Available online at www.sciencedirect.com
ScienceDirect
Procedia CIRP 26 (2015) 335 – 340
www.elsevier.com/locate/procedia

12th Global Conference on Sustainable Manufacturing

The Impact of Carbon Policies on Closed-Loop Supply Chain Network Design

M. Fareeduddin[a]*, Adnan Hassan[a], M. N. Syed[b], S. Z. Selim[b]

[a]*Universiti Teknologi Malaysia, UTM Skudai, 81310 Johor,Malaysia.*
[b]*King Fahd University of Petroleum and Minerals, Dhahran 31261, Saudi Arabia*
* Corresponding author. Tel.:+966-13-860-7453; fax: +966-13-860-2965. *E-mail address:* fareeduddinm@gmail.com

Abstract

Due to increase in environmental concerns along with stringent government legislations, forcing industry practitioners and policy makers to take a fresh look at the impact of their supply chain activities on the environment. Various carbon regulatory mechanisms have been proposed by governmental agencies around the globe, which aims to curb the carbon emission. In this paper, optimization models based on carbon regulatory policies for a closed-loop supply chain design and logistics operations are presented. Specifically, the following three common regulatory policies are considered: strict carbon caps, carbon tax, and carbon cap-and-trade. The proposed models optimize not only costs but also emissions in the supply chain operations. The models capture: the trade-offs that exist between location and transportation modes decisions; and the trade-offs between costs and emissions in the supply chain operations. Numerical experiment illustrates different policies and their impact on the costs and the effectiveness of emission reduction. The results from the models can help policy makers to predict the impact of regulatory policies on overall emissions in the supply chain operations.

Peer-review under responsibility of Assembly Technology and Factory Management/Technische Universität Berlin.

Keywords: Carbon emissions; Carbon footprint; Carbon policies; Closed-loop supply chain; Transportation; Mixed integer linear programming;

1. Introduction

A supply chain in which forward and reverse supply chain activities are integrated is referred to as closed-loop supply chain (CLSC). There are five main reasons that motivates manufacturers to focus towards CLSC; customer awareness, social responsibilities, environmental concerns, governmental legislation, waste management. In the past, CLSC used to be an undesirable constraint but now it is an acceptable necessity, and remarkably, it will be the only remedy to sustain in the future. Supply chain which considers both economic and environmental prospective is called green supply chain, and by the integration of forward supply chain and reverse supply chain (collection, recovery, recycling of used products and safe disposals of scrapped products) is called green closed loop supply chain (GrCLSC). One dimension of mitigating environmental impacts and produce environmental friendly products is through green supply chain. The growing importance of GrCLSC stems not only from the economic benefits of product recovery but also from governmental legislative initiatives.

Supply chain activities are significant source of greenhouse gases (GHG) emissions such as carbon dioxide, methane, ozone, and other greenhouse gases. Government agencies across the world are under growing pressure to pass legislation to limit the amount of GHG emissions and pay attention to develop the environmental strategies including the Kyoto Protocol [1], the European Union Emission Trading System [2] among others. Kyoto Protocol was negotiated in 1997 by countries all over the world as a part of the United Nations Framework Convention on Climate Change to curb GHG emissions. As of May 2008, 181 countries had ratified, adhered or accepted the protocol [3].

The main objective of this paper is to propose optimization models for a CLSC design problem that is able to (1) consider both economic and environmental aspects when designing a logistics network, (2) integrate location, production technology and transportation mode selection related decisions, (3) investigate the impact of the three most common carbon regulatory policies such as carbon cap, carbon tax, and carbon cap-and-trade on supply chain operations.

Peer-review under responsibility of Assembly Technology and Factory Management/Technische Universität Berlin.
doi:10.1016/j.procir.2014.07.042

2. Literature Review

The configuration of supply chain network design (SCND) is one of the crucial strategic decisions in the SCM planning activities that have received growing attention from researchers and industries since early 20s [4]. Fleischmann et al. [5] proposed MILP formulation of CLSC network problem considering product recovery issues in the reverse flow.

Incorporating environmental performance measures in order to mitigate the environmental issues of supply chains induces green SCM [6]. According to the comprehensive review on green SCM by Srivastava [7], two types of greenness are considered in the literature: green design for products and green operations. Our research considers green operations, which are mainly composed of green production by selecting suitable technologies available to use, reverse logistics by collecting end of life products, recycling and safe disposals of scrapped products. Paksoy et al. [8] considered a CLSC network that focus on the cost of transportation activities and their GHG emissions. They investigated the trade-off between operational and environmental performance measures. Abdallah et al. [9] analysed the impact of carbon emissions on SCND and supplier selection using LCA approach. Diabat and Simichi-Levi [10] formulated a MIP for a firm to design their optimal supply chain network while meeting their carbon cap. Chaabane et al. [11] studied the impact of carbon emissions on the design of sustainable CLSC network based on LCA principles. Their model is used to evaluate the tradeoffs between economic and environmental objectives under various cost and operating strategies in the aluminium industry. Diabat et al. [12] studied the issues of facility location problem in CLSC with trading of carbon emission and a cost of procurement. Fahimnia et al. [13] developed a unified MILP model for a CLSC in which carbon foot print is evaluated based on the influence of forward and reverse supply chain, where carbon emissions are expressed in terms of dollar carbon cost.

Recently, Benjaafar et al. [14] proposed optimization models for supply chain operational decision making i.e., lot sizing and EOQ under various carbon regulatory mechanisms. They investigated the impact of these policies on operational decisions. Jin et al. [15] proposed optimization models for major retailers and investigated the impact of the carbon policies on supply chain strategic and transportation mode selection decisions.

3. Model Formulation

3.1 Problem Description

A general CLSC network under investigation is shown in Fig 1. It consists of three layers in the forward direction (manufacturing plants, distribution centers, and customers) and three layers in reverse direction (collection centers, recycling centers, and disposal centers).

In the forward chain, multiple product types $l \in L$ are produced in different manufacturing plants $p \in P$ using a set of technologies $t \in T$.

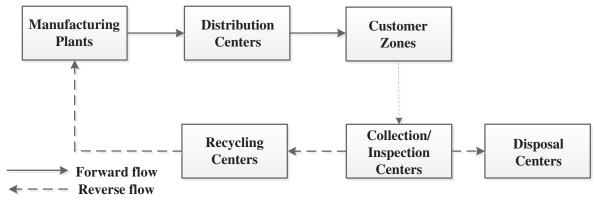

Fig. 1: A general closed-loop logistic network

Manufacturing plant has its own production cost and carbon emission rate for processing one unit of product. In each plant, a set of potential technologies are available to use differ in terms of acquisition and operation costs as well as carbon emission rate. Finished products are shipped to customer zones or markets $c \in C$ through a set of distribution centers $q \in Q$. Different transportation modes $m \in M$ are available to use for shipment of products between the facilities (plants, distribution centers, customers, collection centers, recycling centers, and disposals) with different prices and fuel efficiency rates. In the reverse supply chain network, the end of use or end of life products are collected by the collection centers $k \in K$ where they first disassembled into components, and then they are inspected and separated into recyclable and non-recyclable components. Recyclable components are sent to recycling centers $r \in R$ for further processing, recycled components are then shipped to the plants for reuse in producing new products. The non-recyclable components are destroyed at disposal centers $w \in W$.

3.2 Model Assumptions

The following assumptions will be made in the network configuration:

i. Number, capacity and potential location plants, distribution centers, collection centers, recycling centers, and disposals are known.
ii. Number, location of customer zones are known and predetermined.
iii. Demand of all products is known (deterministic).
iv. Return products rate for each customer zone and average disposal rate are known in advance.
v. Flows are permitted between two consecutive stages. Also, there are no flows between facilities at the same stage.
vi. Emissions for processing the products at facilities and emissions for shipping the products from plants to end users are determined, which is based on the type of technology used in plants and type of transportation mode is used in transport.

To describe the aforementioned CLSC network, indices, input parameters, and decision variables used in formulating the MILP models are presented in Appendix.

3.3 Model formulation of the CLSC network without carbon emission consideration

<u>*Cost-only Model (M1)*</u>

In the following cost only model, strategic and operational decisions are solely based on economic performance. The objective of the cost-only model is to minimize the total expected cost of CLSC.

Total expected cost = Fixed cost + Production cost + (Collection and Inspection cost) + recycling cost + Transportation cost + Disposal cost;

Minimize $Z_1 = Z_{11} + Z_{12} + Z_{13} + Z_{14} + Z_{15} + Z_{16}$; (1)

Fixed cost: Z_{11} =

$$\sum_{p,t} FI_{p,t}\, ZI_{p,t} + \sum_{q} FJ_q\, ZJ_q + \sum_{k} FU_k\, ZU_k + \sum_{r} FV_r\, ZV_r + \sum_{w} FY_w\, ZY_w$$

Production cost: $Z_{12} = \sum_{p,l,t} CI_{p,l,t}\, QI_{p,l,t}$

Collection and Inspection cost: $Z_{13} = \sum_{c,k,l,m} CU_{k,l}\, QAU_{c,k,l,m}$

Recycling cost: $Z_{14} = \sum_{r,p,l,m} CV_{r,l}\, QVI_{r,p,l,m}$

Disposal cost: $Z_{15} = \sum_{k,w,l,m} CY_{w,l}\, QUY_{k,w,l,m}$

Transportation cost: Z_{16} =

$$\sum_{p,q,l,m} CIJ_{p,q,l,m}\, QIJ_{p,q,l,m} + \sum_{q,c,l,m} CJA_{q,c,l,m}\, QJA_{q,c,l,m} + \sum_{c,k,l,m} CAU_{c,k,l,m}\, QAU_{c,k,l,m} + \sum_{k,r,l,m} CUV_{k,r,l,m}\, QUV_{k,r,l,m} + \sum_{r,p,l,m} CVI_{r,p,l,m}\, QVI_{r,p,l,m} + \sum_{k,w,l,m} CUY_{k,w,l,m}\, QUY_{k,w,l,m}$$

Constraints

The following are the constraints of the model (M1):

$$\sum_{t} QI_{p,l,t} = \sum_{q,m} QIJ_{p,q,l,m} \quad \forall p,l \qquad (1.1)$$

$$\sum_{p,m} QIJ_{p,q,l,m} = \sum_{c,m} QJA_{q,c,l,m} \quad \forall q,l \qquad (1.2)$$

$$\sum_{q,m} QJA_{q,c,l,m} = D_{c,l} \quad \forall c,l \qquad (1.3)$$

$$\sum_{k,m} QAU_{c,k,l,m} = D_{c,l}\, \alpha_l \quad \forall c,l \qquad (1.4)$$

$$\sum_{w,m} QUY_{k,w,l,m} = \sum_{c,m} \gamma_l\, QAU_{c,k,l,m} \quad \forall k,l \qquad (1.5)$$

$$\sum_{c,m} QAU_{c,k,l,m} = \sum_{w,m} QUY_{k,w,l,m} + \sum_{r,m} QUV_{k,r,l,m} \quad \forall k,l \qquad (1.6)$$

$$\sum_{p,m} QVI_{r,p,l,m} = \sum_{k,m} QUV_{k,r,l,m} \quad \forall r,l \qquad (1.7)$$

$$\sum_{q,m} QVI_{r,p,l,m} \le \sum_{t} QI_{p,l,t} \quad \forall p,l \qquad (1.8)$$

$$\sum_{l} S_l\, QI_{p,l,t} \le SI_{p,t}\, ZI_{p,t} \quad \forall p,t \qquad (1.9)$$

$$\sum_{p,l,m} S_l\; QIJ_{p,q,l,m} \le SJ_q\, ZJ_q \quad \forall q \qquad (1.10)$$

$$\sum_{c,l,m} S_l\; QAU_{c,k,l,m} \le SU_k\, ZU_k \quad \forall k \qquad (1.11)$$

$$\sum_{k,l,m} S_l\; QUV_{k,r,l,m} \le SV_r\, ZV_r \quad \forall r \qquad (1.12)$$

$$\sum_{k,l,m} S_l\; QUY_{k,w,l,m} \le SY_w\, ZY_w \quad \forall w \qquad (1.13)$$

$$\sum_{t} ZI_{p,t} \le 1 \quad \forall p \qquad (1.14)$$

$$QIJ_{p,q,l,m}, QJA_{q,c,l,m}, QAU_{c,k,l,m}, QUV_{k,r,l,m}, QUY_{k,w,l,m}, QVI_{r,p,l,m} \ge 0$$

$$\&\;\; ZI_{p,t}, ZU_k, ZV_r, ZY_w \in \{0,1\} \qquad (1.15)$$

The cost-only model for CLSC network design is defined by Equations (1) – (1.15). It is a traditional minimum cost logistic network model where the objective function minimizes fix cost of opening facilities, production cost, collection/inspection cost, recycling cost, disposal cost, and transportation cost. Constraint (1.1) states that, sum of the exiting flow from each plant does not exceed its production quantity; Constraint (1.2) ensures that, sum of exiting flow quantity at each distribution center does not exceed the entering flow quantity to each distribution center; constraint (1.3) ensures to satisfy customer's demand i.e., the sum of exiting flow of each product from distribution center must be satisfied the demand of customer. Constraint (1.4) represents the relationship between customer's demand and product return rate at collection center. Constraint (1.5) describes the relationship between scrapped product quantity and collection of returned products in collection center. Constraint (1.5) states that flow entering at each disposal center is equal to the flow exiting at each collection center multiplied by fixed percentage of product scrap. Constraint (1.6) product flow entering and exiting the collection center (node balance equation at collection center). Constraint (1.7) represents balance equation of products entering and exiting recycling center. Constraint (1.8) states that flow exiting at each recycling center does not exceed the production quantity at each plant. Constraint (1.9) states that, production quantity in each planning horizon at each plant does not exceed its production capacity; Constraint (1.10) ensures that, sum of entering flow at distribution center does not exceed its capacity; constraint (1.11) ensures that, sum of the flow of collection of returned products does not exceed the collection center's capacity. Constraint (1.12) ensures that the sum of exiting flow of recyclable product capacity does not exceed recycling center's capacity. Constraint (1.13) state that sum of the flow of scrapped product capacity exiting each collection center does not exceed the disposal center. Constraint (1.14) ensures that at each potential location of plants, at most one technology type can be established. Finally, constraint (1.15) states the restriction on domain for all the variables.

4. Model Extension with Carbon Emission Considerations

This section presents three extensions of the CLSC model formulation to capture the impact that different carbon regulatory policies have on the CLSC design and logistics decisions. These policies include 1) carbon cap where firms are subject to mandatory caps on the amount of carbon they emit; 2) carbon tax where firms are taxed on the amount of emissions they emit; and 3) carbon cap-and-trade where firms are subject to carbon caps but are rewarded (penalized) for emitting less (more) than their caps.

Only carbon dioxide emissions from the supply chain activities are considered, since they contribute more than 95% of the total greenhouse gas emissions.

4.1 Model Formulation of Carbon Cap Policy

Under this policy, firm has a limited amount of carbon allowances to use, which is referred to as the carbon cap to the firm and denoted by C^{cap} (in kgs). By adding an additional Constraint (2.1), Model M1 is referred to as Model M2. Constraint (2.1) represents sum of emissions within the facilities, and emissions due to logistic activities, less than or equals to the amount of carbon cap imposed.

Model M2:

Minimize $Z_2 = Z_1$ (2)

Subject to:

Constraints (1.1) – (1.15) and

$$\sum_{p,l,t} EI_{p,l,t}\ ZI_{p,t} + \sum_{q,l} EJ_{q,l}\ ZJ_q + \sum_{k,l} EU_{k,l}\ ZU_k + \sum_{r,l} EV_{r,l}\ ZV_r + \sum_{p,q,l,m} EIJ_{p,q,l,m}\ QIJ_{p,q,l,m} + \sum_{q,c,l,m} EJA_{q,c,l,m}\ QJA_{q,c,l,m} + \sum_{c,k,l,m} EAU_{c,k,l,m}\ QAU_{c,k,l,m} + \sum_{k,r,l,m} EUV_{k,r,l,m}\ QUV_{k,r,l,m} + \sum_{r,p,l,m} EVI_{r,p,l,m}\ QVI_{r,p,l,m} + \sum_{k,w,l,m} EUY_{k,w,l,m}\ QUY_{k,w,l,m} \le C^{cap} \quad (2.1)$$

4.2 Model Formulation of Carbon Tax Policy

This policy is an alternative to strict carbon cap policy. Under this policy, instead of putting strict caps on emissions as in carbon cap policy, no restriction on emissions but penalizes emissions using a carbon tax (financial penalty per unit of CO_2 emission in supply chain operations). The tax is a financial penalty (δ) which assumes a linear relationship between emissions and carbon tax.

Model M3:

Minimize $Z_3 = Z_1 + \delta\ (Z_{31} + Z_{32})$ (3)

Subject to: Constraints (1.1) – (1.15)

Where

$$Z_{31} = \sum_{p,l,t} EI_{p,l,t}\ ZI_{p,t} + \sum_{q,l} EJ_{q,l}\ ZJ_q + \sum_{k,l} EU_{k,l}\ ZU_k + \sum_{r,l} EV_{r,l}\ ZV_r\ ;$$

$$Z_{32} = \sum_{p,q,l,m} EIJ_{p,q,l,m}\ QIJ_{p,q,l,m} + \sum_{q,c,l,m} EJA_{q,c,l,m}\ QJA_{q,c,l,m} + \sum_{c,k,l,m} EAU_{c,k,l,m} QAU_{c,k,l,m} + \sum_{k,r,l,m} EUV_{k,r,l,m}\ QUV_{k,r,l,m} + \sum_{r,p,l,m} EVI_{r,p,l,m}\ QVI_{r,p,l,m} + \sum_{k,w,l,m} EUY_{k,w,l,m}\ QUY_{k,w,l,m}$$

This model is similar to the original cost-only Model (M1) except that the costs of emissions due to activities at facilities (Z_{31}) and the cost of emissions due to transportation between the facilities (Z_{32}) are changed after incorporating different carbon emission costs on both facilities and the logistics network.

4.3 Model Formulation of Carbon Cap-and-Trade Policy

This policy is an alternative to either hard carbon cap or carbon tax policy. Under this policy, firms are allowed to trade their carbon allowances i.e., if a firm emits less than its prescribed carbon cap then it allows to sell unused amount of carbon emission. Similarly, if a firm emits more than its prescribed carbon cap then it can purchase additional carbon emission in order to maintain its supply chain activities. In this model e^+ and e^- are the two new variables representing amount of selling and buying carbon in kgs.

Model M4:

Minimize $Z_4 = Z_1 - p^+e^+ + p^-e^-$ (4)

Subject to:

$$\sum_{p,l,t} EI_{p,l,t}\ ZI_{p,t} + \sum_{q,l} EJ_{q,l}\ ZJ_q + \sum_{k,l} EU_{k,l}\ ZU_k + \sum_{r,l} EV_{r,l}\ ZV_r + \sum_{p,q,l,m} EIJ_{p,q,l,m}\ QIJ_{p,q,l,m} + \sum_{q,c,l,m} EJA_{q,c,l,m}\ QJA_{q,c,l,m} + \sum_{c,k,l,m} EAU_{c,k,l,m}\ QAU_{c,k,l,m} + \sum_{k,r,l,m} EUV_{k,r,l,m}\ QUV_{k,r,l,m} + \sum_{r,p,l,m} EVI_{r,p,l,m}\ QVI_{r,p,l,m} + \sum_{k,w,l,m} EUY_{k,w,l,m}\ QUY_{k,w,l,m} + e^- \le C^{cap} + e^+ \quad (4.1)$$

Constraints (1.1) – (1.15) & $e^+, e^- \geq 0$; (4.2)

5. Computational Results

In this section, a numerical example is presented in order to test the applicability of the proposed models. Consider two plants (P=2), responsible to produce four different types of products (L=4), using two technologies options at each plant (T=2). Assuming that technology one has less investment cost but produce high carbon emissions, technology two has more investment cost but produce less carbon emissions. Selection of technologies has trade-off between investment cost and amount emissions. Final products satisfy customer's demand located at five locations (C=5) through distribution centers (Q=3). In the reverse chain, returned products are collected at five collection centers (K=5). After inspection at collection centers, recyclable products and scrap products are separated. Scrapped products are sent to two disposal centers (W=2) and recyclable products are sent to three recycling centers (R=3). Finally, recycled materials are sent to plants for manufacturing new products. For logistics activities between the facilities, three transportation modes are available (M=3). It is well known that different transportation modes have a significant difference in carbon emission per ton mile.

The policy parameters are selected as C^{cap} (carbon cap) = 15,000 kg, δ (carbon tax) = 0.6 \$/kg, p^+ (carbon sell) = 0.3 \$/kg, and p^- (carbon buy) = 0.5 \$/kg which is \$ 0.2 lower than p^+ to represent the difference between the selling and buying prices in a market after considering transactional costs. The other parameters are provided in Table 1 and Table 2.

Table 1. Values of the model parameters

Parameter	Values
$D_{c,l}$	Uniform (2,500, 6,500)
$FI_{p,t1}$	Uniform (50,000, 70,000)
$FI_{p,t2}$	Uniform (90,000, 110,000)

FJ_q	Uniform (60,000, 80,000)
FU_k	Uniform (4,000, 8,000)
FV_r	Uniform (12,000, 21,000)
FY_w	Uniform (6,000, 9,000)
$SI_{p,l,t}$	Uniform (30,000, 36,000)
$SJ_{q,l}$	Uniform (25,000, 30,000)
$SU_{k,l}$	Uniform (10,000, 14,000)
$SV_{r,l}$	Uniform (8,000, 12,000)
$SY_{w,l}$	Uniform (6,000, 9,000)
S_l	Uniform (1, 3)
α_l	Uniform (0.4, 0.6)
γ_l	Uniform (0.05, 0.15)

Table 2. The cost and emission of different transportation modes

Mode	Cost ($ / tone-mile)	CO_2 emission factor (kg/ton-mile)
Truck	0.125	0.297
Rail	0.118	0.0252
Water	0.110	0.048

All four models are solved by using GAMS 22.6 and ILOG CPLEX 12.2 MIP solver on a laptop with Intel core i5 with 2.40 GHz processor and 2.0 GB of RAM. The computational time ranges between 10 s and 25 s, which is acceptable for conducting intensive numerical experiments. The comparison of results for the four carbon policies (Models M1, M2, M3 and M4) is presented in Table 3.

Table 3. Result of numerical example: Cost and emission under various policies

	No carbon policy (M1)	Carbon cap (M2)	Carbon tax (M3)	Cap-and-trade (M4)
Cost ($M)	11.89	11.91	12.02	11.90
Carbon emission(ton)	-	15	16	16.16

Table 3 shows that the Carbon Tax Policy (M3) results higher costs for the company, while the other policies have a smaller financial burden. The inflexible carbon cap policy (M2) and cap-and-trade policy (M4) can reduce the carbon emission best without increasing the cost to the company.

6. Conclusions

This paper presents optimization models for a CLSC to understand the influence both supply chain strategic and operational activities. The three most common carbon policies are investigated: strict carbon cap, carbon tax, and carbon cap-and-trade. A numerical example is presented to test the performance of the models and to analyze the impact of various policies on the supply chain's total cost and carbon emissions. The results indicate that carbon cap policy imposes a strict constraint on the amount of carbon emissions generated in supply chain operations. Cap-and-trade policy is heavily dependent on the carbon market price and cap allocation. On the other hand, carbon tax policy provides more flexibility but impose huge financial burden on the companies in order to reach certain emission target compared to other two policies. In summary, due to impact of these policies on supply chain operations, it is necessary for companies or policy makers to restructure their supply chains in terms of strategic and operational decisions to meet the targeted emissions.

References

[1] "UNFCCC", *Kyoto Protocol. 1997* (http://unfccc.int/kyoto_protocol/items/2830.php/)

[2] "EU ETS", *Emissions Trading System. 2009* (http://ec.europa.eu/clima/policies/ets/index_en.htm)

[3] http://unfccc.int/kyoto_protocol/status_of_ratification/items/2613.php

[4] M.T. Melo, S. Nickel, F. Saldanha-da-Gama, "Facility location and supply chain management–A review", *European Journal of Operations Research,* vol.196, 2009. p. 401–12.

[5] M. Fleischmann P. Beullens, J.M. Bloemhof-Ruwaard, L.N. Van Wassenhove, "The impact of product recovery on logistics network design", *Production & Operations Management*, vol.10, 2001. p.156–73.

[6] J. Sarkis, "A strategic decision framework for green supply chain management", *Journal of Cleaner Production*, vol. 11, 2003. p. 397-409.

[7] S. Srivastava, "Green supply-chain management: a state-of-the-art literature review", *International Journal of Management Review*, vol. 9, no. 1, 2007. p. 53-80.

[8] T. Paksoy, T. Bektaş, E. Özceylan, "Operational and environmental performance measures in a multi-product closed-loop supply chain", *Transportation Research Part E: Logistics and Transportation Review*, vol. 47, no. 4, 2011. p. 532-46.

[9] T. Abdallah, A. Farhat, A. Diabat, S. Kennedy, "Green supply chains with carbon trading and environmental sourcing: Formulation and life cycle assessment", *Applied Mathematical Modelling*, vol. 36, 2012. p. 4271–4285.

[10] A. Diabat, D. Simichi-Levi, "A carbon-capped supply chain network problem" *IEEE International Conference on Industrial Engineering and Engineering Management*, 2010. p. 523-27.

[11] A. Chaabane, A. Ramudhin, M. Paquet, "Design of sustainable supply chains under the emission trading scheme", *International Journal of Production Economics*, vol. 135, 2012. p. 37-49.

[12] A. Diabat, T. Abdallah, A. Al-Refaie, D. Svetinovic, K. Govindan, "Strategic Closed-Loop Facility Location Problem With Carbon Market Trading", *IEEE Transactions on engineering Management*, vol. 60, no. 2, 2013. p. 398-408.

[13] B. Fahimnia, J. Sarkis, F. Dehghanian, N. Banihashemi, S. Rahmanm, "The impact of carbon pricing on a closed-loop supply chain: an Australian case study", *Journal of Cleaner Production*, vol. 59, 2013. p. 210-25.

[14] S. Benjaafar, Y. Li, M. Daskin, "Carbon footprint and the management of supply chains: insights from simple models", *IEEE Transactions Automotive Science Eng.* Vol. 10, 2013. p. 99-116.

[15] M. Jin, N.A. Granda-Marulanda, D.Ian, "The impact of carbon policies on supply chain design and logistics of a major retailer", *Journal of Cleaner Production*; vol. 85, , 2014. p. 453-461.

Appendix: Nomenclature

Sets	
p	Set of potential locations for manufacturing plants, $p \in P$
q	Set of potential locations for distribution centers, $q \in Q$
c	Set of fixed locations for customer zones, $c \in C$
k	Set of potential locations for collection centers, $k \in K$
r	Set of potential locations for recycling centers, $r \in R$
w	Set of potential locations for disposal centers, $w \in W$
l	Set of product types, $l \in L$
m	Set of transportation modes, $m \in M$
t	Set of production technologies, $t \in T$
Parameters	
$D_{c,l}$	Demand at customer zone c of product *l*,
$R_{c,l}$	Return of product *l* from customer zone *c*,
$FI_{p,t}$	Fixed cost of opening and operating the manufacturing plant at location *p* with technology *t*,
FJ_q	Fixed cost of opening and operating the distribution center at location *q*,
FU_k	Fixed cost of opening and operating the collection/inspection center at location *k*,
FV_r	Fixed cost of opening and operating the recycling center at location *r*,
FY_w	Fixed cost of opening and operating the disposal center at location *w*,
Capacity of facilities	
$SI_{p,l,t}$	Capacity of p for manufacturing product *l* with technology *t*,
$SJ_{q,l}$	Capacity of *q* for holding product *l*,
$SU_{k,l}$	Capacity of k for collecting and inspecting returned product *l*,
$SV_{r,l}$	Capacity of r for recycling product *l*,
$SY_{w,l}$	Capacity of *w* for disposing scrapped product *l*,
S_l	Unit volume of product *l*
Unit costs	
$CI_{p,l,t}$	Unit manufacturing cost of product *l* at *p* with technology *t*,
$CU_{k,l}$	Unit collection and inspection cost of returned product *l* at *k*,
$CV_{r,l}$	Unit recycling cost of product *l* at *r*,
$CY_{w,l}$	Unit disposal cost of scrapped product l at w,
$CIJ_{p,q,l,m}$	Unit transportation cost for product *l* shipped from *p* to *q* using mode *m*
$CJA_{q,c,l,m}$	Unit transportation cost for product *l* shipped from *d* to *c* using mode *m*
$CAU_{c,k,l,m}$	Unit transportation cost for retuned product *l* shipped from *c* to *k* using mode *m*
$CUV_{k,r,l,m}$	Unit transportation cost for recyclable product *l* shipped from *k* to *r* using mode *m*
$CUI_{r,p,l,m}$	Unit transportation cost for recycled product *l* shipped from *r* to *p* using mode m
$CUY_{r,w,l,m}$	Unit transportation cost for scrapped product *l* shipped from *r* to *w* using mode *m*
α_l	Return ratio for used product *l*
γ_l	Disposal ratio for used product *l*
Parameters related to carbon emission	
$EI_{p,t}$	Carbon emission in kg of manufacturing a unit of product *l* at *p* with technology *t*,
$EJ_{q,l}$	Carbon emission in kg of handling a unit of product *l* at *q*,
$EV_{r,l}$	Carbon emission in kg of recycling a unit of product *l* at *r*,
$EU_{k,l}$	Carbon emission in kg of producing a unit of recyclable product *l* at *k*,
$EIJ_{p,q,l,m}$	Carbon emission in (kg/unit) of shipping product *l* from *p* to *q* using mode *m*
$EJA_{q,c,l,m}$	Carbon emission in (kg/unit) of shipping product *l* from *q* to c using mode *m*
$EAU_{c,k,l,m}$	Carbon emission in (kg/unit) of shipping returned product *l* from c to k using mode *m*
$EUV_{k,r,l,m}$	Carbon emission in (kg/unit) of shipping recyclable product *l* from *k* to *r* using mode *m*
$EUY_{k,w,l,m}$	Carbon emission in (kg/unit) of shipping scrapped product *l* from *k* to *w* using mode *m*
$EVI_{r,p,l,m}$	Carbon emission in (kg/unit) of shipping recycled product *l* from *r* to *p* using mode *m*
C^{cap}	Fixed carbon cap on emission over the entire planning horizon, in kgs
δ	The carbon tax rate per unit (amount of tax paid per unit emitted)
p^+	The carbon selling price per unit (kg) in the carbon market
p^-	The carbon buying price per unit (kg) in the carbon market
Decision Variables	
Binary variables	
$ZI_{p,t}$	Binary variable takes a value of 1 if *p* is open with technology *t*, 0 otherwise,
ZJ_q	Binary variable takes a value of 1 if *d* is open, 0 otherwise,
ZU_k	Binary variable takes a value of 1 if *k* is open, 0 otherwise,
ZV_r	Binary variable takes a value of 1 if *r* is open, 0 otherwise,
ZY_w	Binary variable takes a value of 1 if *w* is open, 0 otherwise,
Continuous variables	
$QI_{p,l,t}$	Quantity of product *l* manufactured in *p* using technology *t*,
$QIJ_{p,q,l,m}$	Quantity of product *l* shipped from *p* to *q* using mode *m*,
$QJA_{q,c,l,m}$	Quantity of product *l* shipped from *q* to *c* using mode *m*,
$QAU_{c,k,l,m}$	Quantity of returned product *l* shipped from *c* to *k* using mode *m*,
$QUV_{k,r,l,m}$	Quantity of recyclable product l shipped from *k* to *r* using mode *m*,
$QVI_{r,q,l,m}$	Quantity of recycled product *l* shipped from *r* to *p* using mode *m*,
$QUY_{k,w,l,m}$	Quantity of scrapped product *l* shipped from *k* to *w* using mode *m*,
e^+	The amount of carbon credit purchased
e^-	The amount of carbon credit sold