accord with the results in Marintek and Trondheim,