On the effectiveness of single firms' initiatives on the overall supply chain emission

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Abstract

The notion of carbon footprinting is ever more widespread as companies are becoming increasingly aware that tackling carbon emissions and being seen to do so is a key issue to face governments, customers and other stakeholders' pressures towards delivering environmentally friendly services and activities. In this contest, many firms are taking self initiatives to reduce their own carbon emissions while some other are constrained to obey to different regulations/policies (e.g. carbon tax or carbon Cap) designed by higher authorities targeting a low-carbon environment. Using buyer vendor framework, this paper provides some insights on how effective are these self initiatives and regulatory policies when only concerning firms at the individual level and not the whole supply chain they are part of. We show that when firms individually engage in reducing their direct carbon emissions either under self initiatives or regulatory policy, an opposite expected outcome resulting in a higher global supply chain emission can occur. This effect is referred to as the carbon seesaw effect. Moreover, we show that coordinating or centralizing the supply chain - contrary to what one may think at first- is not often the appropriate solution to get rid off this effect.

Key-Words: Carbon Emissions; Supply Chain Coordination; EOQ; Sustainable Operations.

1. Introduction

In the past few years there was an increasing consensus that carbon emission is a leading cause of global warming. Therefore, measurement of the carbon associated with supply chain activities - responsible for at least half the global carbon emission - and identification of cost-effective mechanisms to reduce it become a challenging must. A growing number of firms are under pressure from governments and environmental groups to reduce their carbon footprints. This is in particular true in countries that have signed the Kyoto protocol. The legislation enacted by governments has taken various forms, ranging from imposing strict emission caps to imposing taxes on emissions, instituting carbon trading markets, allowing for carbon offsets, and providing incentives for more carbon efficient technologies and fuels. Independently of legislation, there is growing number of voluntary industry initiatives to reduce emissions. In general, the motivation for such initiatives is driven by the recognition that high carbon emission is a sign of inefficiency in the supply chain. Moreover, some firms see a marketing opportunity in offering low carbon footprint products for customers increasingly aware about low carbon society. Thus, firms that are part of the same supply chain network have different sensitivity towards sustainability issues and therefore could individually engage in reducing their own carbon emission. Similarly, the global and network character of nowadays supply chain make it possible that while operating in the same supply chain, only some firms are subject to carbon emission regulations. For example, most of industries in the European

Union are subject to carbon emission legislation while in other countries - in particular those who did not signed the kyoto protocol. The question that immediately arise is how effective are these voluntary and individual initiatives.
This paper aims at studying the effectiveness of firm's voluntary efforts towards reducing carbon emission and its implications on the overall supply chain emission. We used a model consisting of a supply chain where one buyer (retailer) is purchasing an item from one supplier (vendor). The operating costs faced by both the supplier and the buyer include the purchasing cost (or the manufacturing cost if the supplier is a manufacturer), the inventory holding cost, and the fixed cost associated with each order (and/or each production lot for the manufacturer). The buyer has to meet a deterministic demand. We assume that the buyer's inventory policy can be described by the Economic Order Quantity (EOQ) model. We assume that both of the supplier and the buyer account for the emissions associated with their operational decisions. In particular, we consider emissions associated with placing an order (e.g., emissions due to transportation or emissions due to process setup for the manufacturer) and emissions associated with the storage of each unit held in inventory in each period. Using this setting, we aim at first studying situations where only the retailer engage to reduce its own carbon emission either voluntarily or under some carbon regulations and quantify the implications of such decision on the overall supply chain emission. We showed that, contrary to what one might think, efforts towards reducing carbon emission may lead to the opposite effect by increasing the total supply carbon emissions. We extend the analysis to whether coordinating the supply chain is the best option to get rid of the seesaw effect and show that only under some conditions this can be a solution.

The rest of the paper is organized as follows: in the next section we review papers related to our research. In section 3, we introduce our model, notations and settings to be studied. Section 4 describes the carbon seesaw effect, while section 5 describe the supply chain coordination under carbon emissions. In section 6 we summarize our results.

2. Literature Review

Closely related to our work are papers analyzing supply chain's carbon footprint by incorporating carbon emission driven decisions into traditional cost-driven supply chain models. Among these papers, (Benjaafar et al., 2010) showed how carbon emission could be included into operations decisions by considering several traditional supply chain models such as lot sizing, facility location etc. They used empirical studied to show that optimizing and adjusting firms' operations decisions in production, transportation, and inventory to reduce carbon emissions may reduce carbon emissions with less or no cost than adopting low-energy-consumption technologies. Hua et al. (2011) considered carbon trading and managing carbon footprints in inventory management using the framework of Economic Order Quantity (EOQ). The EOQ framework has been used also in (Chen et al., 2013; Bouchery et al., 2012). Chen et al. (2013) discussed the optimal replenishment policy under variety of carbon emission regulations. Their main finding is that some operational adjustment on the classic EOQ formula can lead to significant reductions in emission without increasing the cost. They also found that their observations can be extended to some facility location models and newsvendor models. Bouchery et al. (2012) introduced sustainability dimension in the framework of economic order quantity, by considering it as an independent objective along with cost and therefore studied a multiobjective EOQ problem. As there are different carbon emission regulations such as carbon tax, carbon cap, carbon offset or carbon cap and trade system, Chaabane et al. (2010) introduce mixed integer linear programming based framework for sustainable supply chain design, their model demonstrated that efficient carbon management strategies with help decision makers to achieve sustainability objectives in a cost effective manner. Larsen et al. (2012) used the environmentally extended input-output analysis and life cycle assessment. The experimental results discovered an exciting finding that the majority of the energy and environmental loads which are located in the upstream of the supply chain. They indicated to use the tax or methods to reduce and avoid pollution resources as a measure to help. Abdallah et al. (2012) develop a mixed integer program for the carbon-sensitive supply chain that minimizes emissions throughout the supply chain by taking into consideration green procurement also known as environmental sourcing. They found that decentralizing the supply chain while decreasing the size of facilities to reduce transportation emissions, and centralizing the supply chain while increasing the size of facilities to benefit from economies of scale to install larger rooftop photovoltaic. Mallidis et al. (2012)use a linear model to develop a strategic-tactical decision support model which helps managers to evaluate the effect of incorporating environmental issues in strategic and operational decisions on their region and the objectives are: designing a supply chain network considering the port of entry and transportation mode and deciding the use of shared versus dedicated warehouses and transportation. As a result, the supply chain network had been tested in South-Eastern Europe region and showed that using shared warehouses achieves better cost and environmental performance of a company while using shared transportation operations reduces the amount of CO2 and PM emissions generated, while dedicated use reduces the amount of costs. Paksoy et al. (2010) also used linear programming model to study the operational performance measures which are related to transportation operations in a closed loop supply chain. This linear model formulates the problem using the relation between emissions and transportation in the supply chain. Krikke (2010) study the impact of closed loop network arrangement on carbon foot prints and shows that the arrangement of closed loop network should be considered in order to maximize the impact of the substitution. Other than the linear model, some papers use nonlinear models such as Hongjuan and Jing (2011) which use a nonlinear model to improve the competence in the whole supply chain by having good cooperation among firms using low carbon supply chain concept. Economic model was used in many papers to study the carbon emissions and to explain complex processes using different parameters. Some of the papers are (Caro et al., 2013) which introduce correct counting of carbon emission. It introduce a model where matrices and summations are used to focus on life cycle assessment (LCA) and consider joint production to study supply chain that is already operating and shows that avoiding double counting while calculating the carbon emission is desirable. Plambeck (2012) also discuss approaches to profitably reduce greenhouse emissions in the supply chain benefit from the experience of largest corporations in the world and the experience of the start-up company. Mathematical and analytical model are used by large papers such as **?** which used an analytical model to examine the carbon footprint from both stationary like warehouse and non-stationary like outbound logistics emissions across supply chains process. Show how the choice of fuel used, mode of transportation and distance traveled affects the level of carbon emission, while Wahab et al. (2011) used mathematical and analytical method. This paper established and focused their interest on reducing carbon emission in transporting inventory which will reduces the rate of occurrence of shipments. Also classified the carbon emission cost into fixed and variable. The purpose is to reduce the total expected cost per unit time. Shaofu et al. (2013) study the influence of emission cap as environmental policy on decision makings considering single manufacturer and single supplier using analytical model and numerical analysis.

3. Model Description and Notations

In this paper we consider a system consisting of one buyer purchasing an item from one supplier to face a constant demand with rate D. The supplier can be a manufacturer or a purchaser. The operating cost facing both the supplier and the buyer includes the purchasing cost (or the manufacturing cost if the supplier is a manufacturer), the inventory holding cost, and the fixed cost associated with each order (and/or each production lot for the manufacturer). Let p be the unit selling price and $w(w < p)$ the buyer's unit purchase price (charged by the supplier). Let h_R, and h'_S denote the buyer's and the supplier's yearly unit inventory holding cost, respectively. The buyer's fixed ordering cost per order is A_R, and the supplier's fixed order processing cost per buyer's order and setup (ordering) cost for each setup are A_p, and A'_S, respectively. The supplier's unit cost of manufacturing or purchasing the item is $c, c < w$. The supplier's order, $m.Q(m = 1, 2, ...)$, is an integer multiple of the buyer's order, Q. Other assumptions for our model are: (i) shortage is not allowed, (ii) lead time is zero, and the replenishment rate is infinite. Operational decisions done by both the supplier and the buyer are associated with carbon emissions. For instance, Set-up emission incurred at each order initiated can be, for example, the emission from setting up the machine, the emission related to transportation, etc. Transportation has been causing a large portion of the GHG emissions. Another important source of emission is holding inventory. For example, the heating and/or refrigeration of inventory, if required, are very emission intensive. Therefore, similar to cost, we assume that emissions are associated with ordering, and inventory holding, with $\hat{A_R}$ and $\hat{A_p}, \hat{A'_S}$ denoting the amount of carbon emissions associated per order initiated respectively by the buyer and the supplier. $\hat{h_R}$, and $\hat{h'_S}$ denote the buyer's and the supplier's amount of carbon emissions associated per unit held in inventory per unit time, respectively. Under this cost structure, it has been shown (Weng, 1995) that the supplier holding cost and ordering/processing cost can be rewritten respectively as $h_S.Q/2$ where $h_S = h'_S.(m-1)$ and $A_S D/Q$ where $A_S = A_p + A'_S/m$. Similarly to cost, we can show that supplier's emission associated to holding activities and supplier's emission associated with ordering and processing can be rewritten respectively as $\hat{h_S}.Q/2$ and $\hat{A_S}.D/Q$ where where $\hat{h_S} = \hat{h'_S}.(m-1)$ and $\hat{A_S} = \hat{A_p} + \hat{A'_S}/m$. Giving the introduced notations, the supplier's yearly profit is equal to gross revenue minus the order processing cost, the production set up (or ordering) cost, and the inventory holding cost. While its emissions are equal to emissions resulting from holding plus the amount of emissions resulting from ordering and processing.

Therefore, the supplier's yearly profit function $\Pi_S(Q)$ and supplier's yearly emission function $E_S(Q)$ are given by:

$$\Pi_S(Q) = (w-c).D - A_S.D/Q - h_S.Q/2 \text{ and } E_S(Q) = \hat{A_S}.D/Q + \hat{h_S}.Q/2 \tag{1}$$

Similarly, the retailer's yearly profit is equal to gross revenue minus the ordering cost and the inventory holding cost. Its yearly emissions will be the sum of emissions resulting from both activities.

$$\Pi_R(Q) = (p-w).D - A_R.D/Q - h_R.Q/2 \text{ and } E_R(Q) = \hat{A_R}.D/Q + \hat{h_R}.Q/2 \tag{2}$$

The objective of the retailer is to choose an order quantity Q that minimizes his cost per unit time subject to some constraints on the amount of carbon emitted (if any). While the supplier will find a strategy that fulfills the buyer's orders while maximizing his profit subject to some constraints on the amount of carbon emitted (if any). The constrains on carbon emission can either be driven by self initiatives or by governmental policies such as carbon tax.

In the absence of carbon emission considerations the model is refereed to as business as usual or traditional profit-driven two-level supply chain where both of the supplier and buyer maximize their profits by optimizing decision variables that are under their control. The retailer controlling the order quantity, will naturally order its economic order quantity $Q_R^* = \sqrt{2A_RD/h_R}$ leading to the following optimal profit and associated emission level:

$$\Pi_R(Q_R^*) = (p-w).D - \sqrt{2h_RA_RD} \text{ and } E_R(Q_R^*) = \sqrt{\frac{A_Rh_RD}{2}}(\frac{\hat{A_R}}{A_R} + \frac{\hat{h_R}}{h_R}) \tag{3}$$

The resulting supplier's yearly profit and associated emission level will be as follows:

$$\Pi_S(Q_R^*) = (w-c).D - \sqrt{\frac{A_Rh_RD}{2}}(\frac{A_S}{A_R} + \frac{h_S}{h_R}) \text{ and } E_S(Q_R^*) = \sqrt{\frac{A_Rh_RD}{2}}(\frac{\hat{A_S}}{A_R} + \frac{\hat{h_S}}{h_R}) \tag{4}$$

4. The carbon emission seesaw effect

Chen et al. (2013); Hua et al. (2011) among other authors studied the decision making process of a single firm in the presence of carbon emission considerations. They described the firm's emission driven optimal decisions under two main settings including (1) carbon regulations and (2) self initiatives to reduce emissions. In this section we examine the impact of emission driven optimal decisions taken by individual firms on the overall emission of the supply chain they are part of.

Chen et al. (2013) have used the well-known Economic Order Quantity (EOQ)(Harris, 1913) framework to show that a single firm can significantly reduce its emissions without significantly increasing its cost. This can be done by deviating from the cost optimal order quantity towards the emission optimal order quantity. We use the same setting to extend the analysis to the impact of such decision on the overall two echelons supply chain emission. When carbon emissions are unconstrained, only profit optimal decisions are considered that is the supplier and retailer both maximize their profits by optimizing decision variables that are under their control.

The retailer's yearly profit is equal to gross revenue minus the ordering cost and the inventory holding cost. His yearly emissions will be the sum of emissions resulting from both activities.

$$\Pi_R(Q) = (p-w).D - A_R.D/Q - h_R.Q/2 \text{ and } E_R(Q) = \hat{A_R}.D/Q + \hat{h_R}.Q/2 \tag{5}$$

Similarly, the supplier's yearly profit is equal to gross revenue minus the order processing cost, the production set up (or ordering) cost, and the inventory holding cost. While his emissions are equal to emissions resulting from holding plus the amount of emissions resulting from ordering and processing.

Therefore, the supplier's yearly profit function $\Pi_S(Q)$ and supplier's yearly emission function $E_S(Q)$ are given by:

$$\Pi_S(Q) = (w-c).D - A_S.D/Q - h_S.Q/2 \text{ and } E_S(Q) = \hat{A_S}.D/Q + \hat{h_S}.Q/2 \tag{6}$$

Let Q_R^* denote the order quantity that maximizes the retailer total profit while ignoring the carbon emission constraint (the *cost-optimal* solution). Then, it is easy to see that $Q_R^* = \sqrt{\frac{2A_R D}{h_R}}$, which corresponds to the standard EOQ solution. Let $\hat{Q}_R$ denote the order quantity that minimizes retailer's carbon emission (the *emission-optimal* solution), then it is easy to verify that $\hat{Q}_R = \sqrt{\frac{2\hat{A_R}D}{\hat{h_R}}}$ and the corresponding emission level is $E_{R,min} = \sqrt{2\hat{A_R}\hat{h_R}D}$. In the absence of carbon regulations, the retailer can reduce his emission without decreasing significantly his profit (increasing his cost) by elaborating some adjustments on the cost-optimal order quantity. As explained in (Chen et al., 2013), if $\frac{A_R}{h} = \frac{\hat{A_R}}{\hat{h_R}}$ then the cost-optimal solution is also emission-optimal (i.e., $Q_R^* = \hat{Q}_R$). In that case, emission is already at its minimum and thus there is no operational adjustment that could further reduce it. On the other hand, if $\frac{A_R}{h_R} > \frac{\hat{A_R}}{\hat{h_R}}$ $(\frac{A_R}{h_R} < \frac{\hat{A_R}}{\hat{h_R}})$ there is an opportunity to reduce emissions by decreasing (increasing) the order quantity. Up to certain extend, the decrease (increase) in the optimal order quantity leads to significant decrease in the emission level and insignificant profit decrease.

In the following, we show that order quantity adjustment reduces retailer's carbon emission but in some situations increases the overall emission: this effect is referred to as the carbon *Seesaw Effect* and is captured by the following theorem.

Theorem 1 *If* $\frac{\hat{A_T}}{\hat{h_T}} \leq \frac{A_R}{h_R} < \frac{\hat{A_R}}{\hat{h_R}} (\frac{A_R}{h_R} > \frac{\hat{A_R}}{\hat{h_R}} \geq \frac{\hat{A_T}}{\hat{h_T}})$ *then by increasing (decreasing) his order quantity, the retailer decreases his own emissions but at the same time increases the total supply chain emission.*

Proof: *The proof of the above theorem is driven by the fact that condition* $\frac{\hat{A_T}}{\hat{h_T}} \leq \frac{A_R}{h_R} < \frac{\hat{A_R}}{\hat{h_R}}$ *is equivalent to* $\hat{Q}_T \leq Q*_R \leq \hat{Q}_R$ *which is equivalent to* supply chain emission optimal solution $\leq$ retailer cost optimal solution *leq* retailer emission optimal solution. *In this situation, to reduce his emission level the retailer will increase his order quantity to deviate from his cost optimal solution to approach his emission optimal solution. However, when increasing his order quantity the retailer will further deviate from the supply chain emission optimal solution which means that supply chain emission emission will increase. The proof of the other scenario is similar to this one.*

The above theorem shows that contrary to what one may think, firms individual actions on reducing their direct -called also scope 1- emission could have an opposite effect on the overall emission -known also as scope 3 emission. This is effect is a result of the nature of supply chain nature where all decisions and activities are interdependent. We should mention that what happen under self initiatives to reduce emissions, can also happen when firm is subject to carbon tax policy. In fact when only one firm is subject to carbon tax, it will deviate from traditional cost optimal solution to a newer one, thus same effects can occur under same conditions.

At this level, to get rid of the carbon seesaw effect one may think at first that the solution is to coordinate the supply chain, in the sense that decisions have to taken jointly between both the retailer and the supplier. We devote the next section to study whether acting jointly provide a robust solution towards reducing overall emission. In particular we study the coordination effect on supply chain carbon emission under different scenarios.

5. Channel Coordination

In this scenario only profit optimal decisions are considered, carbon emissions are unconstrained. In this case, the supplier and buyer both maximize their profits by optimizing decision variables that are under their control. The maximum profits resulting from this decentralized policy represent lower bounds on yearly profits attained for both parties if joint coordination prevails. Under joint coordination, the objective is to maximize the joint profit subject to the constraint that both the supplier's profit and the buyer's profit are greater than their profits in the decentralized situation.

The supplier's yearly profit is equal to gross revenue minus the order processing cost, the production set up (or ordering) cost, and the inventory holding cost. While its emissions are equal to emissions resulting from holding plus the amount of emissions resulting from ordering and processing.

Therefore, the supplier's yearly profit function $\Pi_S(Q)$ and supplier's yearly emission function $E_S(Q)$ are given by:

$$\Pi_S(Q) = (w-c).D - A_S.D/Q - h_S.Q/2 \text{ and } E_S(Q) = \hat{A_S}.D/Q + \hat{h_S}.Q/2 \tag{7}$$

Similarly, the buyer's yearly profit is equal to gross revenue minus the ordering cost and the inventory holding cost. Its yearly emissions will be the sum of emissions resulting from both activities.

$$\Pi_R(Q) = (p-w).D - A_R.D/Q - h_R.Q/2 \text{ and } E_R(Q) = \hat{A_R}.D/Q + \hat{h_R}.Q/2 \tag{8}$$

5.1 Decentralized Supply Chain

In the decentralized scenario, the retailer controls the order quantity and will order its economic order quantity $Q_R^* = \sqrt{2A_RD/h_R}$. The resulting optimal retailer's profit and associated emission level are as follows:

$$\Pi_R(Q_R^*) = (p-w).D - \sqrt{2h_RA_RD} \text{ and } E_R(Q_R^*) = \sqrt{\frac{A_Rh_RD}{2}}\left(\frac{\hat{A_R}}{A_R} + \frac{\hat{h_R}}{h_R}\right) \tag{9}$$

Similarly, the supplier's yearly profit and associated emission level are given by:

$$\Pi_S(Q_R^*) = (w-c).D - \sqrt{\frac{A_Rh_RD}{2}}\left(\frac{A_S}{A_R} + \frac{h_S}{h_R}\right) \text{ and } E_S(Q_R^*) = \sqrt{\frac{A_Rh_RD}{2}}\left(\frac{\hat{A_S}}{A_R} + \frac{\hat{h_S}}{h_R}\right) \tag{10}$$

5.2 Centralized Supply Chain

In this situation we assume that joint coordination prevails, the objective is to maximize the joint profit subject to the constraint that both the supplier's profit and the buyer's profit are greater than their profits in the decentralized situation.

The joint /total (retailer + supplier) yearly profit function $\Pi_T(Q)$ and emission function $E_T(Q)$ are respectively given by the summation of the two profit functions and the two emission functions:

$$\Pi_T(Q) = (p-c).D - A_T.D/Q - h_T.Q/2 \text{ and } E_T(Q) = \hat{A_T}.D/Q + \hat{h_T}.Q/2 \tag{11}$$

$$\text{with } A_T = A_R + A_S, h_T = h_S + h_R, \hat{A_T} = \hat{A_R} + \hat{A_S} \text{ and } \hat{h_T} = \hat{h_S} + \hat{h_R}$$

The above joint profit is optimized by the joint economic order quantity $Q_T^* = \sqrt{\frac{2A_TD}{h_T}}$. The resulting joint optimal profit and associated emission level are respectively as follows:

$$\Pi_T(Q_T^*) = (p-c)D - \sqrt{2A_Th_TD} \tag{12}$$

$$E_T(Q_T^*) = (\frac{\hat{A}_T}{A_T} + \frac{\hat{h}_T}{h_T})\sqrt{\frac{A_Th_TD}{2}} \tag{13}$$

Proposition 1 *When ($\frac{A_R}{h_R} = \frac{A_S}{h_S}$), there is no incentives for the retailer and the supplier to act jointly (i.e. the joint optimal order quantity coincides with decentralized optimal order quantity $Q_T^* = Q_R^*$). Otherwise ($\frac{A_R}{h_R} \neq \frac{A_S}{h_S}$), the joint optimal profit is always larger than the sum of the retailer and supplier profits realized in the decentralized situation.*

$$\Pi_T(Q_T^*)\begin{cases} = \Pi_R(Q_R^*) + \Pi_S(Q_R^*) & if\, \frac{A_R}{h_R} = \frac{A_S}{h_S} \\ > \Pi_R(Q_R^*) + \Pi_S(Q_R^*) & otherwise \end{cases} \tag{14}$$

Proof: $\Pi_T(Q_T^*) = (p-c).D - \sqrt{2A_Th_TD}$ *and* $\Pi_R(Q_R^*) + \Pi_S(Q_R^*) = (p-c).D - (\sqrt{2A_Rh_RD} + (\frac{A_S}{A_R} + \frac{h_S}{h_R})\sqrt{\frac{A_Rh_RD}{2}})$ *we have,*

$$(\sqrt{2A_Rh_RD} + (\frac{A_S}{A_R} + \frac{h_S}{h_R})\sqrt{\frac{A_Rh_RD}{2}})^2 - \sqrt{2A_Th_TD}^2 = 2DA_Rh_R(\frac{1}{4}(\frac{A_S}{A_R} + \frac{h_S}{h_R})^2 - (\frac{A_S}{A_R} + \frac{h_S}{h_R}))$$

$$= \frac{DA_Rh_R}{2}(\frac{A_S}{A_R} - \frac{h_S}{h_R})^2 : \begin{cases} = 0 & if(\frac{A_R}{h_R} = \frac{A_S}{h_S}) \\ > 0 & otherwise \end{cases}$$

The above result is a traditional and well-known one in buyer-vendor coordination models (Weng, 1995; Sarmah et al., 2006). In what follows, we analyze joint policy's effects on carbon emissions.

Theorem 2 *The joint coordination is:*

- *Emission neutral only when when:*

$$\frac{\hat{A}_T}{\hat{h}_T} = \sqrt{\frac{A_T}{h_T}\frac{A_R}{h_R}}$$

- *Emission efficient (i.e. leads to carbon emission decrease) only when:*

$$\sqrt{\frac{A_T}{h_T}\frac{A_R}{h_R}} \in [min(\frac{\hat{A}_T}{\hat{h}_T}, \frac{A_R}{h_R}), max(\frac{\hat{A}_T}{\hat{h}_T}, \frac{A_R}{h_R})]$$

- *Emission inefficient (i.e. lead to an overall increase in total supply chain emissions) otherwise*

Theorem 3 *The joint coordination is:*

- *Emission neutral only when when:*

$$\frac{\hat{A}_T}{\hat{h}_T} = \sqrt{\frac{A_T}{h_T}\frac{A_R}{h_R}} \text{ equivalent to: } \frac{\hat{Q}_T^{*\,2}}{Q_R^*} = Q_T^* \tag{15}$$

- *Emission efficient (i.e. leads to carbon emission decrease) only when:*

$$\sqrt{\frac{A_T}{h_T}\frac{A_R}{h_R}} \in [min(\frac{\hat{A}_T}{\hat{h}_T}, \frac{A_R}{h_R}), max(\frac{\hat{A}_T}{\hat{h}_T}, \frac{A_R}{h_R})] \tag{16}$$

$$\text{equivalent to: } Q_T^*[min(\frac{\hat{Q}_T^{*\,2}}{Q_R^*}, Q_R^*), max(\frac{\hat{Q}_T^{*\,2}}{Q_R^*}, Q_R^*)]$$

Under the assumption $A_S > A_R$ and $h_S < h_R$, condition on emission efficiency will be simplified as follows:

$$\sqrt{\frac{A_T}{h_T}\frac{A_R}{h_R}} < \frac{\hat{A}_T}{\hat{h}_T} \Leftrightarrow Q_T^* < \frac{\hat{Q}_T^{*\,2}}{Q_R^*} \tag{17}$$

- *Emission inefficient (i.e. leads to carbon emission increase) otherwise*

Where $\hat{Q}_T^*$ is the joint emission-optimal order quantity.

Proof:

$$E_S(Q_R^*) + E_R(Q_R^*) - E_T(Q_T^*) = \sqrt{D/2}.\hat{A}_T(\sqrt{\frac{h_R}{A_R}} - \sqrt{\frac{h_T}{A_T}}) + \sqrt{D/2}.\hat{h}_T(\sqrt{\frac{A_R}{h_R}} - \sqrt{\frac{A_T}{h_T}})$$

$$= \sqrt{D/2}.(\frac{\hat{A}_T}{\hat{h}_T}\frac{(\sqrt{A_T h_R} - \sqrt{h_T A_R})}{\sqrt{A_R A_T}} - \frac{\sqrt{A_T h_R} - \sqrt{h_T A_R}}{\sqrt{h_R h_T}})$$

$$= 0 \text{ if } \frac{\hat{A}_T}{\hat{h}_T} = \sqrt{\frac{A_T}{h_T}\frac{A_R}{h_R}}$$

$$> 0 \text{ if} \begin{cases} \frac{\hat{A}_T}{\hat{h}_T} \geq \sqrt{\frac{A_T}{h_T}\frac{A_R}{h_R}} & \text{if}(\sqrt{A_T h_R} - \sqrt{h_T A_R}) \geq 0 \\ \frac{\hat{A}_T}{\hat{h}_T} \leq \sqrt{\frac{A_T}{h_T}\frac{A_R}{h_R}} & \text{if}(\sqrt{A_T h_R} - \sqrt{h_T A_R}) \leq 0 \end{cases}$$

$$< 0 \text{ otherwise}$$

Lemma 1 *When the supplier is following of lot-for-lot policy ($m = 1$), the above theorem is simplified as follows: The joint coordination is:*

- *Emission neutral only when when:*

$$\frac{\hat{A}_T}{\hat{h}_R} = \frac{\sqrt{A_T A_R}}{h_R} \tag{18}$$

- *Emission efficient (i.e. leads to carbon emission decrease) only when:*

$$\frac{\hat{A}_T}{\hat{h}_R} > \frac{\sqrt{A_T A_R}}{h_R} \tag{19}$$

- *Emission inefficient (i.e. leads to carbon emission increase) when:*

$$\frac{\hat{A}_T}{\hat{h}_R} < \frac{\sqrt{A_T A_R}}{h_R} \tag{20}$$

The possible raise in carbon emission in the centralized supply chain can be explained as follows: When both of the supplier and the retailer work separately, the optimal order quantity is the retailer's EOQ order quantity (Q_R^*). Deviating from this optimal quantity by ordering a quantity Q leads to a change on the emissions associated with both inventory operations; ordering activities and holding activities. Emissions associated with ordering activities will be divided by the factor $\frac{Q}{Q_R^*}$ while the emissions associated with holding operations will be multiplied by the same factor. When the increase of one inventory operation is not covered by the decrease of the second one , the whole emission will increase. In the particular case of the joint policy, both of the supplier and the retailer ordered the EOQ order quantity (Q_T^*) instead of (Q_R^*), the evolution of carbon emission associated with ordering and holding activities is given by:

$$\frac{\text{Decentralized ordering activities'emission}}{\text{Joint Policy ordering activities'emission}} = \frac{\text{Joint Policy holding activities'emission}}{\text{Decentralized holding activities'emission}} = \sqrt{\frac{h_R A_T}{A_R h_T}}$$

6. Conclusion

In this paper we present a model for analyzing the impact of individual actions towards reducing direct -scope1- emission on the overall supply chain emission -scope 3-. We identified the so called carbon seesaw effect where reducing direct emission increases overall supply chain emission. As one may think that this effect can be neutralized by acting jointly and not individually in the supply chain, we devoted the second part of the paper to study this situation. We showed that acting jointly can partially solve the problem for instance we identified settings where acting jointly leads to a significant increase of the supply chain's overall emissions. In particular we show, under carbon emission considerations, that the centralized solution remains profit-optimal but not necessarily emission-optimal. This means that the joint profit is often increased when the channel is coordinated. However, the amount of total carbon emissions may be higher than what could be emitted by the retailer and the supplier when they work individually. We identify conditions on cost and emission parameters under which the joint policy is both profit and emission optimal. This may be considered as a strong incentive for the supplier and the retailer to cooperate.

References

Abdallah, T., Farhat, A., Diabat, A., and Kennedy, S. (2012). Green supply chains with carbon trading and environmental sourcing:formulation and life cycle assessment. *Applied Mathematical Modelling*, 36:4271–4285.

Benjaafar, S., Li, Y., and Daskin, M. (2010). Carbon footprint and the management of supply chains: Insights from simple models. *IEEE Transactions on automation science and engineering*, 10:99–115.

Bouchery, Y., Ghaffari, A., Jemai, Z., and Dallery, Y. (2012). Including sustainability criteria into inventory models. *European Journal of Operational Research*, 222:229 – 240.

Caro, F., Charles, J., Tan, T., and Zuidwijk, R. (2013). Double counting in supply chain carbon footprinting. *Manufacturing & Service Operations Management*, 15:545 – 558.

Chaabane, A., Ramudhina, A., and Paquet, M. (2010). Design of sustainable supply chains under the emission trading scheme. *International Journal of Production Economics*, 135:37–49.

Chen, X., Benjaafar, S., and Elomri, A. (2013). The carbon-constrained eoq. *Operations Research Letters*, 41:172179.

Harris, W. (1913). How many parts to make at once. *The Magazine of Management*, 10:135–136.

Hongjuan, Y. and Jing, Z. (2011). The strategies of advancing the cooperation satisfaction among enterprises based on low carbon supply chain management. *Energy Procedia*, 5:1225–1229.

Hua, G., Cheng, T., and Wang, S. (2011). Managing carbon footprints in inventory management. *International Journal of Production Economics*, 132:178185.

Krikke, H. (2010). Impact of closed-loop network configurations on carbon footprints: A case study in copiers. *Resources, Conservation and Recycling*, 55:1196–1205.

Larsen, N., Solli, C., and Pettersen, J. (2012). Supply chain management how can we reduce our energy/climate footprint? *Energy Procedia*, 20:354–363.

Mallidis, I., Dekker, R., and D., V. (2012). The impact of greening on supply chain design and cost: a case for a developing region. *Journal of Transport Geography*, 22:118–128.

Paksoy, T., Bektas, T., and Ozceylan, E. (2010). Operational and environmental performance measures in a multi-product closed-loop supply chain. *Transportation Research Part E: Logistics and Transportation Review*, 47:532–546.

Plambeck, E. (2012). Reducing greenhouse gas emissions through operations and supply chain management. *Energy Economics*, 34:S64–S74.

Sarmah, S., Acharya, D., and Goyal, S. (2006). Buyer vendor coordination models in supply chain management. *European Journal of Operational Research*, 175:1–15.

Shaofu, D., Zhu, L., Liang, L., and Ma, F. (2013). Emission-dependent supply chain and environment-policy-making in the cap-and-trade system. *Energy Policy*, 57:61–67.

Wahab, M., Mamun, S., and Ongkunaruk, P. (2011). Eoq models for a coordinated two-level international supply chain considering imperfect items and environmental impact. *International Journal of Production Economics*, 134:151–158.

Weng, k, Z. (1995). Channel coordination and quantity discounts. *Management Science*, 41:1509–1522.

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