Carbon Emission Modeling in a Two Stage Supply Chain

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Carbon emission control has been a global challenge. Carbon tax and carbon cap-and-trade are two globally practiced regulatory schemes to control carbon emission. This paper investigates the joint optimal decisions on lot size in a coordinated supply chain between a retailer and a manufacturer under carbon tax mechanism and under carbon cap-and-trade mechanism. The comprehensive cost based models are proposed to capture the influence of two carbon regulatory schemes on business decisions in such coordinated two stage supply chain. The research results provide managerial implications in operations management and in carbon regulations.

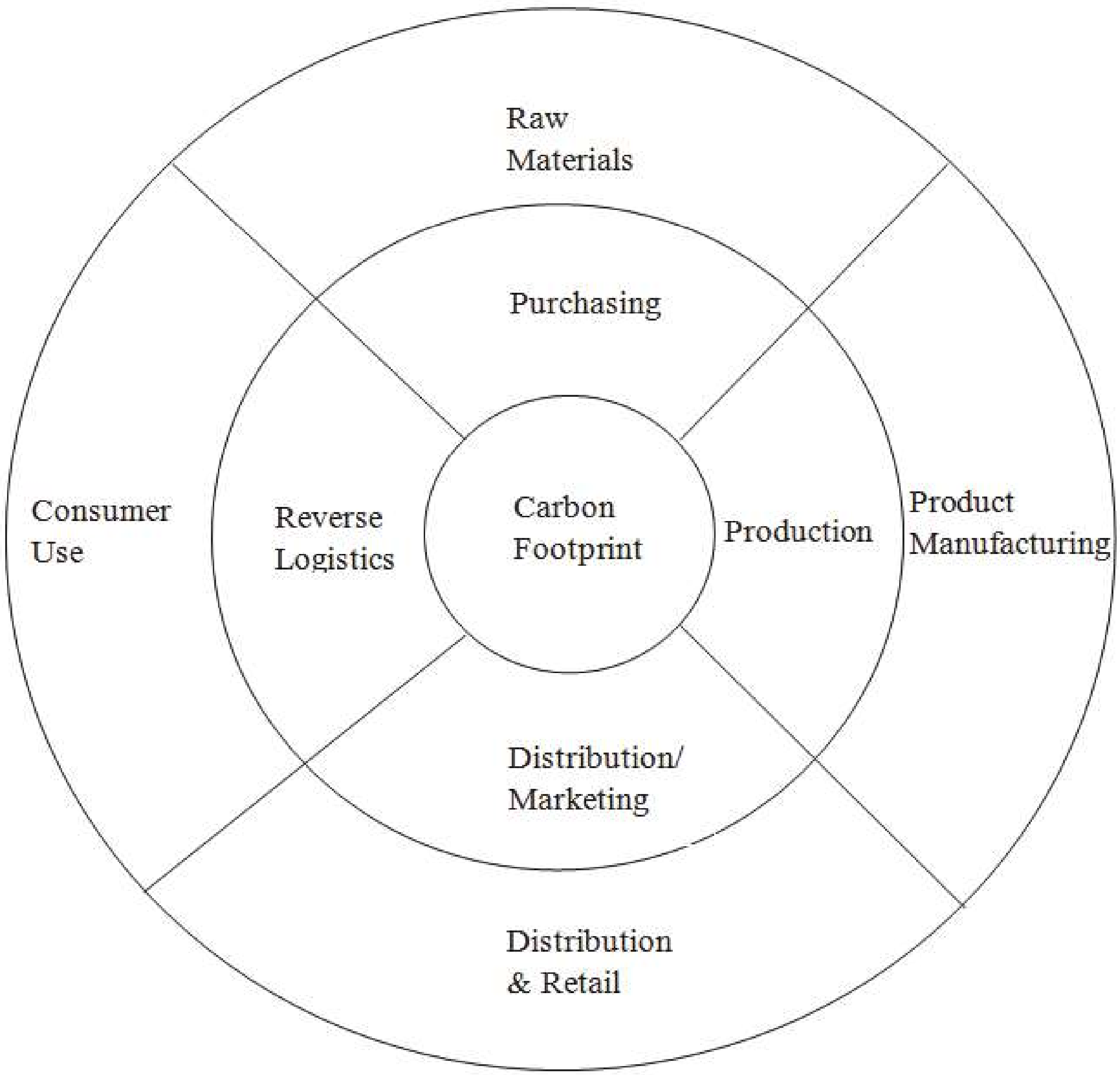
INTRODUCTION

There is consensus that global warming has a direct relationship with carbon emission. To control the carbon emission, many countries have implemented carbon tax scheme or carbon cap-and-trade scheme. With the emergent of environmental challenges in supply chains, carbon footprint management has been proposed as a new dimension of performance measurement to supplement cost, quality, delivery speed and flexibility (Butner et al.2008). Carbon emission, commonly referred to as the carbon footprint, is used to measure the impact of carbon dioxide and other greenhouse gases on the environment. Bell & Callan (2011) reported that carbon dioxide alone accounts for about 70% of the greenhouse effects of carbon emission.

In light of the on-going consumer, regulatory and competitive pressures businesses are becoming increasingly conscious of their carbon footprint and have begun to incorporate environmental thinking into their business strategy and supply chain management. Zhu & Sarkis (2007) classified these pressures as *normative* (market), *coercive* (regulatory), and *mimetic* (competitors). Beamon (1999), Linton et al. (2007), and Srivastava (2007) refer to this new paradigm of incorporating environmental thinking into supply chain strategies as green supply chain management (GSCM).

In lean manufacturing parlance, carbon emission is the new *Muda*, the Japanese term for waste in lean practice. Therefore, reducing carbon emission, which is waste in procurement, production and distribution, is aligned with just-in-time philosophy and lean supply chain management. Carbon emission reduction and environmental stewardship are becoming an immutable part of the supply chain strategies for most firms. Thus, research on reducing carbon emission and optimizing its operations in the extended supply chain is in line with current supply chain management practices.

FIGURE 1
SOURCES OF CARBON EMISSION



According to Katircioglu (2010), carbon emission from supply chain activities is responsible for at least half of all global carbon emissions. Sarkis (2003), Hervani et al. (2005) and Sundarakani et al. (2010) posit that energy use and carbon emission occur across a closed loop supply chain that includes not only materials purchasing, product manufacturing, distribution and delivery, but also reverse logistics which refers to reuse, remanufacturing and recycling of materials into the value chain. As illustrated in

Figure 1, the outside circle shows the carbon emission generated across the extended supply chain of firms and the inner circle shows the carbon emission generated from the perspective of a product.

Knowledge of the sources of carbon emission in every step of their extended supply chain enables firms to strive to reduce their impact on the environment. According to Jones (2011), 93% of multinational companies are now taking steps to address carbon emissions directly related to their businesses. This is achieved by investing in energy efficient equipment, facilities, and vehicles. Firms may also choose to optimize their operational decisions in procurement, production, transportation and inventory along their supply chains as a means of reducing carbon emission. In this paper we develop an optimization model to determine the cost minimizing joint economic lot size for a two stage (manufacturer- retailer) supply chain under carbon tax mechanism and carbon cap-and-trade mechanism.

The contribution of the joint economic lot size (JELS) model with carbon emission developed herein is twofold. First, the ability to measure performance in terms of cost will make the model practical and could lead to the establishment of benchmarks for future comparisons. As the old adage goes, it is difficult to manage what one cannot measure. It is especially important to use cost as the metric to quantify carbon emission performance since the ability to measure carbon emissions is the first step toward reducing their impact on the environment. As Gunasekaran et al. (2004), Lancioni (2000), and Lalonde & Pohlen (1996) address the importance of linking performance measurement with cost as a metric in supply chain management.

Secondly, the vast majorities of joint economic lot size models for supply chain management concentrate only on operational costs such as the cost associated with ordering or setup and holding inventory and ignore environmental costs. Environmental concerns cover broad subjects including energy use, materials/chemical use, waste in the form of gas, liquid, and solids. In this research, environmental issues are modeled using carbon emission reduction, and environmental cost refers to carbon emission cost. Hence, by linking both the operational and environmental objectives we provide management with a more comprehensive model that can be used to examine how carbon emission policies might affect their joint order quantity decisions and costs thereby shedding more light on how best to strategically operate.

The rest of this paper is organized as follows. In Section 2 we review the literature on lot sizing models with sustainability criteria. In Section 3 we present two model formulations for incorporating carbon tax and cap-and-trade mechanisms into the joint lot sizing model for a two stage supply chain and provide numerical illustrations of each model. In Section 4 we summarize and conclude the paper.

LITERITURE REVIEW

Supply chain management is the integration of key business processes and activities to provide value to the end customers, of which the production planning and inventory control processes are viewed as very important processes (Beamon, 1998). A review of the literature on the relationship between inventory control and supply chain management can be found in Thomas & Griffin (1996) and Routroy (2010). Inventory management requires making decisions on two fundamental questions: (1) how large should an inventory replenishment order be and (2) when should the order be placed? The economic lot size models were developed to answer these questions of order quantity and reorder point.

Economic lot size models which address environmental considerations are relatively new to the research stream on economic lot size models. Table 1 provides an overview of traditional lot sizing models (economic order quantity, economic production quantity, newsvendor and JELS). Examining Table 1, the EOQ and newsvendor are the most frequently used models for sustainable lot sizing. Carbon emissions (typically measured in units of carbon dioxide gas) is the most commonly used sustainability criteria. Fixed carbon cost, units of unsold product, the number of emission permits and environmental quality cost have also been used as sustainability criteria. The JELS models represent a beginning attempt to advance inventory-based sustainability modeling to the scope of a supply chain since they integrate the inventory lot sizing decision across two echelons.

TABLE 1
CLASSICAL INVENTORY MODELS WITH SUSTAINABILITY CRITERIA

Author(s)	Type of Inventory Model				Sustainability Criteria
	EOQ	EPQ	NV	JELS	
Chen et al. (2013)	X				Carbon emissions
Jaber et al. (2013)				X	Carbon emissions
Rosič and Jammernegg (2013)			X		Carbon emissions
Bouchery et al. (2012)	X				Carbon emissions
Zhang and Xu (2013)			X		Carbon emissions
Choi and Chiu (2012)			X		Unsold product
Song and Leng (2012)			X		Carbon emissions
Hua et al. (2011)	X				Carbon emissions
El Saadany et al. (2011)				X	Enviromental quality cost
Wahab et al. (2011)	X			X	Carbon emissions
Manikas and Godfrey (2010)			X		Emission permits
Tao et al. (2010)	X	X			Fixed carbon cost

Legend: EOQ = economical order quantity; EPQ = economical production quantity; NV = newsvendor; JELS = joint economical lot size

The models found in Wahab et al. (2011), El Saadany et al. (2011) and Jaber et al. (2013) are JELS models and have the greatest commonality to the model presented herein. As such we further examine how each of these models captured carbon emissions in their model formulation.

Wahab et al. (2011) introduce CO_2 emission costs into the JELS model in the form of fixed and variable emission costs. Fixed CO_2 emission costs are based on factors such as the line haul mileage distance between the buyer and vendor and characteristics of the transport vehicle such as gross vehicle weight, vehicle type, and fuel efficiency. Variable CO_2 emission costs are dependent on the shipment weight of the product. These fixed and variable emission costs are present in the forward loop of the supply chain where the vendor ships the product to the buyer and also in the reverse loop where the buyer returns defective product back to the vendor. The policy variables in this model are the optimal JELS quantity and the optimal number of shipments that minimize total cost.

El Saadany et al. (2011) use a quality cost function to represent a product's total environmental quality. The quality cost function is composed of an additive set of different environmental terms with each term representing a green aspect of the supply chain. Carbon emissions are indirectly captured through the components of the quality cost function which includes terms for transportation distance, air emissions, environmentally friendly purchasing and packaging, and aftermarket reuse, refurbishing and remanufacturing. The policy variables in this profit maximization model are the product selling price, the product aggregate quality measure and the integer multiplier which defines the retailer's incoming order quantity as a function of the manufacturer's economic lot size.

Jaber et al. (2013) present a JELS model where carbon emissions are a function of the manufacturer's production rate in a two stage (manufacturer-buyer) supply chain. The total cost function for the model is composed of the following three costs: (i) supply chain inventory related costs, (ii) the cost of emissions, and (iii) a penalty cost for exceeding the allowed emission limits. The model is optimized to determine the manufacturer's optimal production rate and the lot size multiplier which defines the buyer's incoming order quantity as a function of the manufacturer's economic lot size. The model is illustrated for different scenarios in which an emission penalty without a carbon tax is levied, when a carbon tax without an emission penalty is levied, and when both a carbon tax and an emission penalty are levied.

MODEL DEVELOPMENT

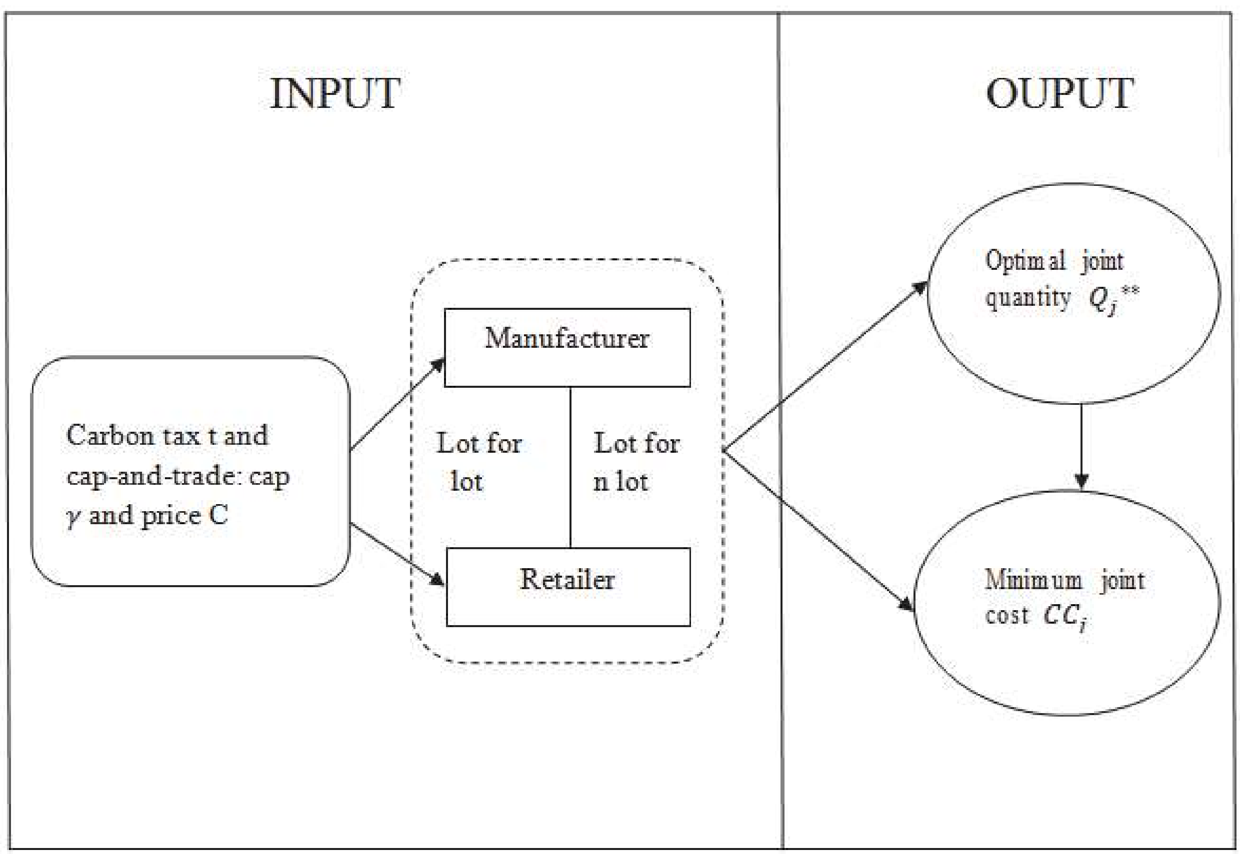
This section develops a set of four JELS models which consider operational and carbon emission costs for a two stage supply chain under carbon tax and carbon cap-and-trade mechanisms. Table 2 and Figure 2 outline the key features of these models.

TABLE 2
JELS EMISSION MECHANISMS AND ORDER POLICIES

	Lot for Lot Policy	Lot for n Lot Policy
Carbon Tax Mechanism	Carbon Tax JELS Model	Generalized Carbon Tax JELS Model
Carbon Trading Mechanism	Cap-and-Trade JELS Model	Generalized Cap-and-Trade JELS Model

Table 2 identifies the ordering policies that are used to coordinate product flow between the manufacturer and the retailer in the supply chain under the two different carbon mechanisms. Figure 2 identifies the input parameters (different lot sizing policies and different carbon mechanisms) and output parameters (JELS order quantity and total cost) of the modeling environment.

FIGURE 2
INPUT-OUTPUT FOR THE TWO STAGE SUPPLY CHAIN



Model Notation

The r subscript is used to designate the retailer; the subscript m is used to designate the manufacturer. Under the lot for lot policy Q is equal to the order or production quantity while under the lot for n lot policy it is the order quantity and production quantity n integer number of times. With subscription j for joint, TC_j is the joint total cost including operational cost from the retailer and manufacturer, CF_j the joint carbon emission from the retailer and manufacturer, and CC_j the comprehensive cost including operational and carbon emission costs from both the retailer and manufacturer.

A:	order cost per cycle
D:	annual demand
Q:	order quantity per cycle
S:	setup cost
p:	production rate
h_r:	inventory holding cost per unit time, per unit quantity for the retailer
t:	carbon tax rate
C:	carbon emission price
$\check{A}$:	carbon emission quantity from order per cycle
$\widetilde{h_r}$:	carbon emission quantity from inventory holding
α:	carbon emission cap for the retailer
CC:	comprehensive cost which includes operation cost and carbon emission cost
$CC(\alpha)$:	comprehensive cost with carbon emission cap
h_m:	inventory holding cost per unit time and per unit quantity for manufacturer
t:	carbon emission tax rate
C:	emission cost per credit
$\check{s}$:	carbon emission from setup
$\widetilde{h_m}$:	carbon emission quantity from inventory holding
β:	carbon emission cap for the manufacturing industry
$CC(\beta)$:	comprehensive cost with cap

Model Formulation

In this section we present formulations for two models which incorporate operational and environmental (carbon emission) costs for the JELS model for a two stage supply chain. We adopt the terminology joint comprehensive cost to reflect that the model formulations contain both operational and environmental costs and use the acronym JCLS (joint comprehensive lot size) to further identify the model. The two carbon emission mechanisms (carbon tax and carbon cap-and-trade) and the two lot sizing policies (lot for lot and lot for n lot) outlined in Table 2 are incorporated into two JCLS formulations since the lot for lot policy (Q, n=1) is a special case of the lot for n lot model (Q, n).

Formulation 1: JCLS Model with Carbon Tax Mechanism

The joint comprehensive cost of the supply chain for the joint lot size (Q, n) model with carbon emission under carbon tax mechanism is,

$$CC_j(Q,n) = \frac{D}{Q}\left[\left(A + t\check{A}\right) + \frac{(S+t\check{s})}{n}\right] + \frac{Q}{2}\left\{\left(h_r + t\widetilde{h_r}\right) + \left[n\left(1+\frac{D}{p}\right) - 1\right](h_m + t\widetilde{h_m})\right\} \tag{1}$$

When $n = 1$, Eq. (1) is reduced to,

$$CC_j = \frac{D}{Q}\left(A + t\check{A}\right) + \frac{Q}{2}(h_r + t\widetilde{h_r}) + \frac{D}{Q}(S + t\check{s}) + \frac{DQ}{2p}(h_m + t\widetilde{h_m}) \tag{2}$$

This is the joint lot size (Q, 1) model with carbon emission under carbon tax mechanism.

Solution Algorithm for JCLS Model with Carbon Tax Mechanism

We adopt the lot for n lot JELS solution algorithm of Goyal (1988) to solve the JCLS model defined in Eq. (1)

Step 1: With a fixed value of *n*, $\frac{dCC_j(Q,n)}{dQ} = 0$, solve for Q.

$$Q(n)^* = \sqrt{\frac{2D\left[(A+t\breve{A})+\frac{(S+t\check{s})}{n}\right]}{(h_r+t\widetilde{h_r})+\left[n\left(1+\frac{D}{p}\right)-1\right](h_m+t\widetilde{h_m})}} \tag{3}$$

Step 2: Substitute $Q(n)^*$ into $CC_j(Q,n)$ and simplify,

$$CC_j(n) = \sqrt{2D\left[\left(A+t\breve{A}\right)+\frac{(S+t\check{s})}{n}\right]\left\{\left(h_r+t\widetilde{h_r}\right)+\left[n\left(1+\frac{D}{p}\right)-1\right](h_m+t\widetilde{h_m})\right\}} \tag{4}$$

Minimize $CC_j(n)$ is equivalent to minimize

$$CC_j(n)^2 = 2D\left[\left(A+t\breve{A}\right)+\frac{(S+t\check{s})}{n}\right]\left\{\left(h_r+t\widetilde{h_r}\right)+\left[n\left(1+\frac{D}{p}\right)-1\right](h_m+t\widetilde{h_m})\right\} \tag{5}$$

Rearrange the terms and ignore those on the right-hand side, which are independent of *n*, the minimization problem is reduced to that of minimizing *Z*(*n*),

$$Z(n) = \left(A+t\breve{A}\right)\left(h_m+t\widetilde{h_m}\right)\left[n\left(1+\frac{D}{p}\right)-1\right]+\frac{(S+t\check{s})}{n}\left\{\left(h_r+t\widetilde{h_r}\right)+\left[n\left(1+\frac{D}{p}\right)-1\right](h_m+t\widetilde{h_m})\right\} \tag{6}$$

Step 3: Specify the optimality condition for *n*.

The economic value of $n = n^*$ is obtained if the following conditions are satisfied,

$$Z(n^*) \geq Z(n^*-1) \tag{7}$$

$$Z(n^*) \leq Z(n^*+1) \tag{8}$$

Substitute n^*-1 into $Z(n-1)$ and n^*+1 into $Z(n+1)$, the following equations are derived,

$$n^*(n^*-1) \leq \frac{(S+t\check{s})\left[(h_r+t\widetilde{h_r})-(h_m+t\widetilde{h_m})\right]}{(A+t\breve{A})(h_m+t\widetilde{h_m})\left(1+\frac{D}{p}\right)} \tag{9}$$

$$n^*(n^*+1) \geq \frac{(S+t\check{s})\left[(h_r+t\widetilde{h_r})-(h_m+t\widetilde{h_m})\right]}{(A+t\breve{A})(h_m+t\widetilde{h_m})\left(1+\frac{D}{p}\right)} \tag{10}$$

Step 4: Then, solve for the optimal *n*.

$$n^*(n^*+1) \geq \frac{(S+t\check{s})\left[(h_r+t\widetilde{h_r})-(h_m+t\widetilde{h_m})\right]}{(A+t\breve{A})(h_m+t\widetilde{h_m})\left(1+\frac{D}{p}\right)} \geq n^*(n^*-1) \tag{11}$$

Numerical Illustration

A numerical example is provided to illustrate the optimal joint quantity and minimum comprehensive cost under the lot for lot policy, and the optimal joint quantity, optimal batch number *n* and minimum comprehensive cost under lot for n lot policy. The parameters are summarized in Table 3.

TABLE 3
PARAMETERS FOR CARBON TAX NUMERICAL EXAMPLE

A	h_r	$\breve{A}$	$\widetilde{h_r}$	S	h_m	š	$\widetilde{h_m}$	t	D	p
200	0.8	400	2	800	0.4	400	1	0.02	60000	80000

Applying the solution algorithm, we find,

$$\frac{(S+t\check{s})\left[\left(h_r+t\widetilde{h_r}\right)-\left(h_m+t\widetilde{h_m}\right)\right]}{\left(A+t\breve{A}\right)\left(h_m+t\widetilde{h_m}\right)\left(1+\frac{D}{p}\right)}=\frac{808*0.42}{208*0.42*1.75}=2.22$$

$$n^*(n^*-1)\leq 2.22\leq n^*(n^*+1)$$

This gives the optimal *n* is 2. The optimal quantity and minimum comprehensive cost are

$$Q(n)^*=\sqrt{\frac{2*60000*\left[208+\frac{808}{2}\right]}{0.84+[2*1.75-1]*0.84}}=4998$$

and

$$CC_j(n)=\sqrt{2*60000*\left[208+\frac{808}{2}\right]\{0.84+[2*1.75-1]*0.42\}}=11781$$

Formulation 2: JCLS Model with Cap-and-Trade Mechanism

Under the carbon cap-and-trade mechanism, the joint comprehensive cost of the supply chain is

$$CC_j(Q,n)=\frac{D}{Q}\left[\left(A+C\breve{A}\right)+\frac{(S+C\check{s})}{n}\right]+\frac{Q}{2}\left\{\left(h_r+C\widetilde{h_r}\right)+\left[n\left(1+\frac{D}{P}\right)-1\right]\left(h_m+C\widetilde{h_m}\right)\right\}-C(\alpha+\beta) \quad (12)$$

When n=1 and $(\alpha+\beta)=0$, there is no cap. Replacing the carbon price, *C*, with the carbon tax rate, *t*, we have,

$$CC=\frac{D}{Q}\left(A+t\breve{A}\right)+\frac{Q}{2}\left(h_r+t\widetilde{h_r}\right)+\frac{D}{Q}(S+t\check{s})+\frac{DQ}{2p}\left(h_m+t\widetilde{h_m}\right) \quad (13)$$

This is the joint lot size model, (*Q*, 1), with carbon emission under cap-and-trade mechanism, which is a special case of the joint lot size model, (*Q*, *n*), with carbon emission under cap-and-trade mechanism. The solution algorithm to sole Eq. (13) is similar to the solution used to solve Eq. (4) and is therefore omitted.

Numerical Illustration

The parameters used in the numerical example are shown in Table 4.

TABLE 4
PARAMETERS FOR CAP-AND TRADE BASED NUMERICAL EXAMPLE

A	h_r	$\breve{A}$	$\widetilde{h_r}$	S	h_m	$\check{s}$	$\widetilde{h_m}$	C	D	p	α	β
200	0.8	400	2	800	0.4	400	1	0.2	60000	80000	8000	6000

Applying the solution algorithm, we find

$$\frac{(S + C\check{s})\left[\left(h_r + C\widetilde{h_r}\right) - \left(h_m + C\widetilde{h_m}\right)\right]}{\left(A + C\breve{A}\right)\left(h_m + C\widetilde{h_m}\right)\left(1 + \frac{D}{p}\right)} = \frac{880 * 0.6}{280 * 0.6 * 1.75} = 1.8$$

$$n^*(n^* - 1) \leq 1.8 \leq n^*(n^* + 1)$$

The optimal n is 1. The optimal order quantity and minimum cost are:

$$Q(n)^* = \sqrt{\frac{2 * 60000 * [280 + 880]}{1.2 + 0.75 * 0.6}} = 9185$$

$$CC_j(n) = \sqrt{2 * 60000 * [280 + 880]\{1.2 + 0.75 * 0.6\}} - 0.2(6000 + 8000) = 12355$$

SUMMARY AND DIRECTIONS FOR FUTURE RESEARCH

Carbon tax is a form of pollution tax; it levies a fee on production, distribution, or the use of fossil fuel based on the amount of carbon emission. Under the carbon tax mechanism, the total carbon emission is taxed at a carbon tax rate (dollar/tons). Carbon emission trading is an alternative means to reduce carbon emission in which a mandatory limit (or cap) is set on carbon emission over a specific time period and a total number of permits or carbon credits are allocated to firms by regulatory institutions. Under the carbon cap-and-trade mechanism carbon cost is based on carbon price and carbon emission quantity in excess of the carbon cap. In this paper we have presented joint economic lot size models to determine the optimal lot size in a coordinated two stage supply chain consisting of a manufacturer and retailer under both carbon mechanisms. The models presented herein expanded the scope of joint economic lot size models in the literature which have included carbon emission as an environmental modeling criterion. Models were developed for a lot for lot policy and then extended to a lot for n lot policy, with both models under the carbon tax mechanism and carbon cap-and-trade mechanism. The optimal joint order quantity, vendor lot size multiplier *n* and total costs were also presented for these models.

There are several aspects of this research that could be expanded. First, the models could be extended to include transportation cost which was not included in the current models since transportation was assumed to be outsourced to a third party. Second, the assumption of deterministic demand could be relaxed in future models. Thus, the current study could be extended to include stochastic demand and the analytical optimization methodology could used to solve it. Lastly, the scope of the supply chain could be expanded beyond two stages to a supply chain network of multiple retailers and manufacturers.

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