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CARBON EMISSION MANAGEMENT FOR GREENING SUPPLY CHAINS AT THE OPERATIONAL LEVEL

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Abstract

Increased concern about global warming in today's world has led to the legislation of regulations that seek to gradually reduce the amount of greenhouse gases emitted by industrial sectors and along their supply chains. This study focuses on the amount of carbon emitted in a two-echelon supply chain in which one supplier delivers a single product to a group of retailers and attempts are made to integrate and coordinate its different members. A mixed integer programming model is thus developed in which the problems of timing and the amount of replenishment for each retailer, the types of vehicles used for transportation as well as the amount of products that must be carried by each type of vehicle are addressed with the aim of reducing the overall cost of the supply chain and its carbon footprints. The objective of this research is to minimize the costs of transportation and those engendered by material handling and inventory holding activities as well as to reduce carbon emissions throughout the supply chain. In order to carry out various scenario analyses, some numerical instances are provided and solved. According to the results obtained, the supplier will opt for lower carbon vehicle types if replenishment timing, distances between members of the supply chain, the rate of carbon tax or the amount of retailers increases.

Key words: carbon emissions, coordination, green supply chain, operational decisions, mixed integer programming

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1. Introduction

Greenhouse gases (GHG) have negatively affected the climate of different regions in the world which has led to the phenomenon of global warming. Thus, the need to control the amount of carbon dioxide produced, which is the main GHG, has turned into a pressing worldwide concern. Not only should experts take such performance criteria of the supply chain as cost, profit, flexibility, visibility and response time into consideration, but they should design and operate the supply chain while taking environmental concerns into account.

Although much research has been conducted in the field of green supply chains in the past decades, only recently has the amount of carbon emissions been taken into consideration. Furthermore, quantitative modellings have not been the main trend, e.g. one recent review highlights that only 36 of some three hundred articles published in the last fifteen years make use of these quantitative models (Seuring, 2013). Based on their level of decision making, studies in this field can be broadly divided into three categories, namely strategic, tactical and operational.

Most of the research conducted at the strategic level are related to network design and supply chain configuration with emphasis on environmental issues. Quariguasi Frota Neto et al. (2008) developed a bi-objective linear programming (LP) model to design a green logistic network which is then applied to the paper industry. With the help of goal programming, Ramudhin et al. (2010) presented a bi-objective model for network design that incorporates carbon emissions and logistic costs which is solved and exemplified in

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the steel industry where caps have been imposed on carbon emissions. Wang et al. (2011) presented a bi-objective mixed integer programming (MIP) model for the design of a green supply chain but focused only on factors involved in long-term decision makings. Pinto-Varela et al. (2011) utilized a bi-objective LP model to design a supply chain and solved it with the help of symmetric fuzzy linear programming. Chaabane et al. (2012) developed a generic bi-objective MIP model for designing supply chains, taking the Emissions Trading Scheme into consideration and chose the aluminum industry as their case study. Paksoy et.al (2012) considered a multi-objective model for designing a closed-loop supply chain which takes carbon emissions into account as one of their objective functions and solved a numerical instance with the help of fuzzy optimization techniques. Abdallah et al. (2012) presented a MIP model with the aim of reducing carbon costs throughout the supply chain, while focusing on green procurement and environmental sourcing. This has been done with the help of the life cycle assessment method. Elhedhli and Merrick (2012) focused on the problem of supply chain network design whilst taking carbon emission into consideration. With the help of a concave function, they modeled the relation of CO_2 emissions to vehicle weight which resulted in a mixed integer nonlinear programming optimization model which was subsequently decomposed using Lagrangian Relaxation techniques. By this means, two sub-problems, namely a capacitated facility location with single sourcing and a concave knapsack resulted. Having solved these, they showed that by taking carbon emission costs into account, the optimal solution of the network design can change.

Some other researchers incorporated environmental concerns into the tactical level of decision makings of the supply chain which involves such activities as production and distribution planning as well as capacity allocation. For instance, Harris et al. (2014) dealt with the capacitated facility location–allocation problem, developing a bi-objective MIP model which was solved with an efficient evolutionary optimization method. Their method was based on Lagrangian Relaxation techniques at the allocation level, within a multi-objective evolutionary structure at the location level. Considering carbon emissions and financial costs simultaneously, they solved large-size problems with the customer allocation level being flexible. Zhang et al. (2014) considered the three indicators of total cost, GHG emissions and lead time in a real-world chemical industry. In order to make tactical decisions, a multi-objective MIP model was suggested. The ε-constraint method was applied to solve the model and find trade-off points between the three objectives. They observed that with a little increase in the total cost, GHG emissions or lead time could be decreased.

Other studies yet focus on optimizing the operational decisions related to supply chains with consideration of carbon emissions. Xue and Irohara (2010) considered a transportation scheduling problem based on time-space network and formulated a MIP model to reduce both transportation and carbon emission costs in the process of distribution. Sadegheih et al. (2011) expanded the transportation problem under the carbon emission trading program with the help of MIP and genetic algorithm (GA). Results show the feasibility of GA for transportation network planning in presence of carbon emissions. Ubeda et al. (2011) presented a vehicle routing problem (VRP) incorporating carbon emissions as part of an objective function and a case study related to a two-level supply chain in the food industry. Zeng et al. (2012) developed a replenishment model for a two-level supply chain to which they applied different carbon emission policies. This study shows once again that it is possible to diminish the carbon footprint without spending huge sums of money. Benjaafar et al. (2013) considered a simple lot-sizing model to which different policies aiming at regulating carbon emissions are applied. It suggests that by making proper operational decisions, it is possible to considerably reduce costs emanating from carbon emissions. Kwon et al. (2013) developed a MIP model for fixed fleet VRP taking carbon emissions into consideration. The proposed problem was solved by deploying Tabu search algorithms and results show that it is possible to reduce carbon emissions considerably while the cost related to the benefit gained form carbon trading is not sacrificed.

Soysal et al. (2014) proposed a multi objective linear programming model which they solved with the ε-constraint method to show trade-offs between the total logistics cost and carbon emissions in a real-life, international beef logistics supply chain. They stressed the importance of distances between actors of the supply chain, fuel efficiency and the effect of these on environmental performance of the supply chain. They conclude that green tax incentives lead to economic and environmental improvement. Validi et al. (2014a) modeled a two-layer supply chain related to the distribution of Irish dairy products, using a bi-objective MIP which both considers the total transportation cost and carbon dioxide emissions. Three separate GA based optimizers were applied to determine non-dominated solutions which were subsequently ranked with the help of TOPSIS. This model can assist decision-makers in geographically locating sustainable transportation routes. Later, they also developed an efficient solution method by combining the design of experiment (DoE) with an MOGA-II optimizer (Validi et al., 2014b). Konur (2014) incorporated carbon emissions into his study of the integrated inventory control and transportation problem. He extended the basic economic order (EOQ) quantity model by considering the carbon emissions of different trucks for inbound transportation, developing a heuristic search method to solve it. Findings show that the employment of heterogeneous trucks for inbound transportation results in the simultaneous reduction of costs and emissions. Treitl et al. (2014) proposed an inventory routing problem (IRP) model with the help of a case study from the petrochemical sector that stresses the environmental and economic effects of routing decisions on a supply chain through Vendor-Managed Inventory (VMI) policy. Even though homogenous vehicles were used, results show that it is possible to simultaneously reduce transportation and carbon emission costs. VMI is a replenishment policy in the supply chain which benefits from information technology such as the internet, Electronic Data Interchange (EDI), Enterprise Resource Planning (ERP) and the Point of Sales (POS) data which enables suppliers to be aware of the demands of the final customers and makes decisions for retailers with regard to their inventory levels, replenishment quantities and time of delivery. In order to do so, the supplier should coordinate the planning of transportation and the management of inventory throughout the supply chain. The benefits of coordination in supply chains are studied by Arshinder et al. (2008).

In order to reduce fuel consumption, Gajanand and Narendran (2013) extended the capacitated VRP into a multiple-route-vehicle-routing problem and solved it selecting, among alternative routes, those which are less harmful to the environment. In their model, the customer's demand cannot be split and is less than the maximum capacity of the vehicle. Results show that it is feasible to reduce vehicular emissions by using alternative routes. Mirzapour Al-e-hashem and Rekik (2013) developed a multi-product, multi-period IRP consisting of multiple suppliers and one plant. By incorporating the carbon emissions of vehicles and the transshipment option as constraints into the model, they were able to shorten the travelled distance and reduce carbon emissions as a result. Lin et al. (2014) provided a comprehensive literature review of Green VRPs, dividing them into the three broad categories of Green-VRP, Pollution Routing Problems and VRP in Reverse Logistics. They reviewed the most recent publications in this field, highlighting the existing gaps and came to the conclusion that there is much to be done in order to incorporate green and sustainability factors into VRP. There is considerable literature on issues pertaining to carbon emissions but only lately have researchers focused on operation management concerns. Efforts to reduce carbon emissions imply a certain amount of coordination between the different stages of the supply chain without which the cost at certain stages may be reduced while the overall cost would augment. Table 1 compares some of the studies alluded to in this paper which are related to the carbon footprint along supply chains and highlights some of the existing gaps.

Table 1. Comparison between studies related to the carbon footprint along supply chains

Studies	***Level of decision making***			***Model properties***								***Carbon policy***				***Source of Carbon Emissions***	***Model type***
	Strategic	***Tactical***	***Operational***	***Multi-echelon***	***Two-echelon*** Origin point(s)	***Two-echelon*** Destination point(s)	***Product(s)***	***Period(s)***	***Vehicle type(s)***	***Number of Vehicles of each type(s)***	***Transportation mode(s)***	***Carbon cap***	***Carbon tax***	***Carbon Cap & trade***	***None / (Other)***		
Ramudhin et al. (2010)	*	-	-	*	-	-	m	s	-	-	m	-	-	*	-	t, p	MO-MILP
Xue and Irohara (2010)	-	-	*	-	s	m	s	m	-	-	m	-	*	-	-	t	MILP
Wang et al. (2011)	*	-	-	-	-	-	m	s	-	-	-	-	-	-	*	t, p	MO-MILP
Pinto-Varela et al. (2011)	*	-	-	*	-	-	m	s	-	-	-	-	-	-	*	t, p	MO-MILP
Sadegheih et al. (2011)	-	-	*	-	m	m	s	s	-	-	m	-	-	*	-	t	MILP
Ubeda et al. (2011)	-	-	*	-	s	m	s	s	s	m	s	-	-	-	*	t	MILP
Zeng et al. (2012)	-	-	*	-	s	s	s	s	-	-	-	*	*	*	(*)	t, p, i	MILP
Chaabane et al. (2012)	*	-	-	*	-	-	m	m	-	-	s	-	-	*	-	t, p	MO-MILP
Paksoy et.al (2012)	*	-	-	*	-	-	m	s	s	m	s	-	*	-	-	t	MO-LP
Abdallah et al. (2012)	*	-	-	*	-	-	m	s	-	-	-	-	-	*	-	t, p	MILP
Elhedhli and Merrick (2012)	*	-	-	*	-	-	s	s	s	s	s	-	-	-	*	t	MINLP
Mirzapour and Rekik (2013)	-	-	*	-	m	s	m	m	m	s	s	*	-	-	-	t	MILP
Benjaafar et al. (2013)	-	-	*	-	-	-	s	m	-	-	-	*	*	*	(*)	t, p, i	MILP
Kwon et al. (2013)	-	-	*	-	s	m	s	s	m	m	s	-	-	*	-	t	MILP
Gajanand and Narendran (2013)	-	-	*	-	s	m	s	s	m	s	s	-	-	-	*	t	MILP
Treitl et al. (2014)	-	-	*	*	-	-	s	m	s	m	s	-	*	-	-	t, d	MILP
Harris et al. (2014)	*	*	-	-	m	m	s	s	s	s	s	-	-	-	*	t, d	MO-MILP
Soysal et al. (2014)	-	-	*	*	-	-	s	m	m	s	m	-	-	-	*	t	MO-LP
Validi et al. (2014a)	-	-	*	*	-	-	s	s	m	s	s	-	-	-	*	t	MO-MILP
Konur (2014)	-	-	*	-	-	-	s	s	m	s	s	*	-	-	-	t	MINLP
Validi et al. (2014b)	-	-	*	*	-	-	s	s	m	s	s	-	-	-	*	t	MO-MILP
Zhang et al. (2014)	-	*	-	*	-	-	m	s	-	-	-	-	-	-	*	t, p	MILP
Current research	-	-	*	-	s	m	s	m	m	m	s	-	*	-	-	t	MILP

s: single, m: multiple, t: transportation, d: depot, p: production/ processing, i: inventory, MO: multi-objective, LP: linear programming, MILP: mixed integer linear programming, MINLP: mixed integer nonlinear programming

To the best of our knowledge, one issue that has not been much touched upon in recent literature is the consideration of carbon emission costs, in addition to other costs that a supply chain entails, in order to coordinate inventory management and transportation planning decisions. In order to fill this gap, this research focuses on the coordinated inventory/transportation planning problem as an important operational issue in presence of carbon emissions. Our objective in this paper is to reduce the overall amount of carbon emitted throughout a coordinated two-level supply chain consisting of one supplier and multi-retailers, whilst taking such factors as the types of vehicle used for the transportation of goods also into consideration. The novel mixed integer programming model we develop lays stress on the following points on which less emphasis has been laid in previous research conducted in this field:

1.We take carbon emission costs into consideration in addition to vehicle, handling and inventory costs.

2.We make use of several vehicle types with different pollution levels (because of the different manufacturing technologies employed, the kind of fuel consumed, the age of the vehicle, etc.)

3.The retailers' demand can be split and goods can be delivered by several vehicles. As a result of which, fewer vehicles are dispatched and the total travelled distance diminishes.

By solving the model, not only are costs minimized but an optimal combination of the quantity and types of vehicles to be dispatched is also obtained. As Lin et al. (2014) have stressed, most studies make use of homogeneous vehicles; thus our study, which makes use of vehicles with different pollution levels can be viewed as a step forward toward overcoming this gap.

So far in this section, we have addressed the importance of carbon footprint along the supply chain and have reviewed the pertinent literature in this field. The problem definition is given in section 2 where a decision model is also presented; as for the values of the parameters and the solution method, they are provided in Section 3. Section 4 deals with some numerical experiments and discusses the results and Section 5 concludes this paper, offering some suggestions for future studies.

2. Decision model

According to a report recently released by the Environmental Protection Agency (EPA, 2012), CO_2 is the major greenhouse gas (95.7%) that is produced by the transportation sector. In order to green supply chain management, it is thus mandatory to incorporate carbon emission concerns in supply chain modeling since these could affect operational decisions. This study attempts to coordinate a two-level supply chain that comprises one supplier and a group of retailers and has the asset of encompassing environmental concerns as well.

The problem we address in this research is the delivery of one type of product by a supplier to a set of retailers based on the latter's demands. The supplier has the responsibility of determining the amount of goods to be transported by the vehicles as well as deciding which vehicle it is best to dispatch based on its carbon emission factor. Its other duties consist in setting the time of delivery as well as the replenishment quantities of the retailers.

The objective of this paper is not only to minimize the customary costs of the supply chain which include transportation and inventory holding costs, but also to reduce the carbon emission costs that the vehicles entail. In order to do so, we have endeavored to extend the coordinated inventory/transportation planning model as developed by Kang and Kim (2010) by adding vehicle types and considering carbon emissions for each type of vehicle based on the assumptions enumerated in Section 2.1.

2.1. Assumptions

Given that the supplier is located in a relatively far distance from the group of retailers, one can assume that the distance of each retailer from the supplier is fixed. Moreover, since the retailers are situated at the same distance within one geographical area, one can suppose that the distances between them is fixed as well. The demands of retailers are known beforehand by the supplier and are dynamic.

The supplier makes a number of decisions which are as follows: determining the types of vehicles, the time of delivery and the amount of goods carried by each vehicle as well as the inventory level and the amount of replenishment for each retailer. The three types of vehicles employed have the same loading capacity but emit different amounts of carbon. The amount of each type of vehicles used in this problem is enough to handle all delivery products.The demands of retailers can be divided and goods can be delivered by several vehicles.Each vehicle can visit several retailers in every trip it makes. The overall transportation cost comprises a fixed cost for every vehicle type and a handling cost that alters based on who the retailer is to which products are being delivered. From the various existing methods for calculating the amount of carbon emitted by vehicles, this study uses the distance-based method in which, the emission factor of each type of vehicle is multiplied by the travelled distance based on the standard provided by The Greenhouse Gas Protocol Initiative (WRI, 2011). The amount of carbon engendered by inventory holding and the retailer-dependent material handling sectors has not been taken into consideration in order to simplify this problem.

2.2. Mathematical formulation of the model

Fig. 1 illustrates a simplified structure of the suggested supply chain model as defined in the problem and the assumptions given.

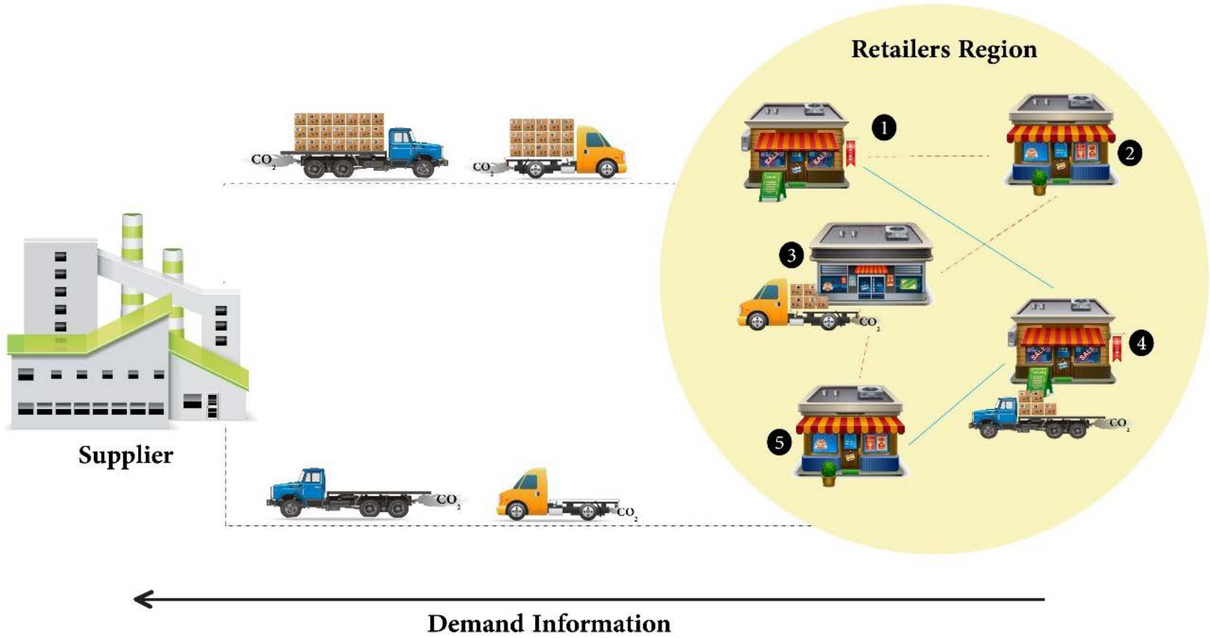

Fig. 1. The suggested supply chain model

Being aware of the retailers demand beforehand through the VMI system, the supplier has the duty to deliver goods by dispatching two types of vehicles that distribute goods among five retailers for one period in which retailers 2, 3 and 4 only receive products from one type of vehicle; whereas, retailers 1 and 5 receive goods from vehicle types 1 and 2.

To solve this problem, a mixed integer programming model is developed. The following nomenclature is used in the model formulation:

- **Indices**

j -Index for retailers $(j = 1, 2, \ldots, J)$;

p -Index for vehicle types $(p = 1, 2, \ldots, P)$;

k -Index for vehicles $(k = 1, 2, \ldots, K)$;

t -Index for periods $(t = 1, 2, \ldots, T)$;

- **Parameters**

d_{jt} -Demand of retailer *j* in period *t;*

h_{jt} -Unit inventory holding cost of retailer *j* at the end of period *t;*

A_p -Fixed transportation cost of vehicle type *p*;

L_j -Fixed material handling cost for retailer *j* when a vehicle visits it;

W-Maximum capacity of a vehicle for loading goods;

M-A very big number ($M = 10^{10}$ in this study);

dsr-Average distance between the supplier and retailers;

drr-Average distance between retailers;

TX-Tax on carbon emissions [$USD/kg\,CO_2$];

E_p -Carbon emission factor [$kg\,CO_2/km$] of vehicle type *p*;

- **Variables**

x_{jpkt} -Amount of products delivered to retailer *j* by vehicle *k* of type *p* in period *t*;

y_{pkt} -Amount of products delivered by vehicle *k* of type *p* in period *t*;

I_{jt} -Inventory level of retailer *j* at the end of period *t*;

$$X_{jpkt} = \begin{cases} 1 & \text{if } x_{jpkt} > 0 \\ 0 & \text{otherwise} \end{cases}$$

$$Y_{pkt} = \begin{cases} 1 & \text{if } y_{pkt} = \sum_j x_{jpkt} > 0 \\ 0 & \text{otherwise} \end{cases}$$

n_{pkt} -Amount of retailers visited by vehicle *k* of type *p* in period *t*;

vt_p -Amount of vehicles of type *p* employed in all periods;

tn_p -Total amount of retailers visited by vehicles type *p*;

- **The model**

Based on the aforementioned notations, the mixed integer programming model is presented as follows (Eqs. 1-11):

Minimize

$$\sum_p \sum_k \sum_t A_p Y_{pkt} + \sum_j \sum_p \sum_k \sum_t L_j X_{jpkt} + \sum_j \sum_t h_{jt} I_{jt}$$
$$+TX \sum_p E_p (2\,dsr\,vt_p + drr(tn_p - vt_p)) \quad (1)$$

Subject to:

$$\sum_p \sum_k x_{jpkt} + I_{j,t-1} - d_{jt} = I_{jt} \qquad \forall j,t; \tag{2}$$

$$y_{pkt} = \sum_j x_{jpkt} \ \forall p,k,t; \tag{3}$$

$$y_{pkt} \le W \ \ \forall p,k,t; \tag{4}$$

$$x_{jpkt} \le MX_{jpkt} \ \forall j,p,k,t; \tag{5}$$

$$y_{pkt} \le MY_{pkt} \ \ \forall p,k,t; \tag{6}$$

$$n_{pkt} = \sum_j X_{jpkt} \ \forall p,k,t; \tag{7}$$

$$vt_p = \sum_k \sum_t Y_{pkt} \ \forall p; \tag{8}$$

$$tn_p = \sum_k \sum_t n_{pkt} \ \ \forall p; \tag{9}$$

$$x_{jpkt}\ , I_{jt}, y_{pkt}, n_{pkt}, vt_p, tn_p \ge 0 \ \ \forall j,p,k,t; \tag{10}$$

$$X_{jpkt}\ , Y_{pkt} \ \in \{0,1\} \ \forall j,p,k,t \tag{11}$$

There are four terms in the objective function: the first indicates the sum of fixed vehicle costs; the second shows the sum of retailer-dependent material handling costs, the third demonstrates the sum of inventory holding costs and the fourth denotes carbon emission costs which is calculated by multiplying the tax on carbon emissions by the amount of carbon emitted from all vehicle types along the supply chain. Based on the distance-based method, the carbon emission factor of vehicle type *p* (E_P) is multiplied by the distance travelled by it from the supplier to the retailers and from the retailers back to the supplier ($2\,dsr\,vt_p$) in addition to the travelled distance between the retailers ($drr(tn_p - vt_p)$) which equals to the total amount of carbon emitted by vehicle type *p*. Eq. (2) illustrates the inventory balance for each retailer i.e. the sum of quantities carried to a retailer plus the inventory remaining from the previous period minus current customer demands equals to the inventory which will be carried unto the next period. Eqs. (3-4) guarantee that the quantity of products delivered by a vehicle in a defined period is not more than the vehicle's loading capacity Eqs. (5-6) satisfy the amount of binary variables. Variables defined in Eqs. (7-9) are employed for the calculation of carbon emissions in the objective function. Eqs. (10-11) designate the non-negativity and binary restrictions respectively.

3. Experimental

3.1. Definition of parameters

In this section, the carbon related parameters of the model are first defined. Factors such as the manufacturing technology of a vehicle, the kind of fuel it consumes and the number of years it has been used affect the amount of carbon it emits. The carbon emission factor of vehicle type *p* (E_p) is calculated on the basis of data taken from the Network for Transport and Environment (NTM, 2013). In their handbook, Maibach et al. (2008) have set upper recommended values for external costs on climate change (tax on carbon emissions (*TX*)) at 45 €*/ton* in 2010 and 70 €*/ton* in 2020. 50 €*/ton* is obtained by interpolating between these two values for the year 2012. As we know one ton is equal to 1000 *kg* and the exchange rate between € and *USD* is 1.4; as a result, the amount of *TX* is 0.07 *USD/kg*.

U(*x*,*y*) and *DU*(*x*,*y*) denote a uniform distribution in the interval (*x*,*y*) and a discrete uniform distribution in the interval [*x*,*y*] respectively. Assuming that:

$$\bar{d} = \sum_j \sum_t d_{jt} \,/\, JT$$

and

$$\bar{h} = \sum_j \sum_t h_{jt} \,/\, JT \ ,$$

we have defined the initial values of the parameters in Tables 2 and 3.

Table 2. Initial values of the parameters

Parameters	***Value***
d_{jt}	*DU*(200,800)
h_{jt}	*U*(5,8)
L_j	$U(0.9,1.1).\bar{h}.\bar{d}$
W	*5000*
$I_{j,0}$	*DU*(0,500)
TX	*0.07*
dsr	*120*
drr	*10*

3.2. Solution approach

Based on the parameters defined in Tables 2 and 3, some problems have been randomly generated to clarify this model. All analyses have been performed using ILOG CPLEX 12.2.0.1 MIP solver within the GAMS modeling language running on a 4 GB memory computer with Intel core 2 duo 2.8 GHz processor. The flowchart provided in Fig. 2 illustrates how the model is solved.

Table 3. Parameters related to carbon emissions

Vehicle type (p)	E_p	A_p
Vehicle type 1	0.252	$1.25 \sum_j L_j / J$
Vehicle type 2	0.532	$\sum_j L_j / J$
Vehicle type 3	1.035	$0.75 \sum_j L_j / J$

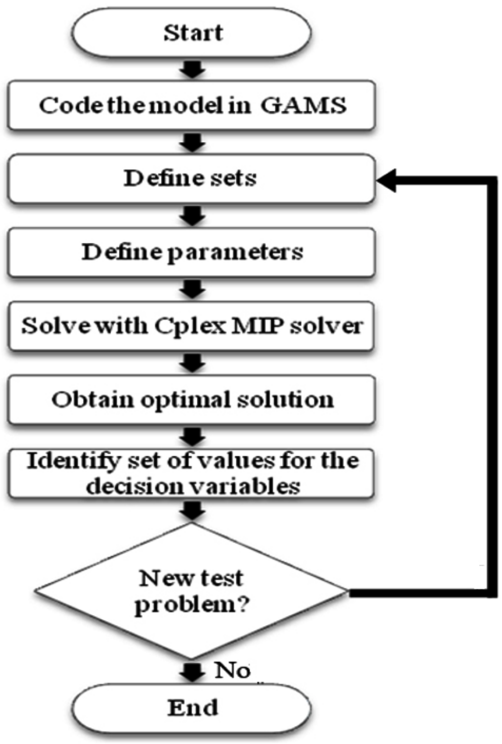

Fig. 2. Flowchart of solution method

Firstly, we solve the model for (*J*, *T* ,*K*) = (10, 10, 10) and after altering the amount of retailers(*J*), periods(*T*) and carbon tax (*TX*) as well as the distances of *dsr* and *drr*, we examine the results. In the case where (*J*, *T*, *K*) = (10, 10, 10), the number of equations, variables and discrete variables are respectively 7638, 7038 and 3300 and these numbers change to 38138, 37538 and 18300 when (*J*, *T*, *K*) = (60, 10, 10) and if (*J*, *T*, *K*) = (10, 60, 10), then these numbers increase to 45788, 42188 and 19800. This shows the complexity of the problem which increases the time required for reaching a solution. For instance, the elapsed time for obtaining a solution with a relative gap of 0.5 percent for (*J*, *T*, *K*) = (60, 10, 10) is 5h.42min.16 sec.; whereas for (*J*, *T*, *K*) = (10, 60, 10) it amounts to 7h.55min.43sec.

4. Results and discussion

In this section, based on the parameters and the procedure provided in the previous section, the following scenarios will be discussed with the help of randomly generated problems:

- changes in the amount of retailers
- changes in the number of periods
- changes in the amount of tax
- changes in distances only the final results related to carbon emissions are registered in the tables and figures and will be subsequently analyzed.

Table 4 depicts that an increase in the number of retailers (more than 50), leads consequently to the augmentation of the cost of carbon emission (*CC*) as well as the total cost (*TC*) and this initiates the supplier's use of lower carbon vehicle types. The percentage of the ratio of *CC* to *TC* has a decreasing trend and amounts to less than 0.1 which is very low but by employing low carbon vehicles, this amount decreases even more. By calculating (*CC /TX*), when there are 10 retailers, the amount of carbon emitted is equal to 3312 kg and when we have 60 retailers this amount increases to 18032.271kg. The average amount of carbon emitted by each retailer along the supply chain is obtained by dividing the total amount of carbon emitted (*CC /TX*) by the number of retailers which is shown in Fig. 3. It demonstrates that the average amount of carbon emitted has a decreasing trend when there are more retailers and, in the case, where there are 50 retailers, this amount reaches a minimum. It is clear that the trend of changes we see in Fig. 4, that illustrates the percentage of carbon emission cost to the total cost, is very similar to Fig. 3. These two figures both represent fractions the numerators of which are multiples of each other. Therefore, we may conclude that there is a direct relationship between the denominators of these two fractions which means that the relationship between the amount of retailers and the total cost is direct.

The results related to an increase in the number of periods are listed in Table 5. One can observe that if the number of periods exceeds 25, the supplier will also make use of lower carbon vehicle types for the transportation of products. With the augmentation of *TC* and *CC* however, (*100.CC/TC*) does not surpass 0.1. The amount of carbon emitted throughout the supply chain divided by the number of periods is equal to the average amount of carbon emitted within each period which is shown in Fig. 5. A glance at Fig. 5 makes it clear that although lower vehicle types have not been used, the lowest amount of carbon emissions for each period occurs in the 15-period planning. One can thus deduce that it is best to opt for this planning horizon.

Table 4. The effect of the number of retailers on carbon emissions

J		*T*	*K*	vt_1	vt_2	vt_3	*Total cost(TC)*	*Carbon emission cost(CC)*	*100.CC / TC*
10		10	10	0	0	11	282966.1	231.8	0.0819
15		10	10	0	0	16	426649.7	336.2	0.0788
20		10	10	0	0	20	570268.3	429.6	0.0753
25		10	10	0	0	26	733806.1	555.7	0.0757
30		10	10	0	0	30	882429.3	644.1	0.0730
40		10	10	0	0	41	1186835.7	870.9	0.0734
50		10	10	1	4	46	1525986.3	1025.0	0.0672
60		10	10	3	8	55	1823898.1	1262.3	0.0692

Table 5. The effect of the number of periods on carbon emissions

J	*T*	*K*	vt_1	vt_2	vt_3	*Total cost(TC)*	*Carbon emission cost(CC)*	*100.CC / TC*
10	10	10	0	0	11	282966.1	231.8	0.0819
10	15	10	0	0	15	423400.5	320.2	0.0756
10	20	10	0	0	21	577816.9	445.6	0.0771
10	25	10	0	1	27	744141.1	577.0	0.0775
10	30	10	1	0	33	895295.3	693.0	0.0774
10	40	10	1	1	43	1190559.9	912.1	0.0766
10	50	10	1	2	55	1516865.4	1136.5	0.0749
10	60	10	0	4	64	1831249.3	1379.9	0.0754

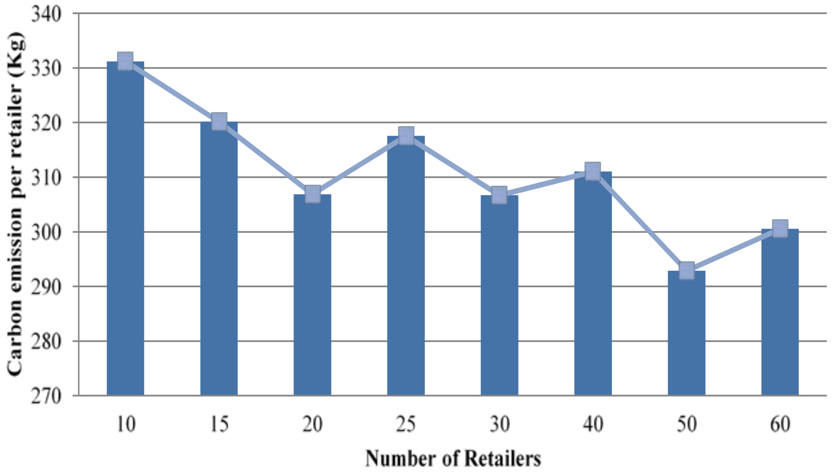

Fig. 3. Average amount of carbon emissions per retailer

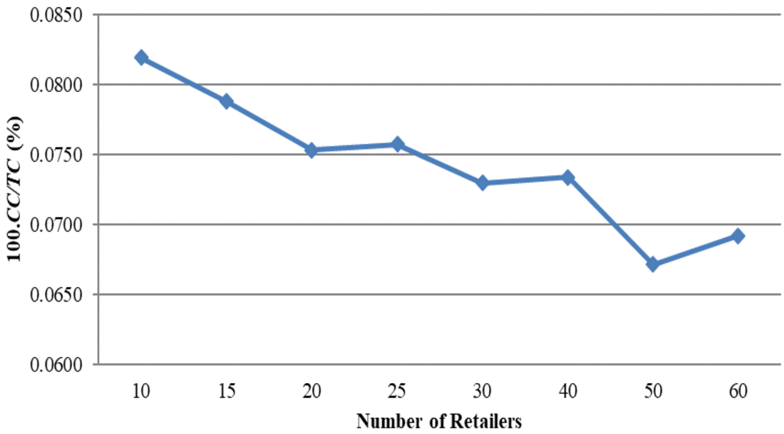

Fig. 4. Percentage of carbon emission cost to total cost

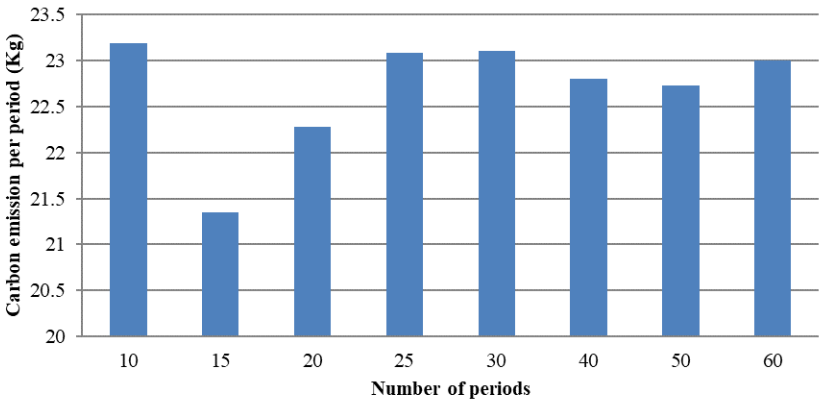

Fig. 5. Average amount of carbon emissions per period

While *TX* rises as depicted in Table 6, *CC* and *TC* increase as well but since (*100.CC/TC*) increases too so the increasing gradient of *CC* is more than that of *TC*. As we can observe, with a 64-fold increase in carbon tax, the supplier tends to use lower carbon vehicle types. Furthermore, in Table 6, the differences in the amounts of carbon emitted in cases that only make use of vt_3, is related to the total number of retailers that the vehicles visit. For instance, when *TX* is equal to 0.07, then $tn_3 = 67$ but when *TX* is equal to 0.28 then $tn_3 = 64$.

To understand the impact that changes in the distances between the supplier and retailers on the one hand and between retailers on the other have on carbon emissions we first increase the amount of *dsr* before subsequently increasing the amount of *drr*. The outcome of these changes is registered in Table 7, which shows that as distances increase, both the amount and the cost of carbon emissions are on the rise; as for the total cost it does not increase much because the carbon tax is very low as a result of which, the type of vehicles dispatched does not alter.

Increases in the tax for long distances affect costs and the vehicle types dispatched as Table 8 illustrates. With an 8-fold increase in the amount of tax or more, lower carbon vehicle types are used in the combination of the vehicles used by the supplier, but when *TX* reaches 2.24, it only employs vt_1 and not vt_2 and vt_3. Before summing up, it is necessary to stress a few important points:

- For the purpose of minimizing costs, a combination of different vehicle types is used to deliver products. It should be emphasized that this combination of different vehicle types does not result from a shortage of any of the vehicle types. In other words, the supplier is free to select as many vehicles from any type which he wishes to. For instance, the worst case of all the instances provided in Table 9 is when (*J*, *T*, *K*) = (60, 10, 10), where only 8 vehicles of vehicle type 3 are employed in period 6.
- We would like to suggest a few reasons why (*100.CC/TC*) in Tables 4 to 8 is an insignificant amount. One reason may be that, in order to simplify this model, the amount of carbon emitted in the inventory and replenishment handling sectors have not been taken into account. Another reason may be the fact that governments have not yet legislated regulations that aim at setting a reasonable amount for *TX*.
- As Tables 6 and 8 indicate, high rates of *TX* result in a significant decrease in the amount of carbon emitted; whereas the total cost of the supply chain does not increase considerably.

Table 6. The effect of the amount of carbon tax on carbon emissions

J	*T*	*K*	vt_1	vt_2	vt_3	*Total cost(TC)*	*Carbon emission cost(CC)*	*100.CC / TC*	*CC /TX*	*TX*
10	10	10	0	0	11	282966.1	231.8	0.0819	3312	0.07
10	10	10	0	0	11	283198.0	463.7	0.1637	3312	0.14
10	10	10	0	0	11	284223.3	918.7	0.3232	3281	0.28
10	10	10	0	0	11	284589.0	1854.7	0.6517	3312	0.56
10	10	10	0	0	11	286620.3	3674.7	1.2821	3281	1.12
10	10	10	0	0	11	288298.5	5564.2	1.9300	3312	1.68
10	10	10	0	0	11	290346.4	7349.3	2.5312	3281	2.24
10	10	10	0	1	10	297667.5	14046.5	4.7188	3135	4.48
10	10	10	1	10	0	310329.6	14430.6	4.6501	1611	8.96

Table 7. The effect of the distance between supplier and retailers and among retailers on carbon emissions

J	*T*	*K*	vt_1	vt_2	vt_3	*Total cost(TC)*	*Carbon emission cost(CC)*	*100.CC / TC*	*CC /TX*	*TX*	*dsr*	*drr*
10	10	10	0	0	11	282966.1	231.8	0.0819	3312	0.07	120	10
10	10	10	0	0	11	283061.8	327.5	0.1157	4678	0.07	180	10
10	10	10	0	0	11	283157.4	423.1	0.1494	6044	0.07	240	10
10	10	10	0	0	11	283293.6	559.3	0.1974	7990	0.07	300	20
10	10	10	0	0	11	284015.2	1280.9	0.4510	18299	0.07	600	80

Table 8. The effect of the amount of carbon tax on carbon emissions for long distances

J	*T*		*K*	vt_1	vt_2	vt_3	*Total cost(TC)*	*Carbon emission cost(CC)*	*100.CC / TC*	*CC /TX*	*TX*	*dsr*	*drr*
10	10		10	0	0	11	284015.2	1280.9	0.4510	18299	0.07	600	80
10	10		10	1	1	9	293998.7	8875.8	3.0190	15850	0.56	600	80
10	10		10	3	4	4	301298.9	12256.1	4.0678	10943	1.12	600	80
10	10		10	5	6	0	305268.8	11824.0	3.8733	7038	1.68	600	80
10	10		10	11	0	0	309686.7	9980.0	3.2226	4455	2.24	600	80

Table 9. Number of vehicles of each type dispatched when (*J*, *T*, *K*) = (60, 10, 10)

Period(*t*)		**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	vt_p
Number of Vehicle type (*p*)	**1**	0	0	0	2	0	0	0	0	0	1	**3**
	2	0	1	0	0	0	0	5	1	1	0	**8**
	3	7	6	5	5	6	8	1	5	6	6	**55**
Sum of vehicles (of all types) in period(*t*)		7	7	5	7	6	8	6	6	7	7	**66**

5. Conclusions

This paper aims at coordinating transportation and inventory planning decisions, while laying stress on environmental concerns in a two-echelon supply chain and focusing specifically on carbon emission costs. In order to do so, three different types of vehicles were taken in to consideration with different amounts of carbon emissions. We developed a novel MIP model with the help of the distance-based method to calculate the amount of carbon footprint. In the model under consideration, goods can be delivered by one or more vehicles based on each retailer’s demand in every period. The ultimate aim is to diminish fixed vehicle and material handling costs as well as inventory holding and carbon emission costs.

By changing distances, the amount of retailers and periods as well as the rate of tax, different scenario analyses were conducted. The results of which show that there is a direct relationship between an increase in the number of retailers and the time of replenishment with the supplier’s tendency to select lower carbon vehicle types. Furthermore, an increase in the rate of carbon tax and in the distances between members of the supply chain results in an augmentation of costs related to carbon emissions and the usage of low carbon vehicle types. Consequently, one can considerably reduce the carbon footprint throughout the supply chain by merely altering operational decisions without drastically increasing the other costs the supply chain entails.

This research can be extended in a number of different directions: one is to take the carbon footprint of the inventory and handling sectors of the supply chain into consideration as well. Another would be to consider the weight and volume for products as well as for the loading capacity of heterogeneous vehicles, using the fuel-based method in order to calculate the costs of carbon emissions.

This study confined itself to the analysis of carbon emissions related to a one-item supply chain, but this model has the potential to be expanded to multi-item supply chains as well. The development of meta-heuristic solution methods to solve such problems in large scales is yet another suggestion for further studies.

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References

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

Arshinder, Kanda A., Deshmukh S.G., (2008), Supply chain coordination: Perspectives, empirical studies and research directions, *International Journal of Production Economics*, **115**, 316-335.

Benjaafar S., Li Y., Daskin M., (2013), Carbon footprint and the management of supply chains: Insights from simple models, *IEEE Transactions on Automation Science and Engineering*, **10**, 99-116.

Chaabane A., Ramudhin A., Paquet M., (2012), Design of sustainable supply chains under the emission trading scheme, *International Journal of Production Economics*, **135**, 37-49.

Elhedhli S., Merrick R., (2012), Green supply chain network design to reduce carbon emissions, *Transportation Research Part D: Transport and Environment*, **17**, 370-379.

EPA, (2012), Fast Facts: U.S. Transportation sector Greenhouse Gas emissions 1990-2010, Office of Transportation and Air Quality, EPA-420-F-12-063, U.S. Environmental Protection Agency, Washington, D.C., On line at: http://www.epa.gov/otaq/climate/measuring.htm.

Gajanand M.S., Narendran T.T., (2013), Green route planning to reduce the environmental impact of distribution, *International Journal of Logistics Research and Applications*, **16**, 410-432.

Harris I., Mumford C.L., Naim M.M., (2014), A hybrid multi-objective approach to capacitated facility location with flexible store allocation for green logistics modeling, *Transportation Research Part E: Logistics and Transportation Review*, 66, 1-22.

Kang J., Kim Y., (2010), Coordination of inventory and transportation managements in a two-level supply chain, *International Journal of Production Economics*, **123**, 137-145.

Konur D., (2014), Carbon constrained integrated inventory control and truckload transportation with heterogeneous freight trucks, *International Journal of Production Economics*, **153**, 268-279.

Kwon Y., Choi Y., Lee D., (2013), Heterogeneous fixed fleet vehicle routing considering carbon emission, *Transportation Research Part D: Transport and Environment*, **23**, 81-89.

Lin C., Choy K.L., Ho G.T.S., Chung S.H., Lam H.Y., (2014), Survey of Green Vehicle Routing Problem: Past and future trends, *Expert Systems with Applications*, **41**, 1118-1138.

Maibach M., Schreyer C., Sutter D., Van Essen H.P., Boon B.H., Smokers R., Schroten A., Doll C., Pawlowska B., Bak M., (2008), *Handbook on Estimation of External Costs in the Transport Sector*, Version 1.1, Delft, Netherlands.

Mirzapour Al-e-hashem S.M.J., Rekik Y., (2014), Multi-product multi-period Inventory Routing Problem with a transshipment option: A green approach, *International Journal of Production Economics* **157**, 80-88.

NTM, (2013), Network for Transport and Environment, Stockholm, Sweden, On line at: http://www.ntmcalc.org/Magellan/render/.

Paksoy T., Pehlivan N.Y., Özceylan E., (2012), Fuzzy multi-objective optimization of a green supply chain network with risk management that includes environmental hazards, *Human and Ecological Risk Assessment: An International Journal*, **18**, 1120-1151.

Pinto-Varela T., Barbosa-Póvoa A.P.F.D., Novais A.Q., (2011), Bi-objective optimization approach to the design and planning of supply chains: Economic versus environmental performances, *Computers and Chemical Engineering*, **35**, 1454- 1468.

Quariguasi Frota Neto J., Bloemhof-Ruwaard J.M., Van Nunen J.A.E.E., Van Heck E., (2008), Designing and evaluating sustainable logistics networks, *International Journal of Production Economics*, **111**, 195-208.

Ramudhin A., Chaabane A., Paquet M., (2010), Carbon market sensitive sustainable supply chain network design, *International Journal of Management Science and Engineering Management*, **5,** 30-38.

Sadegheih A., Drake P.R., Li D., Sribenjachot S., (2011), Global supply chain management under the carbon emission trading program using mixed integer programming and genetic algorithm, *IJE Transactions B: Applications*, **24**, 37-53.

Seuring S., (2013), A review of modeling approaches for sustainable supply chain management, *Decision Support Systems*, **54**, 1513-1520.

Soysal M., Bloemhof-Ruwaard J.M., van der Vorst J.G.A.J., (2014), Modelling food logistics networks with emission considerations: The case of an international beef supply chain, *International Journal of Production Economics*, **152**, 57-70.

Treitl S., Nolz P.C., Jammernegg W., (2014), Incorporating environmental aspects in an inventory routing problem. A case study from the petrochemical industry, *Flexible Services and Manufacturing Journal*, **26**, 143-169.

Ubeda S., Arcelus F.J., Faulin J., (2011), Green logistics at Eroski: A case study, *International Journal of Production Economics*, **131**, 44-51.

Validi S., Bhattacharya A., Byrne P.J., (2014a), A case analysis of a sustainable food supply chain distribution system - A multi-objective approach, *International Journal of Production Economics*, **152**, 71-87

Validi S., Bhattacharya A., Byrne P.J., (2014b), A solution method for A two-layer sustainable supply chain distribution model, *Computers & Operations Research*.

Wang F., Lai X., Shi N., (2011), A multi-objective optimization for green supply chain network design, *Decision Support Systems*, **51**, 262-269.

WRI, (2011), Guidance for Calculating Scope 3 Emissions (Draft), World Resources Institute & World Business Council for Sustainable Development, On line at: http://www.ghgprotocol.org/standard/scope-3-standard

Xue Y., Irohara T., (2010), A time-space network based international transportation scheduling problem incorporating CO_2 emission levels, *Journal of Zhejiang University SCIENCE A*, **11**, 927-932.

Zeng W., Wang C., Zhou H., (2012), *Study on supply chain operations under carbon emission regulatory policies*, Proc. of Int. Conf. on Information Management. Innovation Management and Industrial Engineering, **2**,506-509.

Zhang Q., Shah N., Wassick J., Helling R., van Egerschot P., (2014), Sustainable supply chain optimisation: An industrial case study, *Computers & Industrial Engineering*, **74**, 68-83.