

Socially responsible transportation and lot sizing : insights from multiobjective optimization

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Socially responsible transportation and lot sizing: Insights from multiobjective optimization

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Abstract: This paper applies multiobjective optimization to show how the efficient tradeoffs between cost and carbon emissions may be obtained in the context of socially responsible operations. We thus formulate a model where transportation mode selection and lot sizing decisions are considered jointly. We derive structural properties of the model and develop several insights that remain hidden under single-objective optimization. First, we show that switching to a socially responsible mode of transportation while continuing to optimize the total logistics costs function may lead to a dominated solution. Second, we prove that the modal shift occurs only under strong carbon emissions reduction requirements. Third, we show that the efficient frontier is non-convex. Two classical ways of taking carbon emissions into account in the decision making process are also compared and the results are illustrated through an example of a French retailer.

Keywords: multiobjective optimization, socially responsible operations, transportation mode selection, lot sizing optimization.

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1. Introduction

Environmental and social awareness has considerably increased since the Brundtland report's publication (World Commission on Environment and Development, 1987). Nowadays, many leading companies worldwide are committed in creating value for a broader set of stakeholders instead of focusing solely on creating profits for shareholders or owners. In extending their traditional profit driven perspective, these companies acknowledge the concept of "triple bottom line" where planet driven and people driven perspectives are additionally taken into account (Elkington, 1998). As an example, two thirds of the European companies have intensified their green actions from 2008 to 2010 (Bearing Point, 2010). In line with this trend, the academic literature on socially responsible operations has grown rapidly.

By following the "triple bottom line" principle, socially responsible operations aim at optimizing several objectives. In this context, companies may identify situations where multiple objectives may be improved simultaneously, i.e. win-win situations. However, these situations may become more difficult to find as more socially responsible practices are deployed. Consequently, an increasing number of companies start thinking that "sustainability can only be attained by optimizing seemingly conflicting targets" (DHL, 2010). In this case, a socially responsible company seeks to identify the most favorable trade-off between the considered objectives.

In this paper, we argue that multiobjective optimization would be quite useful for socially responsible operations. Multiobjective optimization is the process of simultaneously optimizing several objectives. In most of the cases, objectives are conflicting and one cannot identify a single solution that simultaneously optimizes each objective. Thus, the aim of multiobjective optimization is to identify particular solutions such that, when attempting to improve an objective further, other objectives suffer as a result (Ehrgott, 2005). These solutions are called efficient or Pareto optimal and they correspond to the tradeoffs that are of interest for socially responsible companies. The paper shows how the efficient tradeoffs between different types of objectives may be obtained in a decision problem related to socially responsible operations. Moreover, some new insights based on the efficient frontier properties analysis are highlighted.

This paper focuses on a model where transportation mode selection and lot sizing decisions are jointly optimized. We indeed acknowledge that inventory and transportation decisions are strongly interrelated. However, there is a lack of papers on socially responsible operations

addressing this issue. The objective functions taken into account intend to reflect the “triple bottom line”. The profit dimension is translated into a cost minimization objective. The planet dimension is taken into account via a carbon emissions minimization objective. The reduction of carbon emissions is indeed one of the main challenges of socially responsible operations as the logistics industry is responsible for around 5.5% of global greenhouse gas emissions worldwide. Moreover, this share is even larger in the EU and US and this one is expected to increase in the future. These carbon emissions are mainly generated by transportation. Nevertheless, inventory contributes to 13% of the logistic sector’s carbon footprint mainly due to indirect emissions from electricity consumption (World Economic Forum, 2009). The people related dimension of socially responsible operations is generally considered as more difficult to assess. This may explain why the social dimension of the “triple bottom line” has received less attention in the literature (White and Lee, 2009). An example of social aspect that may be of interest in a model that simultaneously considers inventory and transportation decisions is the injury rate. Injuries are due to both transportation and warehousing activities and may be related to the order size and to the mode of transportation considered. In this paper, we focus on the first two objectives.

Our multiobjective optimization results enable showing that switching to a greener mode of transportation while continuing to optimize the total logistics costs function may lead to a dominated option (such that it is possible to reach the same level of carbon emissions with a lower cost by solely adjusting the ordering quantity). Second, we prove that a shift towards a more carbon-efficient mode of transportation is interesting only for strong carbon emissions reduction requirements. Otherwise, lot sizing adjustments may enable efficiently greening the supply chain. Third, we show that the efficient frontier is non-convex. This structural property is of great importance as this implies that some non-supported solutions exist (Geoffrion, 1968). This type of solution cannot be generated by using a linear combination of the objectives. Thus, using carbon pricing for such non-convex problems may provide a misleading impression to the decision maker as non-supported solutions would be hidden. The paper also contributes to the literature on green supply chains by studying a new model that aims at simultaneously optimizing the transportation mode selection and the lot sizing decisions while taking carbon emissions into account.

The paper is organized as follows. First, the related literature is reviewed in Section 2. Section 3 is then devoted to the presentation of the model, to the multiobjective optimization

results and to the presentation of a motivating example. Two classical ways of taking carbon emissions into account in the decision making process are then analyzed and discussed in Section 4. In the first one, we assume that the company aims at reducing its carbon emissions by meeting a self-imposed emissions reduction target. In the second one, a regulatory policy based on a carbon tax is imposed to the company. Finally, Section 5 is devoted to the conclusion and to future research directions.

2. Literature review

The number of published papers on socially responsible operations has drastically increased these last years. We refer to Linton et al. (2007), Srivastava (2007), Seuring and Müller (2008), Kleindorfer et al. (2009) and Dekker et al. (2012) for reviews. The planet related dimension of socially responsible operations and more particularly carbon emissions have attracted more attention. Moreover, most of the model-based research on socially responsible operations focuses on mono-objective models. Finally, most of the papers adopt a regulatory perspective, i.e. these papers consider that the companies include the “triple bottom line” in their business model forced by regulation. However, other considerations such as customers’ pressure, company image, resources scarcity issues and employees motivation may also entice the companies to act in a socially responsible way. We conclude that there is a gap in socially responsible literature as regards the use of multiobjective optimization.

This paper shows how the efficient tradeoffs between cost and carbon emissions may be obtained by focusing on a model where transportation and lot sizing decisions are jointly considered. Several papers related to inventory control and carbon emissions have recently been proposed. Bonney and Jaber (2011) briefly study the impact of including vehicle emissions cost into the EOQ model. Only emissions from transportation are taken into account in the form of a fixed emissions cost per shipment. Saadany et al. (2011) study a two-echelon supply chain model where the demand is assumed to be a function of the price and product’s environmental quality. Hua et al. (2011) study how the carbon emissions trading mechanism can influence optimal ordering quantity in the EOQ framework. Carbon emissions issued from both ordering and warehousing are taken into account. The authors present analytical and numerical results and provide some managerial insights. They especially prove that the amount of carbon emissions depends only on the carbon price in the economic order quantity model under a cap and trade

regulation. Jaber et al. (2012) include carbon emissions into a joint economic lot-size problem by considering different emissions trading schemes. Their numerical study proves that coordination minimizes the total system cost without automatically reducing carbon emissions. Bouchery et al. (2012) include sustainability criteria into single and multi-echelon inventory models by using multiobjective optimization. The efficient frontier is analytically characterized for both models and an interactive procedure allowing the company to quickly identify the preferred option is proposed. Chen et al. (2013) study the EOQ model with a carbon constraint. They provide analytical results and discuss the conditions under which the cost increase is relatively less than the carbon emissions decrease. Benjaafar et al. (2013) include carbon emissions constraints on single and multi-stage lot-sizing models with a cost minimization objective. Four regulatory policy settings are considered. Insights are derived from an extensive numerical study. Velázquez-Martínez et al. (2013) examine the limitation of aggregate carbon emissions models by studying different aggregate approaches for transportation carbon emissions in a lot-sizing model. Their numerical experimentation shows that the magnitude of errors can be substantial. Finally, Absi et al. (2013) include carbon emissions constraints on a lot-sizing model. Four types of constraints are proposed and analyzed. One case is shown to be solvable in polynomial time, while the three others are proven to be NP-hard. The papers cited above focus solely on inventory optimization decisions. The impacts of transportation decisions are not taken into account as it is assumed that a single mode of transportation is available. All these papers ignore the effect of transportation mode selection and most of them are mono-objective.

Including some carbon emissions concerns into freight transportation mode selection problems has also attracted some research as freight transportation is recognized as a main contributor of carbon emissions within the supply chain. Winebrake et al. (2008) present an energy and environmental analysis model to explore the tradeoffs in an intermodal transportation network. Bauer et al. (2009) especially focus on determining the optimal planning for intermodal rail transportation in order to minimize the carbon emissions from transportation. Cholette and Venkat (2009) present a case study where several modes of transportation are available in a wine supply chain context. Their analysis takes cost, carbon emissions and energy consumption into account. Pan et al. (2013) investigate how freight consolidation may help in decreasing the carbon emissions from transportation. They formulate a carbon emissions minimization model where both road and rail transportation are available. They apply their model for optimizing the

carbon emissions of two large retail chains. Leal and D'Agosto (2011) consider the transportation mode selection decision in a case study based on a bio-ethanol supply chain. Socio-environmental considerations are included into the model. To our knowledge, there are the only two published papers incorporating carbon emissions into a transportation mode selection and inventory optimization problem. Rosič and Jammerneegg (2013) extend the dual sourcing model based on the newsvendor framework by considering the environmental impact of transportation. They analyze two types of regulatory policies, i.e. the carbon tax and the carbon cap-and-trade mechanism. They prove that it is possible to reduce the carbon emissions from transportation without substantially affecting the economic performance of the system if the cap-and-trade mechanism is applied with appropriate carbon cap setting. In Hoen et al. (2012), a stochastic inventory model is extended to incorporate transport emissions costs. The transport mode and order-up-to level of a base-stock inventory policy are jointly optimized in a single product setting.

Our work extends the existing literature in several ways. First, we use multiobjective optimization in order to efficiently show the existing tradeoffs that a company can face when jointly optimizing transportation mode selection and lot sizing decisions. This process adequately reflects the concept of socially responsible operations. Moreover, multiobjective optimization helps the decision maker to build a conviction of what is possible and to use this knowledge to identify the most valuable trade-off. This conviction may also be reinforced by enabling a graphical representation of the interesting tradeoffs. Second, we focus on a joint transportation mode selection and lot sizing optimization model. We indeed consider that lot sizing decisions have a strong impact both on the transportation mode selection decisions and on the carbon emissions levels. Third, our model allows accounting for realistic transportation costs and carbon emissions structures as piecewise linear functions may be considered. We also include carbon emissions associated with the storage of the product in the analysis instead of considering transportation carbon emissions solely. This amount of carbon emissions may indeed affect the lot sizing decision and should not be disregarded in the analysis. Fourth, we analyze two different decision-making contexts. In the first one, we assume that the company aims at reducing its carbon emissions by meeting a self-imposed emissions reduction target. In the second case, a regulatory policy based on a carbon tax is imposed to the company. We prove that

controlling emissions via a carbon tax has some technical drawbacks mainly due to the fact that the efficient frontier is non-convex.

3. Model description and multiobjective optimization results

3.1 Model description

In this paper, we consider that several transportation options are available for inbound transportation. Each option is characterized by a cost function in the form of a fixed cost (per vehicle) and a variable cost (per item). Moreover, a fixed lead time is associated to each option. The lead time has an effect on the average in-transit inventory level. We also take the capacity of each option into account. Finally, a minimum amount per shipment may be considered in order to make the option available. The proposed model may be applied in a context where several transportation modes including air, water, rail, road and any type of intermodal combination are considered. Moreover, the model may also be used to study the effect of speed reduction for a given transportation mode as speed is recognized to have some major impacts on costs, fuel consumption (Corbett et al., 2009; Fransoo and Lee, 2013) and safety. The model is flexible enough to account for realistic transportation cost structures such as the modified all-unit discount cost structure studied by Chan et al. (2002) and Croxton et al. (2003). Indeed, any type of piecewise linear function may be taken into account by considering each piecewise linear part of the transportation cost function as an option characterized by a fixed cost (per vehicle) and a variable cost (per item). The minimum and maximum capacity limits enable making the option available only for the quantities related to the segment under consideration.

The per shipment transportation cost function for option 1 is defined as follows for all $Q \geq Q_{\min 1}$ ($\lceil x \rceil$ represents the nearest integer $\geq x$):

$$T_{C1}(Q) = T_{VC1}Q + T_{FC1} \left\lceil \frac{Q}{Q_{\max 1}} \right\rceil + h_{TC} L_1 Q, \quad (1)$$

with:

Q = ordering quantity,

$Q_{\min 1}$ = minimum ordering quantity (if applicable),

$Q_{\max 1}$ = transportation option capacity ($Q_{\max 1} \geq Q_{\min 1}$),

T_{VC1} = variable transportation cost (per item),

T_{FC1} = fixed transportation costs (per vehicle),

h_{TC} = in-transit inventory holding costs per product unit and time unit,

L_1 = transportation lead time.

The total inventory holding and transportation cost function per time unit for option 1 is defined as follows:

$$Z_{C1}(Q) = \frac{Q}{2}h_c + \frac{D}{Q}O_c + TC_1(Q)\frac{D}{Q} + P_cD, \quad (2)$$

with:

Q = ordering quantity (decision variable),

D = demand per time unit,

h_c = inventory holding costs per product unit and time unit,

O_c = fixed ordering costs,

P_c = purchase costs per product unit.

Assume that Q_{C1}^* is the ordering quantity that minimizes the total cost function for option 1 (i.e. $Z_{C1}(Q_{C1}^*) = Z_{C1}^*$). In most of the practical situations, we could observe that $Q_{C1}^* \leq Q_{\max 1}$. The only incentive to order more than the vehicle capacity is provided by O_c which represents costs for order forms, authorization, receiving, inspection and/or handling of invoice from the supplier (Axsäter, 2006). These costs are generally small comparing to the costs of requiring a second vehicle for inbound transportation as well as the costs of holding extra inventory. These costs have also been reduced by new technologies such as electronic data interchange or radio frequency identification. In the following, we thus assume that $Q_{C1}^* \leq Q_{\max 1}$ (note that a sufficient condition for having $Q_{C1}^* \leq Q_{\max 1}$ is given by $O_c \leq \frac{hQ_{\max 1}^2}{2D}$). As Z_{C1} is convex on $[Q_{\min 1}; Q_{\max 1}]$,

we obtain that:

$$Q_{C1}^* = \max\left(Q_{\min 1}; \min\left(Q_{\max 1}, \sqrt{\frac{2(O_c + T_{FC1})D}{h_c}}\right)\right). \quad (3)$$

Modeling carbon emissions across the supply chain is attracting more and more research (see e.g. Scipioni et al., 2012; Sundarakani et al., 2010). In the proposed model, three main sources of carbon emissions may be identified. First, carbon emissions are generated by producing the item. We assume that the retailer has no control on the production scheme of the manufacturer (that certainly supplies several other retailers) and that the carbon emissions resulting from producing the items are thus independent of the batch size and of the transportation mode selected by the retailer. A fixed amount of carbon emissions is thus associated to each item due to production. Second, carbon emissions are generated by inbound transportation. The transportation mode selection as well as the batch size decisions may affect the amount of carbon emissions generated by inbound transportation. For a given transportation mode, the generated carbon emissions are modeled with a fixed term (due to emissions generated by the vehicle if running empty) and a linear term in function of the order size (due to the extra energy consumption generated by transporting the items). Note that this modeling is commonly used in the transportation literature (see e.g. Pan et al. (2013) for rail and road transportation) and is consistent with the NTM methodology (NTM, 2008). Third, an amount of carbon emissions is associated with the storage of each product unit per time unit. This amount is mainly due to indirect carbon emissions from energy consumption (mainly electricity) in the warehouse. This amount may become important in case of refrigeration. As noted earlier, warehousing contributes to 13% of the logistics sector's carbon footprint.

For transportation option 1, the total carbon emissions in function of the batch size may be expressed as follows for all $Q \geq Q_{\min 1}$:

$$Z_{E1}(Q) = P_E D + \frac{Q}{2} h_E + T_{FE1} \left\lceil \frac{Q}{Q_{\max 1}} \right\rceil \frac{D}{Q} + T_{VE1} D, \quad (4)$$

with:

P_E = fixed amount of carbon emissions per item,

h_E = inventory holding emissions per product unit and time unit,

T_{FE1} = fixed amount of carbon emissions per shipment,

T_{VE1} = variable amount of carbon emissions per product unit.

Assume that $Q_{E_1}^*$ is the ordering quantity that minimizes the carbon emissions function for transportation mode 1 (i.e. $Z_{E_1}(Q_{E_1}^*) = Z_{E_1}^*$). We can observe that $Q_{E_1}^* \leq Q_{\max 1}$ (there is no incentive to order more than the maximum transportation capacity). It follows that:

$$Q_{E_1}^* = \max \left(Q_{\min 1}; \min \left(Q_{\max 1}; \sqrt{\frac{2T_{FE1}D}{h_E}} \right) \right). \quad (5)$$

3.2 Multiobjective optimization results

In this paper, the costs and the carbon emissions are considered as two distinct objective functions that have to be minimized. An alternative a is thus said to be dominated if there exists another alternative b that performs at least as good as a on one objective and that performs better on the other objective. Multiobjective optimization consists in identifying all the non-dominated alternatives called efficient solutions.

As a first step, we identify the set of efficient solutions when considering transportation option 1 solely. In this case, the only decision variable for the problem is the order quantity and the set of possible values for Q is $A = [Q_{\min 1}; Q_{\max 1}]$. Let $Z_1 : A \rightarrow \mathfrak{R} \times \mathfrak{R}$, $Z_1(a) = \{Z_{C_1}(a); Z_{E_1}(a)\}$, for all $a \in A$, with Z_{C_1} defined by Formula 2 representing the total costs and Z_{E_1} defined by Formula 4 representing the total carbon emissions. $Z_1(A) = \{(Z_{C_1}(Q); Z_{E_1}(Q)) | Q \in A\}$ is the image of A in the criterion space (evaluation space). The set of efficient solutions also called the efficient frontier is a subset of A noted E_1 . Its image in the criterion space is $Z_1(E_1)$. By extension, we also refer to $Z_1(E_1)$ as the efficient frontier (in the criterion space) in what follows. Proposition 1 enables identifying analytically the efficient frontier, when only one transportation option is available. This one can be expressed in function of $Q_{C_1}^*$ and $Q_{E_1}^*$, the optimal ordering quantities defined by Formulas 3 and 5 respectively.

Proposition 1: *Let E_1 be the efficient frontier of the problem when considering transportation option 1 solely, then:*

$$E_1 = [\min(Q_{C_1}^*; Q_{E_1}^*); \max(Q_{C_1}^*; Q_{E_1}^*)].$$

Note that all the proofs from here onwards may be found in Appendix A. In most of practical situations, $Q_{C1}^* < Q_{E1}^*$ thus $E_1 = [Q_{C1}^*; Q_{E1}^*]$. Indeed, $\frac{O_C + T_{FC1}}{h_C}$ is generally lower than $\frac{T_{FE1}}{h_E}$ as the holding cost includes the opportunity cost of the capital tied up into inventory. Moreover, transportation is recognized as a major source of carbon emissions. We consider that $\frac{O_C + T_{FC1}}{h_C} < \frac{T_{FE1}}{h_E}$ in what follows.

The following definitions are used in Proposition 2:

- Let S be a subset of $\mathfrak{R} \times \mathfrak{R}$, $Conv(S)$ is the convex hull of S , i.e. the set of all convex combinations of points in S .
- $Eff(S)$ is the set of efficient solutions of S .
- Let S be a set of efficient solutions (i.e. $Eff(S) = S$), then S is convex iff $Eff(Conv(S)) = S$.

Proposition 2: *Let $Z_1(E_1)$ be the efficient frontier of the problem when considering transportation option 1 solely, then:*

$$Z_1(E_1) \text{ is convex.}$$

Proposition 2 implies that the problem behaves nicely when considering only one transportation option. Indeed, all the elements of a convex efficient frontier may be generated by minimizing a weighted sum of objectives. We prove later that the efficient frontier is non-convex when more than one option is considered (see Proposition 6).

Consider that a second transportation option (option 2) is available. As for option 1, Q_{C2}^* and Q_{E2}^* may be obtained by using Formula 3 and Formula 5 respectively. Moreover, let $Z_{C2}^* = Z_{C2}(Q_{C2}^*)$ and $Z_{E2}^* = Z_{E2}(Q_{E2}^*)$. Proposition 1 and Proposition 2 are also valid for option 2. Without loss of generality, we assume that option 1 is less costly than option 2, i.e. $Z_{C1}^* < Z_{C2}^*$. Propositions 3 and Lemma 1 restrict the possible number of intersection between $Z_1(E_1)$ and $Z_2(E_2)$. Note that $|S|$ corresponds to the cardinality of the set S .

Proposition 3. Let $Z_1(E_1)$ and $Z_2(E_2)$ be the efficient frontiers for transportation option 1 and transportation option 2 respectively, then:

$$|Z_1(E_1) \cap Z_2(E_2)| \leq 2.$$

Lemma 1. Let $Z_1(E_1)$ and $Z_2(E_2)$ be the efficient frontiers for transportation option 1 and transportation option 2 respectively, then:

$$\text{If } Z_{E_1}^* > Z_{E_2}^*, \text{ then } |Z_1(E_1) \cap Z_2(E_2)| \leq 1,$$

$$\text{Else } |Z_1(E_1) \cap Z_2(E_2)| \in \{0;2\}.$$

The efficient frontier of the problem with two available transportation options may be identified by applying Lemma 1 and by acknowledging that $Z_{c_1}^* < Z_{c_2}^*$ as shown in Propositions 4 and Proposition 5.

Proposition 4. Let $Z(E)$ be the efficient frontier for the problem with two available transportation options with $Z_{c_1}^* < Z_{c_2}^*$ and $Z_{E_1}^* > Z_{E_2}^*$ then:

If $|Z_1(E_1) \cap Z_2(E_2)| = 1$, then the intersection point is noted $\{c_\cap; e_\cap\}$ and:

$$Z(E) = \{(c_1; e_1) \in Z_1(E_1) | c_1 \leq c_\cap\} \cup \{(c_2; e_2) \in Z_2(E_2) | e_2 \leq e_\cap\}.$$

Else $|Z_1(E_1) \cap Z_2(E_2)| = 0$:

If $Z_1(Q_{E_1}^*) \subset Z(E)$, then:

$$Z(E) = Z_1(E_1) \cup \{(c_2; e_2) \in Z_2(E_2) | e_2 < Z_{E_1}^*\},$$

Else,

$$Z(E) = \{(c_1; e_1) \in Z_1(E_1) | c_1 < Z_{c_2}^*\} \cup Z_2(E_2).$$

Proposition 5. Let $Z(E)$ be the efficient frontier for the problem with two available transportation options with $Z_{c_1}^* < Z_{c_2}^*$ and $Z_{E_1}^* < Z_{E_2}^*$ then:

If $|Z_1(E_1) \cap Z_2(E_2)| = 0$ then:

$$Z(E) = Z_1(E_1).$$

Else $|Z_1(E_1) \cap Z_2(E_2)| = 2$. Let $\{c_{\cap 1}; e_{\cap 1}\}$ and $\{c_{\cap 2}; e_{\cap 2}\}$ be the two intersection points and assume that $e_{\cap 2} < e_{\cap 1}$, then:

$$Z(E) = \{(c_1; e_1) \in Z_1(E_1) | e_1 \geq e_{\cap 1}\} \cup \{(c_2; e_2) \in Z_2(E_2) | e_{\cap 1} \geq e_2 \geq e_{\cap 2}\} \cup \{(c_1; e_1) \in Z_1(E_1) | e_{\cap 2} \geq e_1\}$$

Propositions 4 and 5 enable quickly identifying the set efficient solutions for the problem with two transportation options.

When $Z_{E_1}^* > Z_{E_2}^*$, i.e. when option 1 is cheaper and option 2 is greener, we can observe that switching to a greener transportation option is efficient only in case of a strong carbon emissions reduction target. Otherwise, increasing the ordering quantity is more efficient. Proposition 4 also implies that switching to a greener mode of transportation while continuing to optimize the total logistic cost function may lead to a dominated solution (for instance if $Z_1(E_1) \cap Z_2(E_2)$ is non-empty). An example of such situation is proposed in Section 3.3. In this case, the same level of carbon emissions may be obtained with a lower cost by only increasing the ordering quantity. This result proves that poor decisions may be taken when ignoring the strong interrelationship between inventory control and transportation mode selection. When $Z_{E_1}^* < Z_{E_2}^*$, we could expect option 2 to be out of interest as this is possible to obtain a cheaper solution as well as a greener solution with option 1. However, these two solutions are not obtained simultaneously in most of the cases. Option 2 may thus be considered in some situations as a better compromise between costs and carbon emissions.

Proposition 6: Let $Z(E)$ be the set of efficient solutions for the problem with two available transportation options, then:

If $Z(E) \neq Z_1(E_1)$ then $Z(E)$ is non-convex.

The study of the global problem with $n > 2$ transportation options may be conducted as follows. First, the efficient frontier for problem k noted E_k (with corresponding image noted $Z_k(E_k)$) may be identified by using Proposition 1 for all $k \in [1; n]$. We assume without loss of generality that for all $k \in [1; n-1]$, $Z_{Ck}^* < Z_{Ck+1}^*$. Propositions 4 and 5 may be applied to compare option $k \in [1; n]$ to all the other available options $j \in [1; n]$ (such that $j \neq k$). $Z_{k,j}(E)$ is the corresponding efficient frontier (by extension, we also consider $Z_{k,k}(E) = Z_k(E_k)$). Let define $Z_k(E_k)^\cap = \bigcap_{j=1}^n Z_{k,j}(E)$. Note that $Z_k(E_k)^\cap$ may be an empty set. The efficient frontier of the global problem may be identified by applying Proposition 7.

Proposition 7. *Let $Z(E)$ be the set of efficient solutions for the global problem with $n > 2$ available transportation options, then:*

$$Z(E) = \bigcup_{k=1}^n Z_k(E_k)^\cap .$$

3.3 Application

We consider that a French retailer orders bottles of wine from an external supplier. We assume that the bottles are delivered on pallets (a full pallet contains 400 bottles) and that the supplier requires to order at least one full pallet. The pallet is chosen as the quantity unit in what follows. We assume that the hypotheses of the EOQ model are fulfilled. The data relative to the problem may be found in Table 1. Inventory holding emissions were estimated by evaluating the electricity consumption for six warehouses of a major French retailer. We accordingly assume that $h_E = 2.65$ kg CO₂ per pallet and per month.

time unit	1	<i>month</i>
quantity unit	1	<i>pallet</i>
nb product / pallet	400	<i>product/pallet</i>
product price	7,5	<i>euro/product</i>
product weight	1,25	<i>kg/product</i>
unit price	3000	<i>euro/pallet</i>
unit weight	500	<i>kg/pallet</i>
inbound distance	500	<i>km</i>
demand	20	<i>pallets/month</i>
h_c	75	<i>euro/pallet.month</i>
h_{tc}	50	<i>euro/pallet.month</i>
O_c	100	<i>euro/order</i>

Table 1: Application's data

We first consider that the retailer decides to use heavy duty trucks for inbound transportation. The truck capacity is 33 pallets and the transportation leadtime is 0.5 day. The transportation costs follow a modified all-unit discount structure with two discount rates. Moreover, the full truckload cost is 600€. In this setting, the company may over-declare a quantity to take advantage of the next discount or to take advantage of the full truckload tariff. The per shipment transportation cost in function of the order quantity (up to the truck capacity) is shown in Figure 1. Note that the in-transit inventory holding cost is also considered in the transportation cost function, thus, the cost of transporting 33 pallets is equal to 627.50€ (i.e. 600€ from the full truckload cost + $33 * 0.5 / 30 * 50 = 27.50$ € from in-transit inventory).

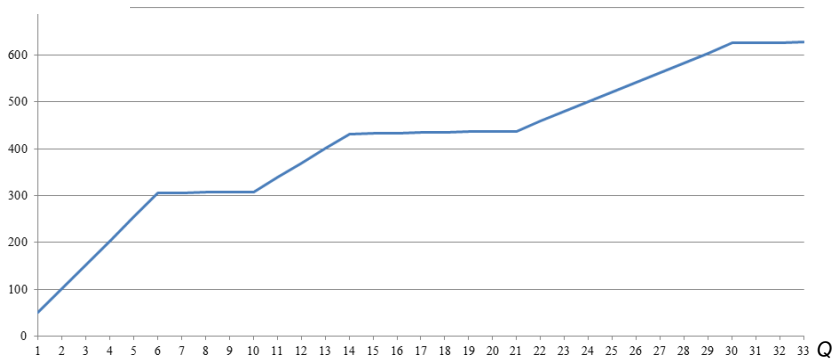


Figure 1: Truck transportation costs in function of the ordering quantity

The NTM methodology (NTM, 2008) was used to evaluate the carbon emissions related to transportation. This methodology allows for computing a per product amount of carbon emissions by considering a given average load factor. We consider in this application that the

load factor depends on the batch size decision. This is indeed common for retailers not to allow the logistics provider for including other type of cargo for inbound transportation. The NTM methodology provides data for empty truck carbon emissions. This gives $T_{FE} = 324$ kg CO₂ for the proposed example. We also consider that the maximum load of the truck is 26 tons of cargo. The truck is thus fully loaded in volume with 33 pallets for a corresponding load factor of 0.63 in this application. This leads to a variable amount of carbon emissions $T_{VE} = 3.69$ kg CO₂ per pallet.

In order to apply the model proposed in Section 3, truck transportation mode is divided into six different transportation options (due to the piecewise linear structure of the transportation cost function). The characteristics of the six options are summarized in Table 2.

	Q_{\min}	Q_{\max}	T_{FC}	T_{VC}	$\sqrt{\frac{2(O_C + T_{FC})D}{h_C}}$	$\sqrt{\frac{2T_{FE}D}{h_E}}$	Z_C^*	Z_E^*	Q_C^*	Q_E^*
option 1	1	6	0	50	7.3	70.0	1575.00	1161.79	6.0	6.0
option 2	6	10	300	0	14.6	70.0	1191.67	735.10	10.0	10.0
option 3	10	14	0	30	7.3	70.0	1191.67	555.25	10.0	14.0
option 4	14	21	420	0	16.7	70.0	1265.67	410.24	16.7	21.0
option 5	21	30	0	20	7.3	70.0	1299.40	329.58	21.0	30.0
option 6	30	33	600	0	19.3	70.0	1608.33	313.92	30.0	33.0

Table 2: Truck transportation options' parameters

For option $i \in [1;5]$, assuming that $Q_{Ci}^* \leq Q_{\max i}$ is reasonable as a better tariff may be achieved for

$Q > Q_{\max i}$. For option 6, we can notice that $\frac{hQ_{\max 6}^2}{2D} \approx 2041 > O_C$ which is a sufficient condition

to assert that $Q_{C6}^* \leq Q_{\max 6}$. Proposition 1 may be directly used to obtain the efficient frontiers of each option solely.

Figure 2 displays the results in the criterion space for $Q \in [6;33]$. The x-axis represents the costs and the y-axis represents the carbon emissions of the available alternatives. The efficient solutions are represented with a straight line and the dominated ones with a dash line. Note that P_C and P_E are not included in the costs and carbon emissions evaluations as they are not affected by a change in the lot size or in the transportation mode. The efficient frontier (composed by the six options in the model) may be easily obtained by using the results provided in Section 3.2. First it may be noticed that option 1 and option 2 are out of interest as they are

dominated by option 3 by applying Proposition 5. By applying Proposition 4 with option 3 and 4, we obtain that $E_{3,4} = [10;13.2] \cup [16.7;21]$. We finally obtain that $E_{Truck} = [10;13.2] \cup [16.7;33]$ by including option 5 and option 6 to the analysis and by applying Proposition 7.

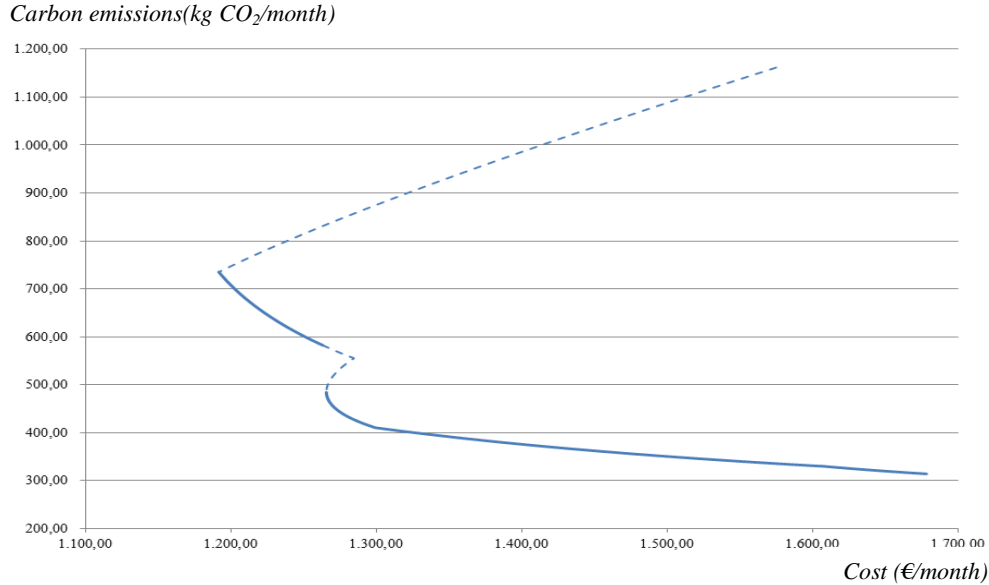


Figure 2: Truck transportation

Assume that the retailer currently orders $Q_{CTruck}^* = 10$ pallets (i.e. that the retailer minimizes its total logistics costs). Figure 2 shows that a carbon emissions reduction of 57% can be achieved by increasing the ordering quantity up to 33 pallets without switching to a greener mode of transportation. Moreover, the required financial effort first remains reasonable when decreasing carbon emissions. For instance, increasing the lot size from $Q = 10$ to $Q = 17$ enables a 35% reduction in carbon emissions for a 6% costs increase. On the opposite, the financial effort will increase as Q is getting closer to Q_{ETruck}^* (the ordering quantity that minimizes the amount of carbon emissions for truck transportation). This feature is commonly highlighted in the literature on inventory control with carbon emissions concerns (Bouchery et al., 2012; Chen et al., 2013).

Consider now that rail transportation is also available for inbound transportation. A train includes 26 freight cars, each of them fully loaded in volume with 36 pallets. The rail transportation leadtime is 2 days. A fixed transportation cost $T_{FC} = 449$ € per freight car is considered. In opposition to truck transportation, several types of cargo (from several retailers)

may be included into the same train. In this case, the carbon emissions associated with the train when running empty may be split between the different users. A fixed amount of carbon emissions per freight car is then derived from the average utilization rate of the train. Moreover, a variable amount of carbon emissions is associated to each pallet. By using average values provided by the NTM methodology, we obtain that $T_{FE} = 333$ kg CO₂ per freight car and $T_{VE} = 1.30$ kg CO₂ per pallet. Due to both costs and carbon emissions structure, there is no incentive in ordering more than one full freight car. The related characteristics are summarized in Table 3.

	Q_{\min}	Q_{\max}	T_{FC}	T_{FE}	$\sqrt{\frac{2(O_C + T_{FC})D}{h_C}}$	$\sqrt{\frac{2T_{FE}D}{h_E}}$	Z_C^*	Z_E^*	Q_C^*	Q_E^*
option 7	1	36	449	333	17.1	71.0	1350.29	258.86	17.1	36.0

Table 3: Train transportation options' parameters

Without performing the multiobjective optimization analysis provided in this paper, the retailer may decide to switch to rail for inbound transportation while continuing to minimize the total cost function in order to decrease the carbon emissions of the supply chain. This solution leads to 1 350 € and 441 kg CO₂ per month. This should be compared to 1192 € and 735 kg CO₂ per month in case of truck transportation with $Q = 10$ (a 40% decrease in carbon emissions for a 13% increase in costs).

Figure 3 displays the efficient frontier for both truck transportation (straight line) and train transportation (dash line) in the criterion space. Figure 3 clearly shows that the solution consisting in switching to rail while continuing to minimize the cost function is a dominated solution. The same decrease in carbon emissions may be achieved with a lower cost by continuing to use truck for inbound transportation and by choosing $Q = 19$ (leading to 1 277 € and 440 kg CO₂ per month). This example clearly shows that switching to a greener mode of transportation while continuing to optimize the cost function may not be the best option to green the supply chain. This highlights the necessity of taking an integrated inventory control and transportation model selection perspective when intending to green the supply chain.

In the proposed application, truck transportation does not always outperform train transportation as the efficient frontier of the global problem includes both truck and train

transportation options. Deciding whether to use truck or train for inbound transportation depends on the company's willingness to reduce its carbon emissions.

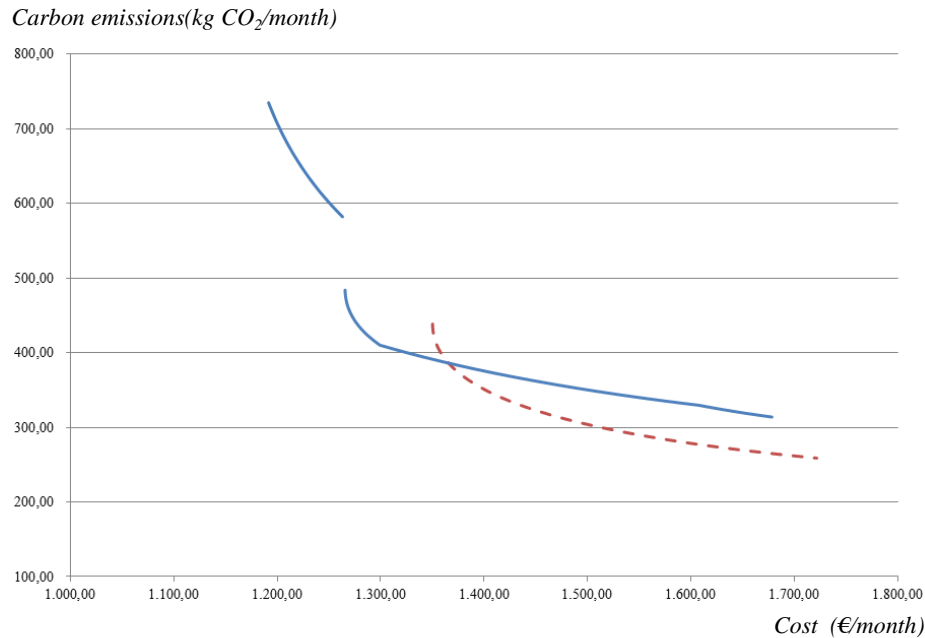


Figure 3: Truck versus train transportation in the criterion space

4. The carbon cap and the carbon tax cases

Multiobjective optimization is a first layer of analysis as this may not lead to a unique solution. In a second step, the decision maker may identify the most valuable trade-off between costs and carbon emissions in the set of the efficient solutions. Moreover, the set of efficient solutions for the joint transportation mode selection and lot sizing optimization problem includes more than one mode of transportation in non-trivial cases. The decision of choosing the greener option thus depends on the company's willingness to pay for reducing its carbon emissions. This willingness to pay may come from several types of pressures that the company can face (i.e. regulation, customers' pressure, employees' pressure) but may also come from a voluntarily effort made by the company (Lieb and Lieb, 2010).

Two ways of taking carbon emissions into account in the decision making process are analyzed in this section. In the first one, we assume that the company aims at reducing its carbon emissions by meeting a self-imposed emissions reduction target. In the second case, a regulatory policy based on a carbon tax is imposed to the company. For the two situations, we consider that

two options are available. We assume that option 1 is cheaper ($Z_{C1}^* < Z_{C2}^*$) and that option 2 is greener ($Z_{E1}^* > Z_{E2}^*$). Several managerial insights are also drawn from comparing the two situations.

4.1 The carbon cap case

In this section, we assume that the company is voluntarily committed to reduce its carbon emissions up to a certain level by self-imposing an upper limit on its carbon emissions. In most of the cases, the companies who voluntarily reduce their carbon emissions also want to disclose this information to other parties in order to experience some positive side-benefits. For instance, Corbett and Klassen (2006) notice that adopting an environmental perspective often yields benefits beyond what was expected beforehand. This may explain that 294 of the Global 500 companies have voluntary emissions reduction targets (Carbon Disclosure Project, 2011).

Companies often express an emissions reduction target as a percentage reduction of its current total emissions. This target may be directly imposed to all the company's departments or to all the company's products. On the other hand, this target can be modulated in order to achieve a stronger reduction for departments or products with a stronger emissions reduction potential. In this section, we consider that the emissions reduction target has been translated into an upper limit CAP on carbon emissions for each product. We further assume that $CAP \geq Z_{E2}^*$, which is the minimum amount of carbon emissions that can be emitted with the two available modes of transportation. Otherwise, no feasible solution exists. In this context, transportation option 2 will performs better than transportation option 1 only if the emissions reduction target is strict enough. This result is stated in Proposition 8.

Proposition 8. *Assume that the company faces an upper limit on carbon emissions noted CAP , then there exists a threshold L_E on carbon emissions such that:*

- if $CAP > L_E$, option 1 performs better option 2,
- if $CAP < L_E$, option 2 is the best option.

The result of Proposition 8 directly follows from Proposition 4. It may also be noticed that the value of L_E is not unique if $Z_2(Q_{C2}^*) \subset Z(E)$. Moreover, when $CAP = L_E$, the best

transportation option has to be determined in a case by case basis. If $Z_1(E_1) \cap Z_2(E_2)$ is non-empty, $L_E = e_\cap$ and the performances of both transportation options are the same. Otherwise, one of the transportation options outperforms the other one in the case of a carbon cap equal to L_E .

4.2 The carbon tax case

In this section, we consider that a cost is associated to the company's carbon emissions. Assume that the company incurs a cost that is linear in function of its total carbon emissions. This cost can be imposed to the company in the case of a carbon tax. However, this cost can also come from an internal evaluation from the company, by considering the cost of the energy used or the cost issued from an environmental accounting analysis. This cost per amount of carbon emissions is noted $\alpha \in [0; \infty)$. In this context, there exists a value $L_C \in (0; \infty)$ that allows deciding which option is the most interesting as show in Proposition 9.

Proposition 9. *Assume that a cost α is associated to the company's carbon emissions, then there exists a unique value L_C such that:*

- if $\alpha < L_C$, option 1 performs better than option 2,
- if $\alpha > L_C$, then option 2 is the best option.

Contrary to the carbon cap case, the value of L_C is unique and corresponds to the slope of the common tangent of $Z_1(E_1)$ and $Z_2(E_2)$. The value of L_C may be easily approximated by finding a value of α_1 such that option 2 is the best option (i.e. $\alpha > L_C$) and by applying the bisection method on the interval $[0; \alpha_1]$ (at each iteration, the interval $[\alpha_i; \alpha_{i+1}]$ such that option 1 is the best option if $\alpha = \alpha_i$ and option 2 is the best option if $\alpha = \alpha_{i+1}$ is considered).

4.3 Discussion

Proposition 1 implies that increasing the batch quantity for a given transportation option may enable reducing the carbon emissions of the supply chain. This gives additional flexibility to supply chain managers who are likely to be focused on low-carbon transportation projects implementation without taking a global supply chain costs and carbon emissions perspective.

Then, the question is to decide whether to only modify the ordering quantity or to switch to a greener transportation option when intending to reduce the carbon footprint of the supply chain. Two different contexts have been analyzed. In the first one, the company aims at reducing its carbon emissions by meeting a self-imposed emissions reduction target. In the second case, a regulatory policy based on a carbon tax is imposed to the company. We have proven that the analysis of these two decision contexts may be simply performed by directly extending the proposed multiobjective optimization results.

These two contexts are illustrated on the example provided in Section 3.3 (see Figure 4). For the carbon cap case studied in Section 4.1, we obtain that $L_E = E_{\cap} = 386$ kg CO₂/month. This amount should be compared with the cost minimization solution where the related level of carbon emissions is 735 kg CO₂/month. Thus, the company should be committed in decreasing its carbon emissions by almost 50% to make the modal shift happen. For the carbon tax case studied in Section 4.2, we obtain that $L_C = 1670.35$ € ton CO₂. This result shows that an extremely high emissions cost is required to induce a modal shift. This result is consistent with other studies such as Hoen et al. (2012).

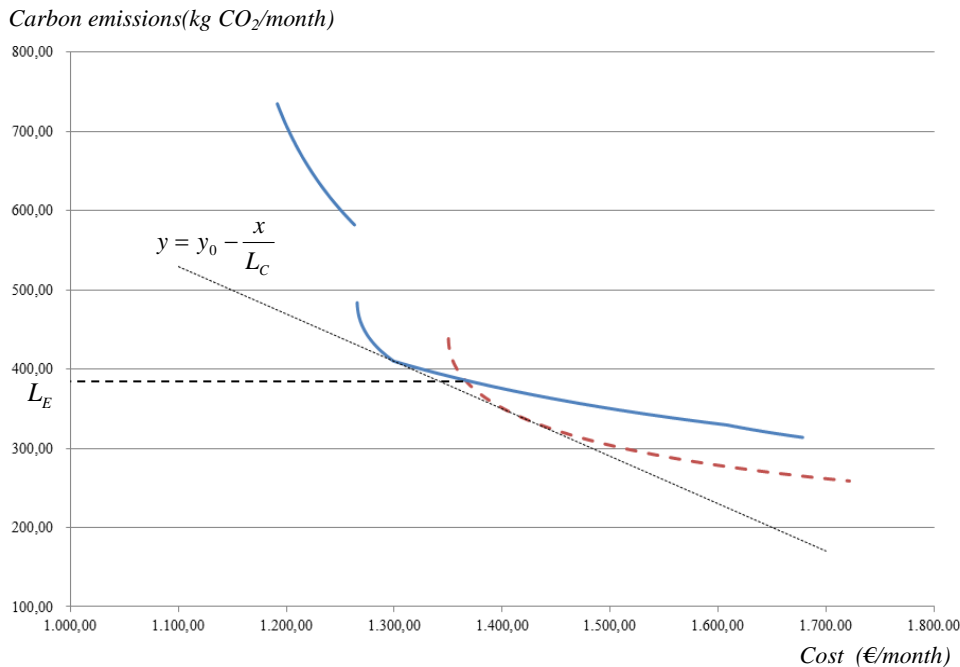


Figure 4: Carbon cap and carbon tax limit values

We can then conclude that realistic values of the emission cost are expected to have a limited effect on modal shift due to the price inelasticity of freight transportation. Moreover, the financial effort will considerably increase as getting closer to the minimum amount of emissions as both operational costs and emissions costs will significantly increase. Our results also show that controlling emissions via a carbon price has some technical drawbacks due to the fact that the efficient frontier is non-convex in most of the situations as proven in Proposition 6. In this case, the non-supported efficient solutions cannot be generated by modifying the value of the carbon tax. However, these solutions may be chosen by companies committed in self-imposed carbon emissions reduction targets. For instance, the efficient solution corresponding to $CAP = L_E$ is non-supported as shown in Figure 4. Several solutions may also be optimal for a given carbon price as in the case where $\alpha = L_C$. However, the costs and the carbon emissions are different for both options. At a macroeconomic level, this operational flexibility implies that the total amount of carbon emissions is hardly controllable by setting a carbon price. Whatever the chosen value of α , some companies may face $\alpha = L_C$. These companies may thus be able to choose among several carbon emissions levels. However, governments are interested in designing regulatory policies that enable to predict and manage the global amount of carbon emissions as many countries have ratified the Kyoto protocol mainly based on a negotiated carbon cap for each country (UNFCCC, 1997).

As a result, using an upper limit on carbon emissions seems to be more effective to green supply chains as the previous drawbacks are avoided. Moreover, using a carbon cap is in accordance with multiobjective optimization principles. Indeed, all the efficient solutions of the problem may be generated by gradually strengthening the constraint on carbon emissions starting from $Z_{E1}(Q_{C1}^*)$ (which correspond to the efficient solution associated to the maximum amount of carbon emissions). This observation is the basis of the epsilon-constraint method (Ehrgott, 2005). However, a regulatory policy based on a carbon cap without the opportunity to trade allowances may be harder to implement as a carbon emissions reduction target has to be set up with a lot of caution for each company. To our knowledge, such a regulatory policy has never been implemented. One way to overcome this issue may consist in designing regulatory policies that entice the companies to self-impose an upper limit on their carbon emissions. For instance, disclosure requirements, innovation supports or technical regulations may be considered.

5. Conclusions

This paper applies multiobjective optimization to show how the efficient tradeoffs between different types of objectives may be obtained in the context of socially responsible operations. Moreover, the efficient frontier properties enables us to identify several insights that remain hidden when considering single-objective models. The paper focuses on joint inventory and transportation model with cost and carbon emissions objectives. We prove that switching to a greener mode of transportation while continuing to optimize the total logistics costs function may lead to a dominated solution. The proposed results give additional flexibility to supply chain managers who are likely to be focused on low-carbon transportation projects implementation without taking a total supply chain costs and carbon emissions perspective. We also prove that the modal shift is interesting only for strong carbon emissions reduction requirements. Otherwise, lot sizing adjustments may enable efficiently greening the supply chain. The proposed model is shown to be applicable in an industry example based on relevant data. In this example, the modal shift is interesting for a 50% carbon emissions reduction target or for a carbon price greater than 1670€/ton CO₂. On other situations, adjusting the ordering lot size would be more efficient to green the supply chain. Two classical ways of reducing supply chain's carbon emissions are studied. For both a regulatory policy based on a carbon tax and a self-imposed carbon emissions reduction target, we prove that there exists a limit value that allows deciding between two available modes of transportation. We also prove that controlling emissions via a carbon tax has some technical drawbacks mainly due to the fact that the efficient frontier is non-convex.

Several research directions can be considered. First, other models related to socially responsible operations could be revisited by using multiobjective optimization. Multiobjective optimization could indeed be efficiently used as a first step of analysis in order to provide an effective decision making support tool to the decision maker by enabling a graphical representation of the existing trade-offs. The decision maker may thus easily build a conviction of what is possible and use this knowledge to identify the most valuable trade-off. Moreover, this process of simultaneously optimizing several conflicting objectives adequately reflects the concept of socially responsible operations as the “triple bottom line” is a good illustration of multiple objectives.

Second, other transportation mode selection and inventory optimization models could be studied. For instance, considering both stochastic demand and stochastic transportation lead times may enable enriching the analysis. In this case, safety stock optimization decisions has to be considered in addition to transportation mode selection and batch size optimization decisions. More complex supply chain structures could also be considered by revisiting the multi-echelon lot sizing models. Considering a carbon-sensitive demand could also be of great interest as customers' pressure is nowadays considered as a main driver of environmental improvements for companies.

Third, other aspects of the “triple bottom line” could also be considered in order to take a broader socially responsible operations perspective. For instance, very interesting analyses may be developed by taking the impact of working conditions into account such as the level of training into operations management models. Other people related dimensions of socially responsible operations such as the risk of accident resulting in injuries or deaths may also be included into the models. This research direction may however be viewed as a challenging one as there is still a lack of consensus on how to assess the people related dimension of socially responsible operations.

Appendix A

Proof of Proposition 1:

Both $Z_{C_1}(Q)$ and $Z_{E_1}(Q)$ are convex on $[Q_{\min 1}; Q_{\max 1}]$.

If $Q_{C_1}^* = Q_{E_1}^*$, $E_1 = Q_{C_1}^*$ as $Q_{C_1}^*$ is the optimal ordering quantity for both costs and carbon emissions.

Assume that $Q_{C_1}^* < Q_{E_1}^*$:

- $Z_{C_1}(Q)$ is strictly increasing on $[Q_{C_1}^*, Q_{E_1}^*]$,
- $Z_{E_1}(Q)$ is strictly decreasing on $[Q_{C_1}^*, Q_{E_1}^*]$,
- $Z_{C_1}(Q)$ and $Z_{E_1}(Q)$ are strictly increasing on $[Q_{E_1}^*, Q_{\max 1}]$ and strictly decreasing on $[Q_{\min 1}, Q_{C_1}^*]$ then the solution is dominated if $Q \notin [Q_{C_1}^*, Q_{E_1}^*]$.

By using the same argumentation in the case where $Q_{E_1}^* < Q_{C_1}^*$, it follows that:
 $E_1 = [\min(Q_{C_1}^*, Q_{E_1}^*); \max(Q_{C_1}^*, Q_{E_1}^*)]$. □

Proof of Proposition 2:

Let $\{c, e\}$ be an element of $Conv(Z_1(E_1))$. $\{c, e\}$ may be expressed as the barycenter of at most three elements of $Z_1(E_1)$ by using Carathéodory's theorem, thus there exists $\{Q_1; Q_2; Q_3\} \in E_1^3$ such that:

$$\{c, e\} = \{\lambda_1 Z_{C_1}(Q_1) + \lambda_2 Z_{C_1}(Q_2) + \lambda_3 Z_{C_1}(Q_3); \lambda_1 Z_{E_1}(Q_1) + \lambda_2 Z_{E_1}(Q_2) + \lambda_3 Z_{E_1}(Q_3)\}$$

with $\sum_{i=1}^3 \lambda_i = 1$.

As $Z_{C_1}(Q)$ and $Z_{E_1}(Q)$ are convex on E_1 , we obtain that $c \geq Z_{C_1}(\lambda_1 Q_1 + \lambda_2 Q_2 + \lambda_3 Q_3)$ and that $e \geq Z_{E_1}(\lambda_1 Q_1 + \lambda_2 Q_2 + \lambda_3 Q_3)$. Moreover, the equalities hold only if $\{c, e\} \in Z_1(E_1)$. We thus conclude that $Eff(Conv(Z_1(E_1))) = Z_1(E_1)$ as $\lambda_1 Q_1 + \lambda_2 Q_2 + \lambda_3 Q_3 \in E_1$. □

Proof of Proposition 3:

Let $\{c, e\}$ be an element of $Z_1(E_1) \cap Z_2(E_2)$. Then there exists $\{Q_1; Q_2\} \in E_1 \times E_2$ such that $c = Z_{C_1}(Q_1) = Z_{C_2}(Q_2)$ and $e = Z_{E_1}(Q_1) = Z_{E_2}(Q_2)$.

$$\begin{cases} Z_{C_1}(Q_1) = Z_{C_2}(Q_2) \\ Z_{E_1}(Q_1) = Z_{E_2}(Q_2) \end{cases} \Leftrightarrow \begin{cases} \frac{h_C}{2D}(Q_1 - Q_2) = \frac{O_C + T_{FC2}}{Q_2} - \frac{O_C + T_{FC1}}{Q_1} + h_{TC}(L_2 - L_1) + T_{VC2} - T_{VC1} \\ \frac{h_E}{2D}(Q_1 - Q_2) = \frac{T_{FE2}}{Q_2} - \frac{T_{FE1}}{Q_1} + T_{VE2} - T_{VE1} \end{cases}$$

$$\begin{aligned} &\Rightarrow h_E \left(\frac{O_C + T_{FC2}}{Q_2} - \frac{O_C + T_{FC1}}{Q_1} + h_{TC}(L_2 - L_1) + T_{VC2} - T_{VC1} \right) = h_C \left(\frac{T_{E2}}{Q_2} - \frac{T_{E1}}{Q_1} + T_{VE2} - T_{VE1} \right) \\ &\Rightarrow \frac{A}{Q_2} + \frac{B}{Q_1} = C, \quad \text{with} \quad A = \frac{h_E(O_C + T_{FC2}) - h_C T_{FE2}}{h_C h_E}, \quad B = \frac{h_C T_{FE1} - h_E(O_C + T_{FC1})}{h_C h_E}, \quad \text{and} \\ &C = \frac{h_{TC}(L_1 - L_2) + T_{VC1} - T_{VC2} + T_{VE2} - T_{VE1}}{h_C}. \end{aligned}$$

As $\frac{O_C + T_{FC1}}{h_C} < \frac{T_{FE1}}{h_E}$ and $\frac{O_C + T_{FC2}}{h_C} < \frac{T_{FE2}}{h_E}$, we obtain that $A < 0$ and $B > 0$.

If $C = 0$, $Q_1 = -\frac{B}{A}Q_2$. By substituting, we obtain that:

$$\begin{aligned} \frac{h_E}{2D} \left(-\frac{B}{A}Q_2 - Q_2 \right) &= \frac{T_{FE2}}{Q_2} + \frac{A}{B} \frac{T_{FE1}}{Q_2} + T_{VE2} - T_{VE1} \\ \Rightarrow P(Q_2) &= \frac{h_E}{2D} \left(\frac{B}{A} + 1 \right) Q_2^2 + (T_{VE2} - T_{VE1})Q_2 + T_{FE2} + \frac{A}{B} T_{FE1} \end{aligned}$$

Then $P(Q_2)$ is a second degree polynomial that has at most two roots, thus $|Z_1(E_1) \cap Z_2(E_2)| \leq 2$.

If $C \neq 0$, then: $Q_1 = \frac{BQ_2}{CQ_2 - A} > 0$, thus $Q_2 > \frac{A}{C}$ as $B > 0$. $Q_2 = \frac{AQ_1}{CQ_1 - B} > 0$, thus $Q_1 < \frac{B}{C}$ as

$A < 0$.

If $C < 0$, then $\frac{B}{C} < 0$ and $|Z_1(E_1) \cap Z_2(E_2)| = 0$.

Assume that $C > 0$:

By taking $Q_1 = \frac{BQ_2}{CQ_2 - A}$, we obtain that:

$$\begin{aligned} \frac{h_E}{2D} \left(\frac{BQ_2}{CQ_2 - A} - Q_2 \right) &= \frac{T_{FE2}}{Q_2} - \frac{T_{FE1}(CQ_2 - A)}{BQ_2} + T_{VE2} - T_{VE1} \\ \Rightarrow P_1(Q_2) &= \alpha.Q_2^3 + \beta.Q_2^2 + \gamma.Q_2 + \delta, \quad \text{with} \quad \alpha = -\frac{h_E C}{2D} < 0, \\ \beta &= \frac{h_E}{2D}(A + B) + \frac{T_{FE1}C^2}{B} + (T_{VE1} - T_{VE2})C, \\ \gamma &= A(T_{VE2} - T_{VE1}) - \frac{2T_{FE1}AC}{B} - T_{FE2}C \quad \text{and} \quad \delta = AT_{FE2} + \frac{A^2 T_{FE1}}{B}. \end{aligned}$$

If $\delta \leq 0$ then $P_1(Q_2)$ has at least one negative root as $P_1(Q_2)$ tends to ∞ as Q_2 tends to $-\infty$ ($\alpha < 0$). Therefore, $P_1(Q_2)$ has at most two strictly positive roots, thus $|Z_1(E_1) \cap Z_2(E_2)| \leq 2$.

Assume that $\delta > 0$:

$\frac{\partial P_1(Q_2)}{\partial Q_2} = 3\alpha Q_2^2 + 2\beta Q_2 + \gamma$. Let Δ be the discriminant of $\frac{\partial P_1(Q_2)}{\partial Q_2}$, then $\Delta = 4\beta^2 - 12\alpha\gamma$.

If $\Delta \leq 0$, then $\frac{\partial P_1(Q_2)}{\partial Q_2}$ has at most one root. In this case, the sign of $\frac{\partial P_1(Q_2)}{\partial Q_2}$ changes at most once, then $P_1(Q_2)$ has at most two roots and we can conclude that $|Z_1(E_1) \cap Z_2(E_2)| \leq 2$.

If $\Delta > 0$, the two roots of $\frac{\partial P_1(Q_2)}{\partial Q_2}$ are $q_1 = \frac{-2\beta - \sqrt{\Delta}}{6\alpha}$ and $q_2 = \frac{-2\beta + \sqrt{\Delta}}{6\alpha}$.

If $\beta \leq 0$, then $q_2 = \frac{-2\beta + \sqrt{\Delta}}{6\alpha} \leq 0$. As the sign of $\frac{\partial P_1(Q_2)}{\partial Q_2}$ changes at most once on \mathfrak{R}_+^* , then $P_1(Q_2)$ has at most two strictly positive roots and we can conclude that $|Z_1(E_1) \cap Z_2(E_2)| \leq 2$.

Assume that $\beta > 0$:

If $\gamma \geq 0$, then $\sqrt{\Delta} \geq 2|\beta|$ thus $q_2 = \frac{-2\beta + \sqrt{\Delta}}{6\alpha} \leq 0$ as $\alpha < 0$. As the sign of $\frac{\partial P_1(Q_2)}{\partial Q_2}$ changes at most once on \mathfrak{R}_+^* , then $P_1(Q_2)$ has at most two strictly positive roots and we can conclude that $|Z_1(E_1) \cap Z_2(E_2)| \leq 2$.

Assume finally that $\gamma < 0$:

Let $p = \frac{\gamma}{\alpha} - \frac{\beta^2}{3\alpha^2}$, $r = \frac{2\beta^3}{27\alpha^3} + \frac{\delta}{\alpha} - \frac{\beta\gamma}{3\alpha^2}$ and $s = \frac{r^2}{4} + \frac{p^3}{27}$. $p = -\frac{\Delta}{12\alpha^2}$, thus $0 > p > -\frac{\beta^2}{3\alpha^2}$ as $0 < \Delta < 4\beta^2$. Moreover, $\frac{r^2}{4} > \frac{\beta^6}{729\alpha^6}$ thus $s = \frac{r^2}{4} + \frac{p^3}{27} > 0$.

As $s > 0$, $P_1(Q_2)$ is a third degree polynomial with only one root thus $|Z_1(E_1) \cap Z_2(E_2)| \leq 1$. \square

Proof of Lemma 1:

Recall that $Z_{C_1}^* < Z_{C_2}^*$.

If $Z_{E_1}^* > Z_{E_2}^*$, then there exists either zero or an odd number of intersections between $Z_1(E_1)$ and $Z_2(E_2)$. As $|Z_1(E_1) \cap Z_2(E_2)| \leq 2$ by applying Proposition 3, then $|Z_1(E_1) \cap Z_2(E_2)| \leq 1$.

If $Z_{E_1}^* < Z_{E_2}^*$, then there exists an even number of intersections between $Z_1(E_1)$ and $Z_2(E_2)$. As $|Z_1(E_1) \cap Z_2(E_2)| \leq 2$ by applying Proposition 3, then $|Z_1(E_1) \cap Z_2(E_2)| \in \{0; 2\}$. \square

Proof of Proposition 4:

As $Z_{E_1}^* > Z_{E_2}^*$, then $|Z_1(E_1) \cap Z_2(E_2)| \leq 1$ by applying Lemma 1.

If $Z_1(E_1) \cap Z_2(E_2) = \{c_{\cap}; e_{\cap}\}$:

$Z_1(Q_{C_1}^*)$ is efficient, moreover, both $Z_1(E_1)$ and $Z_2(E_2)$ are continuous as convex by applying Proposition 2. This implies that all the elements $(c_1; e_1) \in Z_1(E_1)$ with $c_1 \leq c_{\cap}$ are efficient and that all the elements $(c_2; e_2) \in Z_2(E_2)$ with $e_2 > e_{\cap}$ are dominated.

As $Z_2(Q_{E_2}^*)$ is efficient, we conclude that all the elements $(c_1; e_1) \in Z_1(E_1)$ with $c_1 > c_{\cap}$ are dominated and that all the elements $(c_2; e_2) \in Z_2(E_2)$ with $e_2 \leq e_{\cap}$ are efficient. We conclude that $Z(E) = \{(c_1; e_1) \in Z_1(E_1) | c_1 \leq c_{\cap}\} \cup \{(c_2; e_2) \in Z_2(E_2) | e_2 \leq e_{\cap}\}$

Else $Z_1(E_1) \cap Z_2(E_2) = \emptyset$:

If $Z_1(Q_{E_1}^*) \subset Z(E)$, then all the element of $Z_1(E_1)$ are efficient. Moreover, the only efficient solutions of $Z_2(E_2)$ are the ones with lower carbon emissions thus:

$$Z(E) = Z_1(E_1) \cup \{(c_2; e_2) \in Z_2(E_2) | e_2 < Z_{E_1}^*\}.$$

Else all the elements of $Z_2(E_2)$ are efficient and the only efficient solutions of $Z_1(E_1)$ are the ones with lower costs thus:

$$Z(E) = \{(c_1; e_1) \in Z_1(E_1) | c_1 < Z_{C_2}^*\} \cup Z_2(E_2).$$

□

Proof of Proposition 5:

As $Z_{E_1}^* < Z_{E_2}^*$, then $|Z_1(E_1) \cap Z_2(E_2)| \in \{0; 2\}$ by applying Lemma 1.

If $Z_1(E_1) \cap Z_2(E_2) = \emptyset$, then all the elements of $Z_2(E_2)$ are dominated by elements of $Z_1(E_1)$ thus $Z(E) = Z_1(E_1)$.

Else, $Z_1(E_1) \cap Z_2(E_2) = \{c_{\cap 1}; e_{\cap 1}\} \cup \{c_{\cap 2}; e_{\cap 2}\}$ with $e_{\cap 2} < e_{\cap 1}$. By using the same arguments as for Proposition 4, we conclude that:

$$Z(E) = \{(c_1; e_1) \in Z_1(E_1) | e_1 \geq e_{\cap 1} \text{ or } e_1 \leq e_{\cap 2}\} \cup \{(c_2; e_2) \in Z_2(E_2) | e_{\cap 2} \leq e_2 \leq e_{\cap 1}\}.$$

□

Proof of Proposition 6:

If $Z(E) = Z_1(E_1)$ then $Z(E)$ is convex by applying Proposition 2.

Else:

If $Z_1(E_1) \cap Z_2(E_2) = \emptyset$, then $Z(E)$ is non-continuous thus non-convex.

Else, assume that $\{c_{\cap}; e_{\cap}\}$ is the element of $Z_1(E_1) \cap Z_2(E_2)$ with the biggest evaluation in terms of carbon emissions. Let ε be a small positive number. Then both $(c_1; e_1) \in Z_1(E_1) | e_1 = e_{\cap} + \varepsilon$ and $(c_2; e_2) \in Z_2(E_2) | e_2 = e_{\cap} - \varepsilon$ are included into $Z(E)$ by applying Propositions 4 and 5. Let

$(c_3; e_3) \mid c_3 = \frac{c_1 + c_2}{2}, e_3 = \frac{e_1 + e_2}{2}$. $(c_3; e_3)$ is an element of $Conv(Z(E))$, moreover, $(c_3; e_3)$ dominates $\{c_\cap; e_\cap\}$. This proves that $Eff(Conv(Z(E))) \neq Z(E)$ thus $Z(E)$ is non-convex. \square

Proof of Proposition 7:

Assume that $(c_k; e_k) \in Z_k(E_k)^\cap$ with $k \in [1; n]$. Then $(c_k; e_k) \in Z(E)$ by definition of an efficient solution thus $\bigcup_{k=1}^n Z_k(E_k)^\cap \subset Z(E)$.

Let $(c; e) \in Z(E)$. As $Z(E) \subset \bigcup_{k=1}^n Z_k(E_k)$, there exists $k \in [1; n]$ such that $(c; e) \in Z_k(E_k)$. If $(c; e) \notin Z_k(E_k)^\cap$, then it is a dominated element thus $(c; e) \notin Z(E)$ which is a contradiction.

Thus, $Z(E) \subset \bigcup_{k=1}^n Z_k(E_k)^\cap$.

This proves that $Z(E) = \bigcup_{k=1}^n Z_k(E_k)^\cap$. \square

Proof of Proposition 8:

A feasible value of L_E may be constructed as follows:

If $Z_1(E_1) \cap Z_2(E_2) = \{c_\cap; e_\cap\}$, then $L_E = e_\cap$,

If $Z_1(Q_{E1}^*) \subset Z(E)$, then $L_E = Z_{E1}(Q_{E1}^*)$,

Else $L_E = Z_{E2}(Q_{C2}^*)$.

By using Proposition 4, we can conclude that:

- if $CAP > L_E$, option 1 performs better than transportation mode 2 as $(c; e) \in Z(E)$ such that $e = CAP$ is included into $Z_1(E_1)$.

- if $CAP < L_E$, option 2 is the best option as $(c; e) \in Z(E)$ such that $e = CAP$ is included into $Z_2(E_2)$. \square

Proof of Proposition 9:

In the criterion space, for $\alpha \in (0; \infty)$, the cost minimization problem resulting from associating a cost α to the company's carbon emissions is equivalent to find the tangent point between the efficient frontier $Z(E)$ and a straight line of slope $-\frac{1}{\alpha}$. As $Z_{E1}^* > Z_{E2}^*$, there is a unique

common tangent to $Z_1(E_1)$ and $Z_2(E_2)$. Let $-\frac{1}{L_C}$ be the slope of this common tangent. Then:

- if $\alpha < L_C$, option 1 performs better than option 2,

- if $\alpha > L_C$, then option 2 is the best option. \square

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