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Emission policies and their analysis for the design of hybrid and dedicated closed-loop supply chains

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ABSTRACT

Government legislation and consumer awareness on carbon emissions have required industries to seek alternative ways to reorganize their supply chains. Therefore, industries have to consider not only the activities in the forward supply chain but also in the reverse supply chain. An integrated supply chain, that combines the activities of both the forward and reverse supply chains, is referred to as the closed loop supply chain (CLSC). There are two main types of CLSC structures: hybrid and dedicated. In this research, we analyze the effect of carbon emissions consideration on the design of both hybrid and dedicated CLSCs. In particular, we develop a set of integrated mixed integer linear programming (MILP) models to quantify and compare both of the environmental and economic impacts of carbon emissions policies (carbon cap, carbon tax, and carbon cap-and-trade), and market factors (scale effect, product return rate, and the customer demand) on the design of CLSCs with respect to both CLSC structures. Our analysis shows that when market conditions are considered, total cost and total emissions are more sensitive to customer demand than to the scale effect and the product return rate. When an industry faces fluctuation on the quantity of the returned products, adopting a dedicated CLSC would lead to a lower total cost. Under cap-and-trade policy, dedicated CLSC can produce less total emissions. We also observe that dedicated CLSC is more cost efficient under carbon cap policy and hybrid CLSC is more emissions efficient when the carbon tax is introduced.

1. Introduction

Increasing carbon emissions driven by economic activities has been a concern to researchers, scientists, and leaders (Eskandarpour et al., 2015). Many countries have implemented various carbon emissions policies (or, carbon policies in short) — carbon tax, carbon cap, and cap-and-trade policies—in order to address this concern. Under a carbon tax policy, the firms are charged a fee for each unit of carbon emitted (Palak et al., 2014). In a carbon cap policy, the government sets a level of emissions allowance (called carbon cap) for different companies. In a carbon cap-and-trade policy, if a company produces lesser emissions than the carbon cap, then this difference in emissions, between the generated and cap level, can be sold in the trading market to those companies that produce more emissions than the carbon cap (Zakeri et al., 2015).

The industries have started incorporating carbon emissions for the redesign of existing or the design of a new supply chain (Chaabane et al., 2012; Mallidis et al., 2012). Based on the carbon policy of the government, appropriate measures are considered by the companies for supply chain designs in order to reduce emissions (Gao and Ryan, 2014; Jin et al., 2014). However, different types of policies have differential effects on a supply chains' emissions cost (Choudhary et al., 2015; Gao and Ryan, 2014; Palak et al., 2014)—be it a forward or a reverse supply chain. However, for a more effective reduction in emissions, companies have to focus on the closed loop supply chains (CLSCs), which is an integration of activities both in forward and reverse supply chains (Paksoy et al., 2011).

Researchers are focusing not only on the emissions generated at particular stages, such as production or supply, but also on the total lifecycle of the product. This requires companies to move away from traditional school of maximizing the long-term economic performance to the minimization of the social and environmental impacts from a total product life-cycle perspective (Elhedhli and

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Merrick, 2012; Metta and Badurdeen, 2013), which requires the analysis of emissions from the CLSC perspective. In other words, in addition to including activities associated with production, transportation, and delivery of final products to the market, the analysis should also include activities associated with the returned of the products (such as collection, handling, and disposal) due to warranty issues and end-of-life process. For collection and handling of returned products, firms can either build new dedicated facilities such as collection centers, or use certain capacity of the existing facilities. Similarly, for processing of returned products, firms can either build a new dedicated processing facility or use a certain capacity of the existing facilities.

1.1. *Closed loop supply chains and research questions*

The CLSC with dedicated facilities (referred to as DCLSC here), as shown in Fig. 1, has dedicated facilities for collecting, repairing, and disposing the returned products (Fareeduddin et al., 2015; Hasani et al., 2014; Pishvaee et al., 2011; Ramezani et al., 2013, 2014; Zeballos et al., 2014). On the other hand, in a hybrid CLSC (referred to as HCLSC here), shown in Fig. 2, the returned products from customers are handled in existing distribution centers and manufacturing plants (Abdallah et al., 2012; Easwaran and Üster, 2010; Li et al., 2014). Also, in HCLSC, remanufacturing and repairing are performed in a single facility and it is assumed that the distribution centers perform functions of both distributing new products, collecting returned products, and distributing the repaired or remanufactured products. This type of arrangement in HCLSC eliminates substantial additional investments required for building new infrastructure, equipment, and human resources (Easwaran and Üster, 2010). The reduction on investment with shared facilities and operations is described as scale effect (Wessels, 1997). In a broader sense, not only the fixed cost, but also the variable cost and emissions could be reduced in HCLSC due to the scale effect.

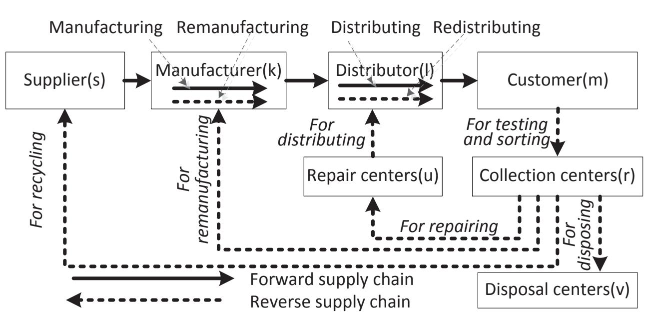

Fig. 1. Dedicated closed-loop supply chain.

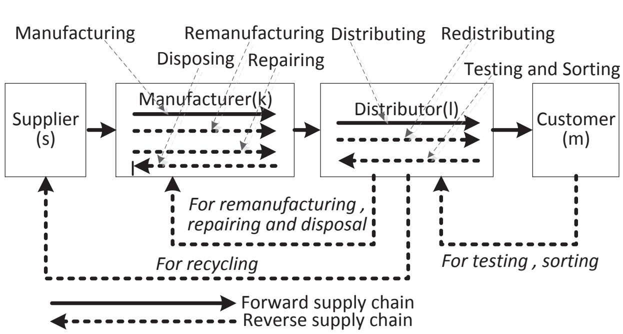

Fig. 2. Hybrid closed-loop supply chain.

Given the carbon emissions target (dictated by carbon policies or self-initiatives) as well as market conditions, companies may want to decide on the choice of the best CLSC structure. For an industry to make a decision on a CLSC structure, two important research questions should be addressed: 1) how should the industry decide on the design and operation of the CLSC in presence of carbon policies and market conditions, namely scale effect, return rate (the ratio of the products returned over the sold products at a particular time) and customer demand?, and 2) what is the differential impact, in terms of cost and emissions, of the carbon policies and market conditions on the design and operation of HCLSC and DCLSC?

1.2. *Contributions*

Consideration of emissions costs can lead to a change in the optimal configuration of the supply chain (Altmann and Bogaschewsky, 2014; Elhedhli and Merrick, 2012). Literature review shows that the market environment, such as the level of returned products (Abdallah et al., 2012; Jin et al., 2014) and customer demand (Abdallah et al., 2012; Gao and Ryan, 2014), plays a major role in reducing supply chain costs and emissions. However, most of the existing literature on CLSCs is focused mainly on the economic aspects of the supply chain. There are a handful of papers, which consider carbon emissions; but they only study DCLSCs (Chaabane et al., 2012; Fahimnia et al., 2013; Gao and Ryan, 2014; Fareeduddin et al., 2015). Therefore, this paper addresses the research gaps by analyzing the impact of carbon policies and market conditions on HCLSC.

Our work presented here contributes by comparing cost and emissions performance of HCLSC and DCLSC. In addition to considering both CLSC structures in the presence of most commonly used existing carbon policies, we also include another major driver of the CLSC: the market condition. In summary, our research extends the current literature from two perspectives: the first one is related to the supply chain structure considered, and the second one is the supply chain environment, which simultaneously considers market conditions and carbon policies.

A set of integrated mixed integer linear programming (MILP) models is presented for the design of a multi-part, multi-product, multi-facility, and capacitated CLSC under various carbon policies and market conditions in a centralized decision making setting. The paper provides answers to the two research questions mentioned earlier by quantifying and analyzing the environmental and economic performances of CLSCs. The results from the models provide practical insights under which CLSC structures are cost and emissions efficient. The analysis shows that: 1) in a DCLSC, a reduction in the total cost can be achieved under the carbon cap policy and reduction of total emissions can be achieved under the cap-and-trade policy; 2) total emissions are lower in HCLSC when carbon tax is implemented, 3) both DCLSC and HCLSC are more sensitive to customer demand than to the scale effect and return rate; 4) the total cost of DCLSC is lower no matter how many products are returned from the customers, and 5) cost and emissions of the individual firms can be decreased in both DCLSC and HCLSC setups.

The remainder of this paper is as follows: a brief overview of the CLSC design is provided in Section 2. In Section 3, the integrated MILP formulations are given. In Section 4, the results from a computational study are presented along with the insights derived from the results. Finally, the conclusions, limitation of the proposed model, and possible future research directions are provided in Section 5.

2. Literature review

Ramudhin et al. (2010) is one of the first studies that contained a proposal for carbon market sensitive strategic planning model for supply chain network design. Supply chain was analyzed with both emissions and costs by Wang et al. (2011) through a multi-objective optimization model. Mallidis et al. (2012) explored the impact of cost on greening of a supply chain design. Further examination of the supply chain with cost emissions and lead time was provided by Zhang et al. (2014) with a multi-objective programming formulation. Focusing on retail supply chain, Park et al. (2015) show that exclusively minimizing operating costs may substantially increase emissions relative to the minimum level of emissions.

Elhedhli and Merrick (2012) developed a model to minimize emissions throughout the supply chain by considering environmental sourcing. Benjaafar et al. (2013) provided optimization models for supply chain operational decision making under carbon policies. Yang et al. (2014) investigated the influence of carbon policies on channel coordination for a two-echelon supply chain consisting of one supplier and one retailer. Tseng and Hung (2014) provided an analysis to show that a legislation that forces the enterprises to bear the social costs of carbon emissions is an effective approach to reducing emissions. Using the EOQ model, Chen et al. (2013) discussed the condition under which it is possible to reduce emissions by modifying order quantities. Bing et al. (2015) focused on a global reverse supply chain redesign for household plastic waste under the carbon trading policy and mentioned that the strategic location/relocation of product re-processors can lead to a reduction in cost and total transportation emission.

The concept of product lifecycle emissions are also studied by the researchers (Abdallah et al., 2012; Chaabane et al., 2012; Metta and Badurdeen, 2013). Metta and Badurdeen (2013) mentioned that when product lifecycle is considered, the total perspectives of the product can be analyzed for the design of a supply chain. (Eskandarpour et al. (2015) mentions that as the lifecycle concept is becoming important, environmental impact in each process (or entity) in the supply chain should also be considered. That means, costs and emissions should be considered both in the forward and the reverse supply chains (Metta and Badurdeen (2013).

If a supply chain is subjected to carbon tax, the incorporation of carbon emissions in the design of supply chains becomes more important. Similarly, in countries with an opportunity for carbon trading, industries can develop an emissions efficient supply chain. Zakeri et al. (2015) show that carbon tax policy or a stable carbon trading policy can lead to cost and emissions efficient supply chain design. However, higher carbon tax can also impact the total supply chain cost and thereby increasing the cost of the product. The research by Fahimnia et al. (2015) on durable parts manufacturing sector in Australia shows that a carbon tax above \$60/ton may impose unacceptable economic costs to the industry.

Like the forward supply chains, reverse supply chains should also comply with carbon policies (Gobbi, 2011). Research is being carried out on direct and indirect carbon emissions control in product recycling, reuse, and disposal, in order to develop a strategy for eco-friendly supply chains (Shaw et al., 2013).

Chaabane et al. (2012) presented a formal decision model for DCLSC design under the carbon trading policy and show that efficient carbon management strategies will help decision makers achieve sustainability objectives in a cost-efficient manner. Fahimnia et al. (2013) developed a unified optimization model for a DCLSC, in which carbon emissions are expressed in terms of dollar carbon cost. The authors show that variations in cost and environmental impacts occur over ranges of carbon pricing. Gao and Ryan (2014) used carbon policies to analyze a DCLSC network design problem considering uncertainties in the demands and returns. Their research shows that the share of transportation by the low-emitting modes increases when carbon price or carbon tax changes uniformly within a wider range. Fareeduddin et al. (2015) investigated the impacts of carbon policies on DCLSC designs and stated that it is necessary for companies to restructure their supply chains to meet the targeted emissions. As cost is an important driver for strategic decisions on CLSCs, using a HCLSC would reduce investment requirements compared to that for a DCLSC (Easwaran and Üster, 2010; Jin et al., 2014); but DCLSC may be more attractive if emissions are considered.

There exists several studies in the literature that aims to understand cost and emissions implications for forward supply chains (Park et al., 2015; Ramudhin et al., 2010), for the reverse supply chains (Bing et al., 2015), and for DCLSCs (Bing et al., 2015; Fahimnia et al., 2013; Fareeduddin et al., 2015), but not for HCLSC. On the other hand, there are only a few studies that analyze the effects of the market factors, such as customer demand (Abdallah et al., 2012; Gao and Ryan, 2014), and the carbon policies, such as cap-and-trade (Chaabane et al., 2012; Gao and Ryan, 2014), and carbon tax (Fahimnia et al., 2013; Fareeduddin et al., 2015; Gao and Ryan, 2014), on the performance of DCLSC. In many cases, resource sharing is seen as a pragmatic solution rather than investing in new facilities. Therefore, in this study, we examine and compare cost and emissions of both DCLSC and HCLSC under the same decision environment so that decision makers can better understand the implications of making a strategic decision on one or the other type of CLSC.

3. Closed loop supply chain models

In this section, we propose mathematical models and MILP formulations for the design of HCLSCs and DCLSCs in order to answer the research questions stated in Section 1. The formulations are characterized by models containing both continuous and discrete variables, which are important features of the CLSC design problems (Gass, 1957). The CLSC design problem under carbon polices contains numerical state variables, which refer to resources (Hoffmann, 2002), particularly the emissions resources. Moreover, given that the prescriptive modeling may also involve descriptive analysis in optimization (Stillman et al., 2015), we adopt the MILP formulation approach and the comparative sensitivity to capture the multifaceted features of the CLSC design problems. In addition, when carbon policies are introduced, the MILP formulation can be considered as an effective method for the analysis of the supply system, such as the forward supply chain (Jin et al., 2014; Mallidis et al., 2012) and DCLSC (Fahimnia et al., 2013; Fareeduddin et al., 2015).

3.1. Assumptions

The following assumptions are made for the development of the MILP formulation for the CLSC problem.

(1) Both in DCLSC and HCLSC, testing and sorting, distributing, and redistributing activities are performed by the distributors; and manufacturing, remanufacturing, repairing, and disposal activities are performed by the manufacturers. That means the fixed cost of the facilities as well as the variable cost and emissions of the activities would be incorporated into the calculations of total emissions and cost of the corresponding supply chain members.

(2) Remanufactured products are distinguished from the brand-new products; but both of them have the same performance and quality as mentioned in Pokharel and Liang (2012).

(3) All new products have a defined warranty period for product return.
(4) Some of the customers, who return the product during the warranty period, may switch to other brands instead of receiving a refurbished or remanufactured product.
(5) Under the carbon cap-and-trade system, carbon permits can be either purchased or sold at the same price (Palak et al., 2014; Yang et al., 2014).
(6) HCLSC has the same handling capacity as that of DCLSC, including the number of new and returned products and product handling capacities.
(7) The aggregated capacities of testing and sorting, repairing, and disposing in HCLSC are equal to those in DCLSC.
(8) Testing and sorting, repairing, and disposing capacities of the facilities in HCLSC is proportional to the distributors' and the manufactures' capacities, respectively.
(9) The aggregated fixed costs of the testing and sorting, repairing, and disposing facilities in DCLSC are smaller than those in HCLSC because of facility sharing (Easwaran and Üster, 2010).
(10) The fixed costs of the facilities for testing and sorting, repairing, and disposing in HCLSC are proportional to the distributors' and the manufactures' fixed costs, respectively.
(11) The average cost and emissions for testing and sorting, repairing, and disposing in DCLSC are bigger than those in HCLSC due to the scale effect (Jenkins, 1997; Katayama and Bennett, 1999).
(12) Cost and emissions for testing and sorting, repairing, and disposing in HCLSC are proportional to its distributing and manufacturing cost and emissions, respectively.

3.2. Parameters and variables

To formulate the problem, the following notations are used to define the sets:

P: set of products, indexed by p;
A: set of parts, indexed by a;
S: set of fixed location of suppliers, indexed by s;
K: set of potential location of manufacturing plants (or manufacturers), indexed by k;
L: set of potential location of distributers, indexed by l;
R: set of potential location of collection centers, indexed by r;
U: set of potential location of repair centers, indexed by u;
V: set of fixed location of disposal centers, indexed by v;
T: set of transportation modes, indexed by t;
M: set of fixed location of customers, indexed by m;
I,J,G,H,Y,Z: set of facilities, indexed by i,j,g,h,y,z *separately* ;
$i,j,g,h,y,z \in S \cup K \cup L \cup M \cup R \cup U \cup V$;
X: set of sequential operations represented by x. The operations include manufacturing, distribution, consumption, sorting and testing, remanufacturing, repair, redistribution, recycling, and the disposal of the products in all the facilities.

The following notations are used to define the parameters:

Num_{pa}: unit of part a in per unit product p, $\in A$, $p \in P$;
C_{pt} : unit transportation cost of product p per mile using transportation mode t;
C^x_{pi} : unit handling cost of product p at facility i with operation x;
C_{as}: unit handling cost of part a at supplier s;
CF_i : fixed cost for opening the facility i;
d_{ij} : distance between facility i and facility j;
CP_s : manufacturing capacity of supplier s;
CP^x_i: capacity of facility i with operation x;
CPU_p : capacity utilisation rate per unit of product p;
CPU_a : capacity utilisation rate per unit of part a;
DM_{mp} : demand of customer m for product p;
RT_p: ratio of return for product p from customers due to quality defects;
RR_p : ratio of repair for returned product p;
RD_p : ratio of disposal of returned product p;
RM_p: ratio of remanufacturing of returned product p;
RC_p : ratio of recycling of product p;
ET^t : carbon emissions for transportation mode t, in ton per mile;
EP^x_{pi}: carbon emissions in ton for handling unit product p at facility i with operation x, $i \in N$;
EP_{as} : carbon emissions in ton for manufacturing unit part a at supplier s;

α,β,γ are the fixed cost level, variable cost level, and carbon emissions level due to the influence of the scale (in manufacturers and distributors): $\alpha,\beta,\gamma=1$ in DCLSC and $\alpha,\beta,\gamma<1$ in HCLSC.

To understand the impact of different control parameters on CLSC decision process, several decisions touching various aspects of CLSCs should be taken into consideration. Given that the fixed cost and network structure are determined by the facilities incorporated in CLSCs (Chaabane et al., 2012; Fahimnia et al., 2013), the first decision variable is considered for facility selection decision. Even the same type of facility, such as a remanufacturing plant, could be different in terms of their locations, capacities, or the emissions per unit of production (Altmann and Bogaschewsky, 2014).

The following decision variables represent forward and reverse logistics flows for parts, new products and used products. For new and used products, the variables not only indicate the transportation quantities, but also the quantities of the parts that are handled by the facilities (Chaabane et al., 2012). Since the purchasing and selling carbon credits could be an economic option for firms to achieve their emissions targets (Palak et al., 2014), the last decision variable (φ) is considered for carbon trading decisions.

f_i : binary variable equals “1” if the location i is open and “0” if otherwise ;
QF^{sk}_a: quantity of part a purchased by manufacturer k from supplier s;
QF^{ij}_{px} : quantity of new product p shipped from i to j for operation x in forward logistics;
QB^{ij}_{px} : quantity of used product p shipped from i to j for operation x in reverse supply chain;
φ : quantity of carbon credit brought or sold by the supply chain, $\varphi \geq 0$ if the supply chain purchase carbon credit form the carbon market, else $\varphi<0$.

3.3. Unified formulation of cost and emissions

In spite of the different network structures, mathematical formulations for DCLSC and HCLSC are similar. The formulation with unified cost components, emissions components, and the constraints are given in this section. The detailed expressions of the equations for DCLSC and HCLSC are given in Appendix A and B. The combinations of these equations form the basis for describing the models under various scenarios. However, some parameters may differ in scope in DCLSC and HCLSC because the two CLSCs are different in terms of the use of facilities. In order to denote the parameters which have a different scope in a CLSC, we use the subscript H for HCLSC and D for DCLSC. For example, in the fixed cost calculation expression $\sum_i CF_i f_i$, i is written as i_H for HCLSC and as i_D for DCLSC, where $i_H \in K \cup L$ and $i_D \in K \cup L \cup R \cup U \cup V$. This means the decision for HCLSC is to build a hybrid distribution center or plant, while the decision for DCLSC would be to decide on the type of facilities for their possible locations.

3.3.1. Cost components

The total cost for the CLSC design and operations are formulated in three parts: the fixed cost (Z_f), handling cost (Z_h), and the transportation cost (Z_t) as given in equations (1)-(3).

$$Z_f = \sum_i CF_i f_i \tag{1}$$

$$Z_h = \sum_a \sum_s \sum_k C_{as} QF_a^{sk} + \sum_p \sum_{i \in K \cup L} \sum_{x \in \{x2,x3\}} \sum_{j \in L \cup M} C_{pi}^x QF_{px}^{ij} + \sum_p \sum_g \sum_{x \in \{x4,x6,x9\}} \sum_h \beta C_{ph}^x QB_{px}^{gh} + \sum_p \sum_y \sum_{x \in \{x5,x7,x8\}} \times \sum_z C_{pz}^x QB_{px}^{yz} \tag{2}$$

$$Z_t = \sum_a \sum_s \sum_k C_{at} d_{sk} QF_a^{sk} + \sum_p \sum_{i \in K \cup L} \sum_{x \in \{x2,x3\}} \sum_{j \in L \cup M} C_{pt} d_{ij} QF_{px}^{ij} + \sum_p \sum_g \sum_{x \in \{x4,x5,x6,x7,x8,x9\}} \sum_h C_{pt} d_{gh} QB_{px}^{gh} \tag{3}$$

Because the facilities used for manufacturing and distributing are hybrid facilities, their fixed costs are calculated according to assumption (6).

Handling costs given by equation (2) consist of four components: the first two are the handling costs for parts and products in the forward logistics and the latter two are the handling costs for the reverse logistics. The parameters in equation (2) are specified as follows: in DCLSC, $g_D \in M \cup R$, $h_D \in R \cup U \cup V$, $y_D \in R \cup U$, $z_D \in S \cup K \cup L$; in HCLSC, $g_H \in L \cup M$, $h_H \in K \cup L$, $y_H \in L \cup K$, $z_H \in S \cup K \cup L$.

The first component of the transportation costs in equation (3) represents the cost of shipping the parts and the following two components refer to transportation cost of products. In DCLSC, $g_D \in K \cup L \cup R \cup U \cup M$, $h_D \in K \cup L \cup R \cup U \cup M \cup V$; in HCLSC, $g_H \in K \cup L \cup M$, $h_H \in K \cup L \cup M$.

3.3.2. Emissions components

The operations for parts and products in CLSCs are the main source of the emissions. These are grouped as handling emissions (E_h) and the transportation emissions (E_t). The expressions for these emissions are given in equations (4) and (5).

$$E_h = \sum_a \sum_s \sum_k EP_{as} QF_a^{sk} + \sum_p \sum_{i \in K \cup L} \sum_{x \in \{x2,x3\}} \sum_{j \in L \cup M} EP_{pi}^x QF_{px}^{ij} + \sum_p \sum_g \sum_{x \in \{x4,x6,x9\}} \sum_h \gamma EP_{ph}^x QB_{px}^{gh} + \sum_p \sum_y \sum_{x \in \{x5,x7,x8\}} \times \sum_z EP_{pz}^x QB_{px}^{yz} \tag{4}$$

$$E_h = \sum_a \sum_s \sum_k ET_{at} d_{sk} QF_a^{sk} + \sum_p \sum_{i \in K \cup L} \sum_{x \in \{x2,x3\}} \times \sum_{j \in L \cup M} ET_{pt} d_{ij} QF_{px}^{ij} + \sum_p \sum_g \sum_{x \in \{x4,x5,x6x7,x8,x9\}} \times \sum_h ET_{pt} d_{gh} QB_{px}^{gh} \tag{5}$$

The handling emissions consist of the carbon generated from parts manufacturing in suppliers and the carbon generated from handling products in the forward and reverse logistics. In DCLSC, $g_D \in M \cup R$, $h_D \in R \cup U \cup V$, $y_D \in R \cup U$, $z_D \in S \cup K \cup L$; in HCLSC, $g_H \in L \cup M$, $h_H \in K \cup L$, $y_H \in L \cup K$, $z_H \in S \cup K \cup L$. The transportation emissions incorporates carbon discharged by shipping the parts and transporting the products in both forward and reverse supply chains. In DCLSC, $g_D \in K \cup L \cup R \cup U \cup M$, $h_D \in K \cup L \cup R \cup U \cup M \cup V$; in HCLSC, $g_H \in K \cup L \cup M$, $h_H \in K \cup L \cup M$.

3.3.3. Constraints

The main constraints in modeling the CLSC design problem are classified into two groups: balance and capacity constraints. Equations (6)–(12) are the balance constraints, which ensure the incoming flows equal to the outgoing flows of parts and products at all facilities in the CLSC. Constraint (6) states that the quantity of a part shipped from suppliers are used in manufacturing in a plant. Constraint (7) ensures that the quantity of a product shipped from plants are distributed. Constraint (8) ensures that the flow of the returned products that enters a distribution center is equal to the flow that leaves the facility. In this set of constraints, $i_D \in K \cup U$ for DCLSC and $i_H \in K$ for HCLSC. Constraint (9) only works for DCLSC and confirms the flow balance in plant or repair centers; while constraint (10) ensures the reprocessed products is balanced in HCLSC plant. Constraint (11) ensures that all customers would receive the new products as per their requirements. Constraint (12) ensures that the reprocessed products would be shipped back to the customers returning the products.

$$\sum_s QF_a^{sk} = \sum_p \sum_l Num_{pa} QF_{p,x2}^{kl}, \quad \forall a, k \tag{6}$$

$$\sum_k QF_{p,x2}^{kl} = \sum_m QF_{p,x3}^{lm}, \quad \forall p, l \tag{7}$$

$$\sum_i QB_{p,x7}^{il} = \sum_m QB_{p,x3}^{lm}, \quad \forall p \tag{8}$$

$$\sum_r QB_{px}^{ri} = \sum_l QB_{px}^{il}, \quad \forall p, x \in \{x_5, x_6\}, i \in \{U, K\} \tag{9}$$

$$\sum_l \left(QB_{p,x6}^{lk} + QB_{p,x5}^{lk} \right) = \sum_l QB_{p,x7}^{kl}, \quad \forall p, k \tag{10}$$

$$\sum_l QF_{p,x3}^{lm} = DM_{mp}, \quad \forall p, m \tag{11}$$

$$\sum_l QB_{p,x3}^{lm} \le RT_p DM_{mp}, \quad \forall p, m \tag{12}$$

Constraint (13) ensures that all of the returned products would be collected, where $i_D \in R$ for DCLSC and $i_H \in L$ for HCLSC. Constraint (14) ensures that all the returned products would be handled rightly, where RX_p represents RR_p, RM_p,RC_p,RD_p, respectively for different returned products. In equation (14), $i_D \in R, j_D \in U \cup V \cup S \cup K$ for DCLSC and $i_H \in L, j_H \in L \cup S$ for HCLSC.

$$DM_{mp}RT_p = \sum_i QF^{mi}_{p,x4}, \quad \forall p, m \tag{13}$$

$$\sum_m QB^{mi}_{p,x7} RX_p \le \sum_i QB^{ij}_{px}, \ \forall p, m, x \in \{x5, x6, x8, x9\} \tag{14}$$

The capacity constraints of the facilities are given by constraints (15)–(17). Constraint (15) limits manufacturing within the available capacity. Constraints (16) and (17) ensure that the quantity of products that were handled in a facility is less than processing capacity of the facility in the forward and the backward logistics. For j in constraint set (17) $j_D \in S \cup K \cup L \cup U \cup R \cup V, i_D \in R \cup U \cup K \cup M$ for DCLSC and $j_H \in M \cup K \cup L, \ i_H \in S \cup K \cup L$ for HCLSC. Constraints (18)–(20) enforce the binary restrictions and the non-negativity on the decision variables, respectively.

$$\sum_a \sum_k QF^{sk}_a CPU_a \le f_s CP_s, \quad \forall s \tag{15}$$

$$\sum_p \sum_{j \in L \cup M} CPU_p QF^{ij}_{px} \le f_i CP^x_i, \quad \forall x \in \{x2, x3\}, j \in K \cup L \tag{16}$$

$$\sum_p \sum_i CPU_p QB^{ij}_{px} \le f_j CP^x_j, \quad \forall x \in \{x4, x5, x6, x7, x8, x9\} \tag{17}$$

$$f_i \in \{0, 1\} \quad \forall i \in I \tag{18}$$

$$QF^{sk}_a \ge 0, \quad \forall a, s, k \tag{19}$$

$$QF^{ij}_p \ge 0, QB^{ij}_p \ge 0 \quad \forall p, i, j \tag{20}$$

3.4. Models under different scenarios

Following the formulations of cost and emissions as well as the constraints, the expected total cost (Z_c) and emissions (Z_e) can be represented in equations (21) and (22).

$$Z_c = Z_f + Z_h + Z_t \tag{21}$$

$$Z_e = \mathrm{E_h} + \mathrm{E_t} \tag{22}$$

For the analysis, the economic part is represented by the total supply chain cost while the environmental part is evaluated by the total carbon emissions.

There are four modeling situations for the CLSC design, as shown in Table 1. In the first scenario, only the economic performance is considered. In the second scenario, the carbon cap policy is considered. This requires a strict total emissions control, that is, the total supply chain emissions should not exceed the carbon emissions limit *EL*. In the third scenario, carbon tax policy is considered; the firms are charged a fee, θ, for each unit of carbon emission. In the fourth scenario, carbon cap-and-trade is considered; the carbon credits are sold or bought in the market with a price δ per ton of emissions. Under a carbon trading policy, the cost of carbon in the market is influenced by a firm's carbon emissions level (Fahimnia et al., 2013; Jin et al., 2014). It is clear that in a free carbon trading market, more demand for carbon credit will result in higher prices and *vice versa;* thus, impacting the total cost of operation.

4. Computational study

We implement the proposed model in a case study and evaluate the trade-offs among the different optimization criteria in DCLSC and HCLSC. Specifically, we consider a supply chain of two plastic products, well known for massive emissions during the manufacturing and recycling. It is assumed that there are four candidate suppliers, three potential plants, four possible distribution centers and five customers in the forward supply chain, and two candidate disposal centers, three potential collection centers and two possible repair centers in the reverse supply chain in DCLSC. Eight MILP formulations for DCLSC and HCLSC designs are solved using IBM ILOG CPLEX Optimization Studio 12.6 on a PC with Intel Core2 i7 processor and 16GB DDR II RAM at 2.2 GHz.

4.1. Data description

Each plastic product includes two main types of parts, which are made from polyethylene terephthalate and polystyrene. The usage of the parts for per unit product is shown in Table 2.

Since the strategic level decisions are of interest here, we employ estimates of these values using publicly available data. The distance between the facilities and the capacities in the example provided by Paksoy et al. (2011) has been adopted here with modifications for the analysis.

Based on the data given by Paksoy et al. (2011), the fixed and handling costs and handling capacity of the facilities are presented in Table 3. It is assumed that the parts and the products have the same unit transportation cost, which is given based on Hasani et al. (2012). Rodrigue et al. (2013) mentions that road transportation within a range of 420 miles is more profitable. Therefore, road transportation (within this range of transportation) is also adopted for the application of the model. The transportation cost and carbon emissions per ton-mile are assumed as $ 0.125 and 0.297 kg (Fahimnia et al., 2013).

The equivalent emissions of the production process for materials, generated based on the data provided by Sprayall (2015), are

Table 2
Usage of part a per unit of product p.

Product(P)	Utilization of part a = 1	Utilization of part a = 2
p = 1	0.5	0.5
p = 2	0.75	0.25

Table 1
Summary of the four modeling situations.

S.N.	Modeling situation	Objective function	Constraints to be used
1	Without emissions consideration	Minimize Z_c	Constraints (6)–(20)
2	With carbon cap policy	Minimize Z_c	Constraints (6)–(20), and $Z_e \le$ EL
3	With carbon tax policy	Minimize ($Z_c + \theta \times Z_e$)	Constraints (6)–(20)
4	With cap-and-trade policy	Minimize ($Z_c + \delta \times Z_e$)	Constraints (6)–(20), and $Z_e - \varphi \le$ EL

Table 3
The fixed cost ($), handling cost ($/ton), and handling capacity (ton).

Parameter	Value	Parameter	Value	Parameter	Value
CF_k	[500,000,600,000]	C_{pl}^{x3}	[9,12]	CP_k^{x1}	[1500,1700]
CF_l	[10,000,15,000]	C_{pl}^{x4}	[10,13]	CP_k^{x2}	[150,170]
CF_r	[1,000,1,400]	C_{pr}^{x5}	[2,4]	CP_l^{x3}	[1300,1900]
CF_u	[2,000,3,000]	C_{pv}^{x6}	[1,3]	CP_l^{x4}	[130,190]
CF_v	[8,000,10,000]	C_{pu}^{x7}	[4,6]	CP_r^{x5}	[400,500]
C_{pk}^{x1}	[30,50]	C_{ps}^{x8}	[5,7]	CP_v^{x6}	[100,150]
C_{pk}^{x2}	[12,14]	C_{as}	[10,13]	CP_u^{x7}	[200,300]
CF_l	[10,000,15,000]	C_t	0.125	CP_s^{x8}	[150,220]
				CP_{as}	[1500,2200]

Table 4
Carbon emissions in transportation (ton/ton-mile) and handling (ton/ton).

Parameter	Value	Parameter	Value
ET^t	0.000297	EP_{pr}^{x5}	[0.5,1]
EP_{pk}^{x1}	[1,2.5]	EP_{pv}^{x6}	[1,3]
EP_{pk}^{x2}	[1.5,3]	EP_{pu}^{x7}	[0.5,1]
EP_{pl}^{x3}	[0.5,1.5]	EP_{ps}^{x8}	[1.5,3.5]
EP_{pl}^{x4}	[1,2]	EP_{as}	[2,4]

given in Table 4. The calculation of carbon emissions factors due to operations on products is based on the statistics from US Environmental Protection Agency (2010) and Tesco (2012). The fixed costs, variable costs and emissions for each operation in each facility are generated with the following steps: First, based on the average value of the parameters, in terms of fixed cost, variable cost and emissions, cost and emissions per ton are estimated. Second, given the capacity of a facility, the linear estimation is used to approximate the exact handling costs and fixed costs (Verter and Dincer, 1995), as well as the emissions. The principle is that a facility with larger capacity have a higher fixed cost and lower unit handling cost due to economies of scale (Van Mieghem, 2003; Verter and Dincer, 1995). We also follow the assumption that a lower handling cost leads to a higher handling emissions for per unit product (Hart and Ahuja, 1996; Porter and Van der Linde, 1996).

Table 5
Values relevant to reverse supply chain and other reminder parameters.

Parameter	Value	Parameter	Value
RT_p	[0.05,0.35]	RC_p	[0.05,0.15]
RR_p	[0.4,0.6]	CPU_p	[1,3]
RD_p	[0.1,0.2]	CPU_a	[1,2]
RM_p	[0.2,0.3]		

The statistics performed by Srivastava (2008) on the return percentages of a series of products, including the televisions, refrigerators, and computers, for which estimated return rates range between 20.6% and 30.7%. A particular case study on HP printers by Davey et al. (2005) reveals a return percentage of 5.7%. Based on the available data, the rate of product return is estimated to be between 5% and 35% for this study. The values of the parameters related to reverse supply chain and capacity utilization rates of parts and products are presented in Table 5.

4.2. Results from the analysis of the models

In this research, to analyze the performance of DCLSC and HCLSC, we adopt the comparative sensitivity analysis with two steps. First, the sensitivity analysis is conducted to evaluate the influences of the parameters, such as return rate, on cost and emissions of DCLSC and HCLSC separately. Such a sensitivity analysis can provide valuable information about regions of compatibility and admissibility of solutions in linear programming (Deif, 2012). Second, the change rate of the performance (for example, on cost and emissions) when varying the values of a specific parameter is obtained using the following expression:

$$\text{Performance change rate} = \frac{\text{value of the performance in HCLSC} - \text{value of the performance in DCLSC}}{\text{value of the performance in DCLSC}} \tag{23}$$

The performance change rate is used for comparing the performance of HCLSC andDCLSC in various carbon policies and market environments. A positive rate would mean that DCLSC is a better option as HCLSC will have more cost and more emissions. The performance in this formulation also refers to the handling cost and emissions of supplier, manufacturer, and the distributor.

We have analyzed and compared the multi-dimensional performance of HCLSC and DCLSC. However, only the figures that denote significant managerial implications are presented in the following subsections.

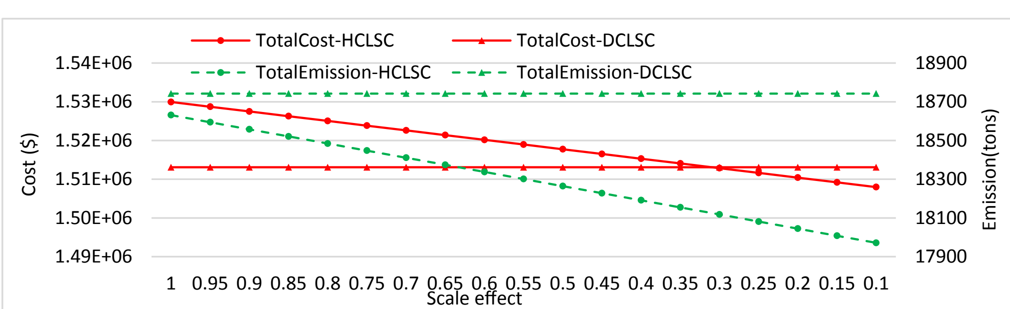

Fig. 3. Impact of scale effect on total cost and total emission.

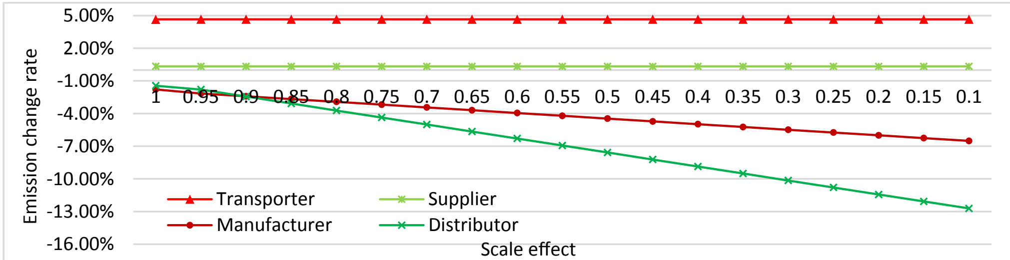

Fig. 4. Impact of scale effect on emissions change rate.

Table 6
Facility selection decisions in DCLSC.

Return rate	Plants (Manufacturer)	Distribution centers	Collection centers	Repair centers	Disposal centers
5%	[1 0 1]	[1 0 0 1]	[0 0 1]	[0 1]	[0 1]
17%	[1 0 1]	[1 0 0 1]	[0 0 1]	[0 1]	[1 0]
25%	[1 0 1]	[1 1 0 1]	[1 0 1]	[1 0]	[1 1]
29%	[1 0 1]	[1 0 1 1]	[1 0 1]	[1 0]	[1 1]
31%	[1 0 1]	[1 1 1 1]	[1 0 1]	[1 1]	[1 1]
35%	[1 0 1]	[1 1 1 1]	[1 1 1]	[1 1]	[1 1]

Table 7
Facility selection decisions in HCLSC.

Return rate	Hybrid plants (Manufacturer)	Hybrid distribution centers
5%	[1 0 1]	[1 0 0 1]
21%	[1 0 1]	[1 1 0 1]
29%	[1 1 1]	[1 1 0 1]
31%	[1 1 1]	[1 1 1 1]

4.2.1. Model 1: Business as usual

Comparative economic and environmental performances of DCLSC and HCLSC without carbon consideration are analyzed under three scenarios: changing scale effect, flexible return rate, and uncertain demand. The scale effect indicates the levels that the fixed cost, handling cost and the emissions would be reduced in HCLSC. The results show that both the overall cost and emissions decrease with an increasing scale effect in HCLSC (see Fig. 3); but it has no impact on DCLSC. Fig. 4 shows that, with increased scale effect, emissions from the manufacturers and the distributors decrease in HCLSC; and this contributes to a lower total emissions in HCLSC (Fig. 3). Further analysis shows that when the same number of facilities are used (in DCLSC and HCLSC), HCLSC results in a higher total cost under a higher scale effect.

In order to explain the changes of the total cost and total emissions, facility selection decisions in CLSCs under various return rates as shown in Tables 6 and 7 are studied. In the tables, the value *1* represents that a facility is opened and *0*, otherwise. For example, in Table 6, for 5%, the expression *[1 0 0 1]* states that only the first and the fourth distribution center are opened. An increasing in return rate results in enlarging handling capacities for returned products in DCLSC, as shown in Table 6. As for HCLSC, more returned products require selecting the plants with larger capacities of remanufacturing, repairing and disposing, and the distributing (Table 7). The changes in terms of the facility selection decisions are marked in grey in the two tables.

Fig. 5 illustrates the effect of the return rate on the overall cost and emission. Compared with HCLSC, DCLSC has a lower total cost. This happens mainly because new distribution centers should be built for DCLSC when more products are returned (see Table 7). It is evident that building dedicated collection centers is more cost efficient. For a return rate of more than 15%, HCLSC yields higher total emissions. When the return rate is 29% or more, total emissions increase due to the increased emissions from the suppliers and the distributors (see Fig. 6).

Fig. 6 shows that the emissions of transporter and supplier are always higher in HCLSC over the range of the return rate. Though a higher level of return rate results in more returned products and raises emissions in distributors, it is observed that the emissions in HCLSC increases faster when the return rate is larger than 27%.

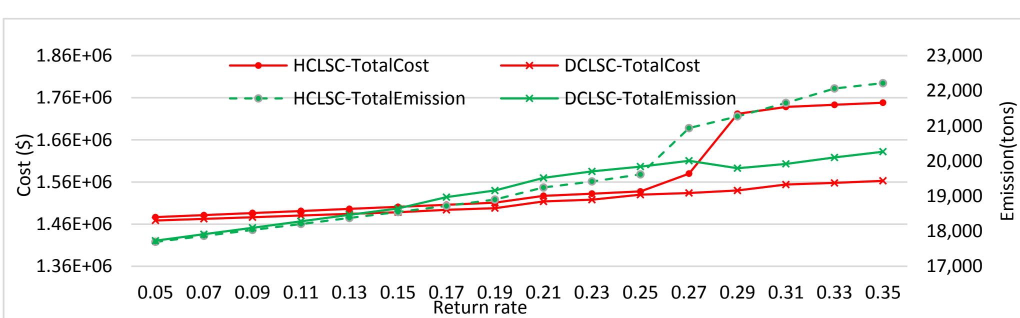

Fig. 5. Impact of return rate on total cost and total emissions.

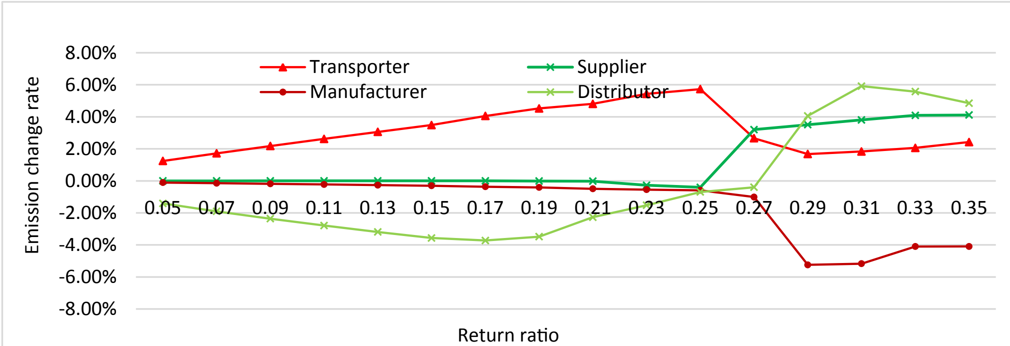

Fig. 6. Impact of return rate on emissions change rate.

Because DCLSC and HCLSC have different handling capacities in reverse logistics and they respond to changing return rates in different ways, such as under what return rate level the new facility for collection should be opened and how purchasing orders should be allocated. There are dramatic changes in the emissions of all the firms when the return rate is up to 27% because new facilities have to be opened in HCLSC to increase handling capacities for returned products.

The sensitivity of the supply chain performances on due to customer demand by ±30% in increments of 5% is also analyzed. Fig. 7 shows that there is no significant comparative advantage of either of CLSCs. However, the performance disparity between DCLSC and HCLSC solution gets smaller when demand increases by more than 25%. This happens because most of the candidate facilities need to be selected in the design when demand is high. This shows that the overall performance can be determined by the scale effect.

4.2.2. Model 2: Carbon cap policy

From Fig. 8 and Fig. 9, it can be concluded that a loose carbon cap will reduce the cost and increase the emissions level more significantly in manufacturers in HCLSC. Further investigation shows that when the limitation on emissions goes up to 16,500 tons, the manufacturing plants with a lower unit cost and higher unit emissions are incorporated into HCLSC. The similar situation occurs to DCLSC with the carbon cap up to 17,500 tons. These two reasons contribute to the bowl in cost change rate of the manufacturer in Fig. 8 and the bowl in the emissions change rate of the manufacturer in Fig. 9.

The distributors in HCLSC show a comparative advantage in both handling cost and emissions except when the value of the cap is extremely low (Figs. 8 and 9). This result is not surprising, because the decision makers are enforced by the carbon cap policy to seek environmental competitive partners and reallocate their orders regardless of the associated cost. Fluctuating cost change rate and higher emissions in suppliers in HCLSC can be explained with the same reasoning. The one policy implication is that the carbon cap policy works effectively in total emissions control, but it does not have equal impact on all firms.

4.2.3. Model 3: Carbon tax policy

Based on the World Bank data (World Bank, 2014), the models were run for a hypothetical scenario of carbon tax between $0/ton and $85/ton (this range covers most of the carbon tax policies in the world). Fig. 10 shows that irrespective of the type of the CLSC, higher carbon tax increases the total cost, but it promotes a

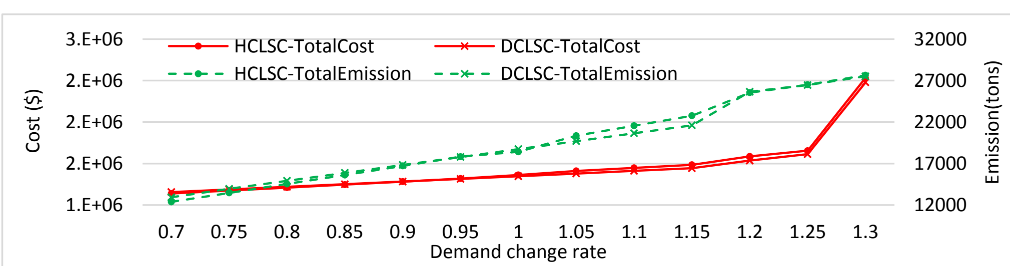

Fig. 7. Impact of demand on total cost and total emissions.

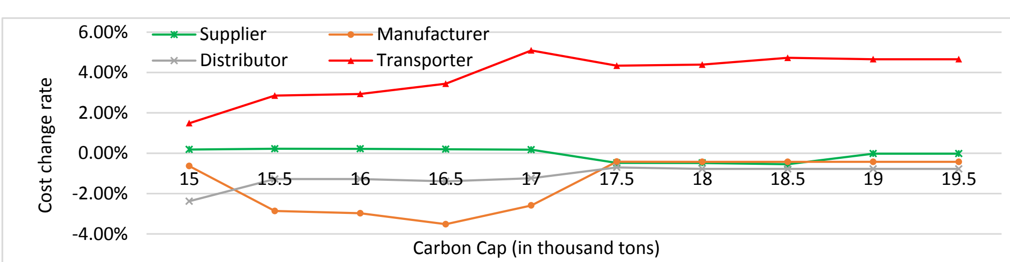

Fig. 8. Impact of carbon cap on cost change rate.

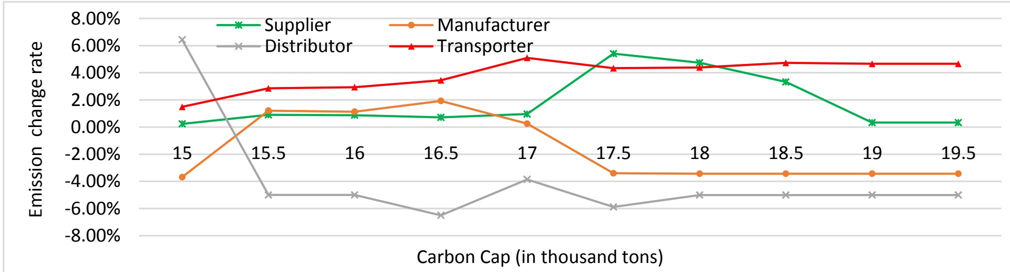

Fig. 9. Impact of carbon cap on emissions change rate.

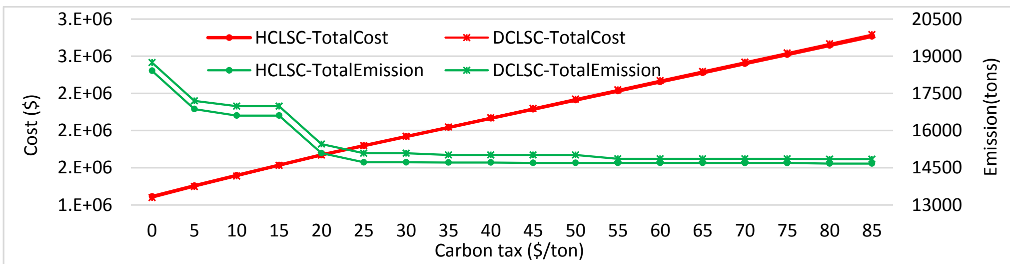

Fig. 10. Impact of carbon tax on total cost and total emissions.

reduction in carbon emissions. However, the figure also indicates that beyond a certain tax amount, there may not be any further reduction in the emissions, although the total cost due to tax will continue to increase. Though the firms would try their best to lower the emissions, there could be technological limits for further reduction on emissions.

As shown in Figs. 11 and 12, the distributors and manufacturers yield a lower cost and emissions in DCLSC under carbon tax policy. However, a notably opposite is observed for suppliers. When the carbon limitation changes, supplier selection and order allocation decisions would also be changed in order to allocate the carbon credit among the supply chain members. The carbon cap policy works in the same way in DCLSC and HCLSC, however, it results in different optimal solutions for each of them.

4.2.4. Model 4: Cap-and-trade policy

The impact of the carbon cap-and-trade policy depends on the method used to allocate the cap and the market price (Jin et al., 2014). The European Climate Exchange (ECX) data shows carbon price limits between \$3.12/ton and \$19.53/ton during 2009–2015. However, the price in the EU is anticipated to be up to \$35/ton in future to fulfil its emissions reduction target by 2020 (Wacket,

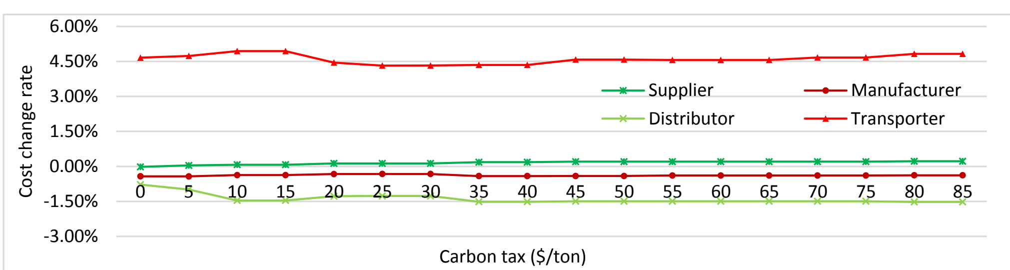

Fig. 11. Impact of carbon tax on cost change rate.

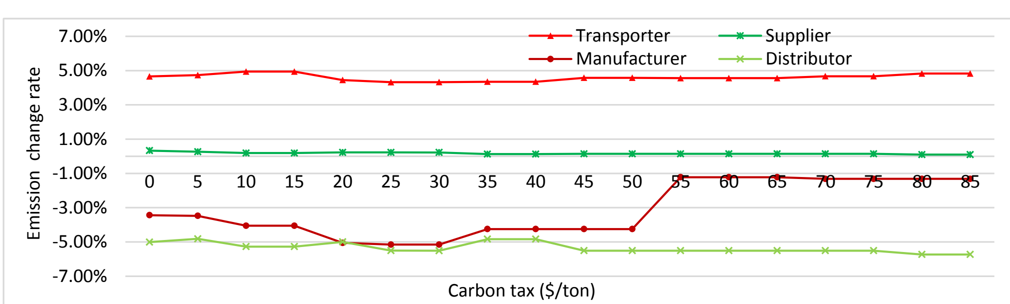

Fig. 12. Impact of carbon tax on emissions change rate.

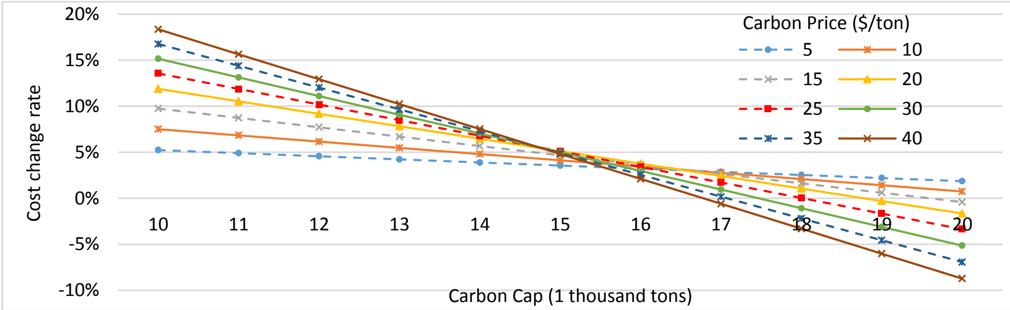

Fig. 13. Impact of cap-and trade on total cost.

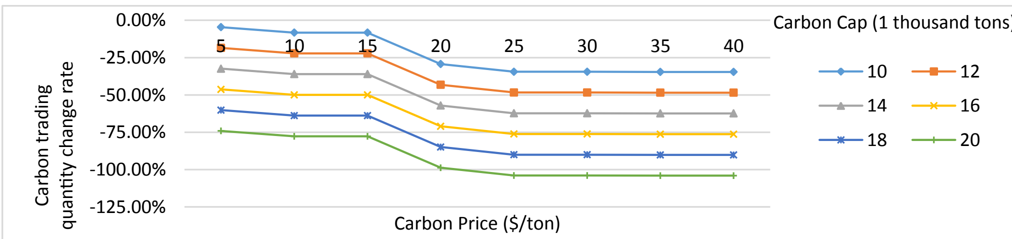

Fig. 14. Impact of cap-and-trade on carbon trading quantity change rate.

2015). Based on these information, the carbon price $5/ton to $40/ton carbon price is assumed to analyze the models.

As per the fourth model mentioned in Table 1, there is a linear relationship between carbon cap and the total cost both in DCLSC and HCLSC. The total cost of HCLSC is higher under a tight cap, and the opposite result is achieved under a loose cap (see Fig. 13). The analysis shows that the total cost can be reduced using HCLSC rather than using DCLSC under the carbon cap policy. Once the firms are allowed to trade their carbon credit in the market, more profits are obtained for HCLSC because of its lower total emissions compared to that of DCLSC. The cost change rate curve gets steeper with the rise in carbon price (see Fig. 13), because per unit emissions would pose great effect on the total cost when the price is at a higher level. From Fig. 14 it can be observed that increasing carbon cap enlarges the carbon trading amount disparity between DCLSC and HCLSC. This means that with HCLSC, there is a possibility of purchasing less or selling more carbon credits than that with DCLSC. One of the managerial implications of this outcome is that the profit of HCLSC and the carbon reduction of DCLSC rely on the carbon market. The result in Fig. 14 also indicates that the carbon

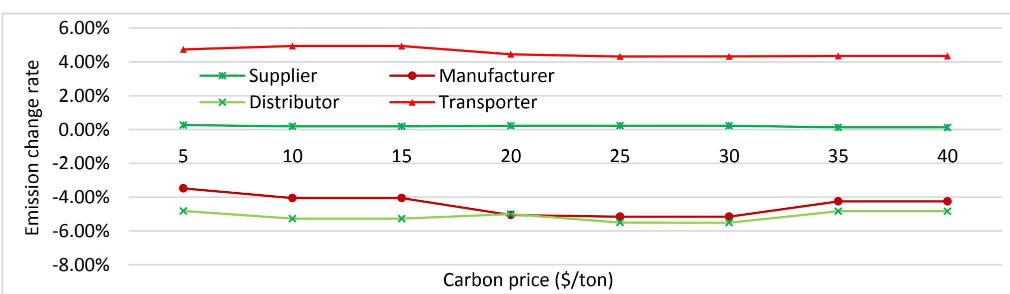

Fig. 15. Impact of cap-and-trade on emissions change rate.

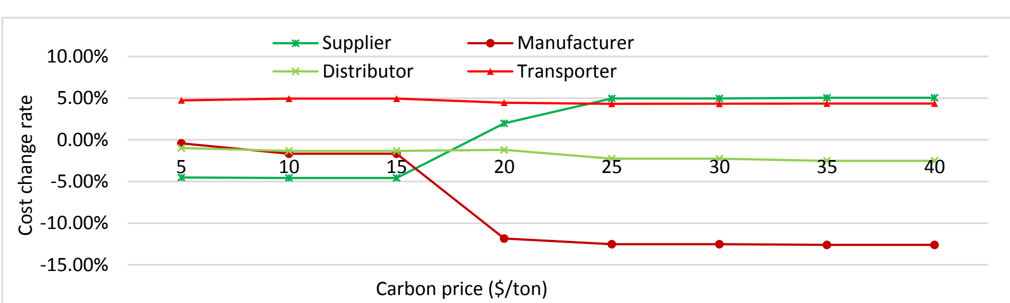

Fig. 16. Impact of cap-and-trade on cost change rate.

trading decisions in both DCLSC and HCLSC are more sensitive to carbon price than to carbon cap.

The analysis shows that carbon caps have equal impacts on the emissions or cost change rate, therefore, only the influence of the carbon price is shown (see Figs. 15 and 16). In Fig. 15, emissions of the transporters in HCLSC increase by almost 5%, while the emissions of the manufacturers and the distributor in HCLSC decrease by nearly 5%, similar to that under the carbon tax policy. Fig. 16 shows that the cost of suppliers in HCLSC is lower than that in DCLSC when the carbon price is low, but it is changed with an increasing carbon price. The main reason for this phenomenon is the selection of suppliers with lower emissions but higher cost per unit of parts in HCLSC. As there is a limit to emissions reduction, higher carbon price does not bring additional incentives, as shown in Fig. 16.

4.3. Insights from sensitivity analysis and discussion

The design of a CLSC is a strategic decision and has a long term impact on a firm; this means that a firm has to anticipate possible policy or market environment changes that will take place in the future. For example, there is no wide range application of any carbon policy in China or India, but Chinese government is planning to enforce the cap-and-trade policy in 2016 (Han et al., 2012). As a firm, whether it is a supplier or manufacturer or distributor, it should take this policy into consideration. We highlight below as to how the combination of the policy and environmental factors and the types of CLSCs affect cost and emissions, especially from the perspective of an individual firm.

4.3.1. Sensitivity analysis of cost and emissions in dedicated and hybrid closed loop supply chains

In order to assess the impact of changes in some parameters on the CLSC decision, a sensitivity analysis is performed. It is assumed that if $(Max_z - Min_z)/Min_z \geq 10\%$, the result is regarded as sensitive to the chosen parameter. The performance metrics show various sensitivities, as presented in Table 8, to the policy parameters. The different sensitivity also implies different challenges during the implementation of the policies (Jin et al., 2014). In Table 8, a blank cell indicates that there is no noticeable impact of the factor on the policy (economic or emission) that is adopted by a company. We highlight some of the insights based on Table 8.

- If the company is concerned with the scale effect policy, then for a HCLSC, it is important to analyze the emissions from the distributors. If the company is concerned with the scale effect when choosing a HCLSC structure, it is also important to analyze the emissions from the distributors. This is mainly because the only the emissions of the distributor show sensitivity to the scale effect.
- Customer demand can affect both DCLSC and HCLSC design, in terms of total cost and total emissions. The total costs of both HCLSC and DCLSC show a high dependence on emissions limitation in the carbon cap policy. Similar results also obtained by Palak et al. (2014). However, compared with the emissions limitation, the carbon price in the cap-and-trade impacts not only the cost but also the emissions. Therefore, if the cap-and-trade policy is implemented, it can be anticipated that firms may not be encouraged to cut down on the emission. They will seek carbon market to balance the limit and their actual emission. Firms' carbon trading decisions in the carbon market are determined by both the carbon price and cap level under cap-and-trade policy (Palak et al., 2014). Given the carbon price level, our further investigation reveals that the shift from purchasing to selling carbon credits in HCLSC occurs at a lower cap level than in DCLSC.
- The emissions reduction under cap-and-trade policy rely on a high carbon price or a tight cap (Chaabane et al., 2012; Jin et al., 2014). Our research also shows that a tight cap is more efficient to control the emissions than a higher carbon price, both for DCLSC and HCLSC. Only a high carbon price (more than $10/ton) can be used as an effective way to motivate the organization to take low-carbon actions. These observations enable the policy makers take a fresh look at the effectiveness of the carbon trading policy.

4.3.2. Comparison of cost and emissions of dedicated and hybrid closed loop supply chains

Based on the analysis in the previous section, a comparison of cost and emissions for two CLSCs are given in Table 9, which shows under what conditions HCLSC or DCLSC would have a lower emissions and cost. A blank cell in Table 9 indicates that there is no evidence of either DCLSC or HCLSC being more cost or emissions efficient. When industry faces fluctuating product return rates, DCLSC solution (*D* in the second row and third column) is more cost efficient. Since all the performance metrics are sensitive to customer demand (as shown in Table 8), it can be seen from Table 9 that the performance of DCLSC or HCLSC isn't always more competitive than the other. Some managerial implications from Table 9 are listed below.

- When increasing the carbon price steadily, an erratic nonlinear emissions reduction trend is observed in a carbon tax policy because of the reconfiguration of HCLSC and DCLSC (See Fig. 10).

Table 8
Sensitivity of cost and emissions in DCLSC (D) and HCLSC (H).

Factors to be considered	Under market conditions only			Under emissions policy			
	Scale effect	Return rate	Customer demand	Carbon cap	Carbon tax	Cap-and-trade	
						Carbon cap	Carbon price
Total cost			H,D		H,D		H,D
Total emission			H,D	H,D	H,D	H,D	H,D
Transporter emission		H,D	H,D	D	H,D	H,D	H,D
Supplier emission			H,D	H,D	H,D	H,D	
Manufacturer emission		D	H,D	H,D	H,D	H,D	H,D
Distributor emission	H	H,D	H,D	D	H,D	H,D	H,D
Supplier cost			H,D	H,D		H,D	D
Manufacturer cost			H,D		H,D	H,D	H
Distributor cost		H,D	H,D			H,D	
Transporter cost		H,D	H,D	D	H,D	H,D	H,D

Table 9
Comparison of cost and emissions of DCLSC (D) and HCLSC (H).

Factors to be considered	Under market conditions only			Under emissions policy			
	Fluctuating Scale effect	Fluctuating Return rate	Fluctuating Customer demand	Carbon cap	Carbon tax	Cap-and-trade	
						Carbon cap	Carbon price
Total cost		D		D			
Total emission					H	D	D
Transporter emission	D	D		D	D	D	D
Supplier emission				D	D		
Manufacturer emission	H	H	H		H	H	H
Distributor emission	H				H	H	H
Supplier cost	H					D	D
Manufacturer cost	H	H		H	H	H	H
Distributor cost				H	H	H	H
Transporter cost	D	D		D	D	D	D

A similar result is also obtained by Zakeri et al. (2015) and Fahimnia et al. (2015). However, our analysis also reveals that the total emission of DCLSC is higher than that of HCLSC under carbon tax policy, while the opposite result is observed under cap-and-trade policy. Given that the manufacturer is the major emissions generator in the supply system, the higher emissions in manufacturing and remanufacturing in DCLSC result in this phenomenon.
- The manufacturers in HCLSC tend to have a lower cost and emissions under carbon tax or cap-and-trade policy due to sharing of facilities. In general, in terms of transportation emissions and cost, DCLSC are always better than those in HCLSC, except under changing customer demand environment.

5. Conclusions and limitations

5.1. Conclusions

In this research, integrated MILP formulations are proposed for CLSCs design. A comparative sensitivity analysis is performed to evaluate cost and emissions of DCLSCs and HCLSCs. In order to address the first research question mentioned in Section 1, integrated MILP formulations are developed to examine the impact of carbon policies and market factors on CLSCs. Two types of CLSCs are considered for examination: one, with dedicated facilities in the current supply chain for reverse logistics (or, DCLSC), and two, a combined use of some of the facilities (or, HCLSC) for reverse logistics as well. Decision to develop either a DCLSC or a HCLSC is strategic and therefore, analysis in terms of economics and emissions is important. Comparative sensitivity analysis is also performed to evaluate cost and emissions of DCLSC and HCLSC. We have conducted analysis in Section 4.2 to show the impact of carbon policies and market conditions. For example, in Section 4.2.1, it is shown that when scale effect is considered, overall costs and emissions decrease for HCLSC but it becomes indifferent for DCLSC. However, when the number of facilities do not change, there is an increase in costs and emissions for HCLSC. Further analysis is done and the results are summarized in Section 4.3.1. The analysis shows that not only the total cost and emissions of the whole supply systems, but also cost and emissions of each supply chain entity are affected by the market conditions and carbon policy.

As the response to the second research question in Section 1, the comparison of cost and emissions of DCLSC and HCLSC is presented. The results show that the supply network, which is DCLSC or HCLSC, has significant influences on cost and emissions of both the entire supply chain and its sections. We conducted sensitivity analysis in Section 4.2, to compare cost and emission performances of DCLSC and HCLSC. For example, in Section 4.2.3, under the carbon tax policy, distributors and manufacturers yield a lower cost and emissions in DCLSC than in HCLSC. However, the result is different when it comes to suppliers. The results of the comparison are summarized in Table 9, which shows market and carbon policy conditions under which either DCLSC or HCLSC is more competitive. These results provide valuable insights for industry to make the best decision on the CLSC network selection, which is, DCLSC or HCLSC.

From the viewpoint of organizations, the modeling approach enables industry to make the best decisions for designing DCLSCs and HCLSCs, while the comparative sensitivity analysis is useful to help managers select an appropriate CLSC network, namely DCLSC or HCLSC. For policy makers, the models and the resulting analysis presented here offer a better understanding of the differential impacts of the carbon policies on cost and the emissions of DCLSC and HCLSC. The type of analysis presented here can be applied to a wide variety of industries like plastics, aluminum, and steel, where the emission is usually larger and there is a possibility of receiving returned products for reproduction, reprocessing, reuse or recycling. The generic models and comparative sensitivity analysis approach proposed in this research can be applied for a broad investigation in the analysis of emissions efficiency in supply chain systems.

5.2. Limitations

We acknowledge some limitations in the current study, but these limitations also provide opportunities for further research.

- First, the results of this research rely on a case in plastic industry and the sensitivity analysis is influenced by the selected parameters. Therefore, one extension of this research could be to include data from a broader industry application.
- Second, while comparing DCLSC and HCLSC, linear relations between the capacity and the variable cost or emissions of a handling facility are assumed. Relaxing this assumption on the non-linear relations between the elements due to the economy of scale would result in a more challenging but more realistic models.
- Third, models use deterministic values for the parameters, such as the customer demand, product returns, and the carbon price. A stochastic formulation would better represent the ability of decisions to adapt to the uncertainties in market conditions in the face of carbon policies. Similarly, there are some transaction costs for carbon trading. We would like to thank an anonymous reviewer for mentioning that such costs can play a pivotal role in the total costs calculations and on the transaction costs of individual entities in the supply chain. Heindl (2015) has pointed

that such costs depend on the size of the company and the quantity of the emissions being considered and traded. Therefore, the extension of the model by including such transaction costs of the individual supply chain partners could provide a better picture when all the emissions and exact costs of transactions are known. This can provide a basis for the companies joining the supply chain to assess their potential for loss or gain in the closed loop supply chain.

- Fourth, the reverse logistics activities, such as remanufacturing and recycling, face challenges in global supply chain. It would be interesting to explore the impact of various carbon policies on the global supply chain configuration at least due to the handling of returned products or waste. Similarly, the total emissions generated by the product during the use phase can be an important consideration for obtaining the total emissions of the product (Joshi, 1999; Östlin et al., 2009). We are thankful to an anonymous reviewer for pointing out that the use of the product may have to be considered in the evaluation of total emissions generated by a particular product. This can be important if the products are recyclable or remanufacturable rather than maintainable. Maintainability for an extended period of time may mean that more emissions are generated by such products rather than that by the newer version of such products. Kim et al. (2006) studied energy efficiency improvement scenarios for refrigerators, which shows reduced total GHG emissions with newer versions of the product. Inclusion of this type of scenario requires an extension of the model in terms of recyclability of the product and the anticipated increase in energy efficiency.

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Appendix A. Formulations in DCLSC

A.1 Cost and emissions components

(1) Fixed cost

$$Z_f = \sum_{i\in K\cup L\cup R\cup U\cup V} CF_i f_i \tag{A.24}$$

(2) Handling cost

$$\begin{aligned} Z_h = & \sum_a \sum_s \sum_k C_{as} QF_a^{sk} + \sum_p \sum_{i\in K\cup L} \sum_{x\in\{x2,x3\}} \\ & \times \sum_{j\in M\cup L} CP_{pi}^x QF_{px}^{ij} + \sum_p \sum_{g\in M\cup R} \sum_{x\in\{x4,x6,x9\}} \\ & \times \sum_{h\in R\cup U\cup V} \beta C_{ph}^x QB_{px}^{gh} + \sum_p \sum_{y\in R\cup U} \sum_{x\in\{x5,x7,x8\}} \\ & \times \sum_{z\in S\cup K\cup L} C_{pz}^x QB_{px}^{yz} \end{aligned} \tag{A.25}$$

(3) Transportation cost

$$\begin{aligned} Z_t = & \sum_a \sum_s \sum_k C_{at} d_{sk} QF_a^{sk} + \sum_p \sum_{i\in K\cup L} \sum_{x\in\{x2,x3\}} \\ & \times \sum_{j\in M\cup L} C_{pt}\, d_{ij} QF_{px}^{ij} + \sum_p \sum_{g\in K\cup L\cup R\cup U\cup M} \\ & \times \sum_{x\in\{x4,x5,x6,x7,x8,x9\}} \sum_{h\in K\cup L\cup R\cup U\cup M\cup V} C_{pt}\, d_{gh} QB_{px}^{gh} \sum_p \\ & \times \sum_{g\in K\cup L\cup R\cup U\cup M} \sum_{x\in\{x4,x5,x6,x7,x8,x9\}} \\ & \times \sum_{h\in K\cup L\cup R\cup U\cup M\cup V} C_{pt}\, d_{gh} QB_{px}^{gh} \end{aligned} \tag{A.26}$$

(4) Handling emission

$$\begin{aligned} E_h = & \sum_a \sum_s \sum_k EP_{as} QF_a^{sk} + \sum_p \sum_{i\in K\cup L} \sum_{x\in\{x2,x3\}} \\ & \times \sum_{j\in M\cup L} EP_{pi}^x QF_{px}^{ij} + \sum_p \sum_{g\in M\cup R} \sum_{x\in\{x4,x6,x9\}} \\ & \times \sum_{h\in R\cup U\cup V} \gamma EP_{ph}^x QB_{px}^{gh} + \sum_p \sum_{y\in R\cup U} \sum_{x\in\{x5,x7,x8\}} \\ & \times \sum_{z\in S\cup K\cup L} EP_{pz}^x QB_{px}^{yz} \end{aligned} \tag{A.27}$$

(5) Transportation emission

$$\begin{aligned} E_t = & \sum_a \sum_s \sum_k ET^t d_{sk} QF_a^{sk} + \sum_p \sum_{i\in K\cup L} \sum_{x\in\{x2,x3\}} \\ & \times \sum_{j\in M\cup L} ET^t\, d_{ij} QF_{px}^{ij} + \sum_p \sum_{g\in K\cup L\cup R\cup U\cup M} \\ & \times \sum_{x\in\{x4,x5,x6,x7,x8,x9\}} \sum_{h\in K\cup L\cup R\cup U\cup M\cup V} ET^t d_{gh} QB_{px}^{gh} \end{aligned} \tag{A.28}$$

A.2 Constraints

(1) Balance constraints

Constraints (A.29) and (A.30) are the flow balance in plant and distribution centers for forward logistics. Constraints (A.31) and (A.33) ensure the flow balance in plant, distribution centers and repair centers for reverse logistics. Constraints (A.34) and (A.35) ensure that the new and reprocessed products would be shipped to customers under their requirement. Constraints (A.36) ensures that all the returned products would be collected.- Constraints (A.37) promises the returned products would be shipped to the facilities for further process, where RX_p represents RR_p, RM_p,RC_p,RD_p, respectively for different returned products. In equation (A.37), x∈{x5,x6,x8,x9} and $i\in U\cup K\cup S\cup V$.

$$\sum_s QF_a^{sk} = \sum_p \sum_l Num_{pa} QF_{p,x3}^{kl} \ \forall a,k \tag{A.29}$$

$$\sum_k QF_{p,x2}^{kl} = \sum_m QF_{p,x3}^{lm} \ \forall p,l \tag{A.30}$$

$$\sum_{r} QB^{rk}_{p,x2} = \sum_{l} QB^{kl}_{p,x4} \ \forall p,k \tag{A.31}$$

$$\sum_{k} QB^{kl}_{p,x7} + \sum_{u} QB^{ul}_{p,x7} = \sum_{m} QB^{lm}_{p,x3} \ \forall p,k \tag{A.32}$$

$$\sum_{r} QB^{ru}_{p,x6} = \sum_{l} QB^{ul}_{p,x7} \ \forall p,u \tag{A.33}$$

$$\sum_{l} QF^{lm}_{p,x3} = DM_{mp} \ \forall p,m \tag{A.34}$$

$$\sum_{l} QB^{lm}_{p,x3} \le RT_p DM_{mp} \ \forall p,m \tag{A.35}$$

$$DM_{mp} RT_p = \sum_{r} QB^{mr}_{p,x4} \ \forall p,m \tag{A.36}$$

$$\sum_{m} QB^{mr}_{p,x4} RX_p = \sum_{i} QB^{ri}_{p,x} \ \forall p,r \tag{A.37}$$

(2) Capacity constraints

Constraints (A.38)-(A.40) are the handling capacity constraints in forward logistics. Constraints (A.41)-(A.46) are the handling capacity constraints in reverse logistics.

$$\sum_{a} \sum_{k} CPU_a QF^{sk}_{a} \le f_s CP_s \ \forall s \tag{A.38}$$

$$\sum_{p} \sum_{l} CPU_p QF^{kl}_{p,x2} \le f_k CP^{x1}_{k} \ \forall k \tag{A.39}$$

$$\sum_{p} \sum_{k} CPU_p \, QF^{kl}_{p,x2} \le f_l CP^{x2}_{l} \ \forall l \tag{A.40}$$

$$\sum_{p} \sum_{r} CPU_p QB^{rs}_{p,x8} \le CP^{x8}_{s} \ \forall s \tag{A.41}$$

$$\sum_{p} \sum_{r} CPU_p \, QB^{rk}_{p,x5} \le f_k CP^{x5}_{k} \ \forall k \tag{A.42}$$

$$\sum_{p} \left(CPU_p \left(\sum_{u} QB^{ul}_{p,x7} + \sum_{k} QB^{Kl}_{p,x7} \right) \right) \le f_l CP^{x7}_{l} \ \forall l \tag{A.43}$$

$$\sum_{p} \sum_{m} CPU_p \, QB^{mr}_{p,x4} \le f_r CP^{x4}_{r} \ \forall r \tag{A.44}$$

$$\sum_{p} \sum_{r} CPU_p \, QB^{ru}_{p,x6} \le f_u CP^{x6}_{u} \ \forall u \tag{A.45}$$

$$\sum_{p} \sum_{r} CPU_p \, QB^{rv}_{p,x9} \le f_v CP^{x9}_{v} \ \forall v \tag{A.46}$$

(3) Binary and the non-negativity restrictions

$$f_i \in \{0,1\} \ \forall i \tag{A.47}$$

$$QF^{sk}_{a} \ge 0 \ \forall a,s,k \tag{A.48}$$

$$QF^{ij}_{p} \ge 0, QB^{ij}_{p} \ge 0 \ \forall i,j \tag{A.49}$$

Appendix B. Formulations in HCLSC

B.1 Cost and emissions components

(1) Fixed cost

$$Z_f = \sum_{i \in K \cup L} CF_i f_i \tag{A.50}$$

(2) Handling cost

$$Z_h = \sum_{a} \sum_{s} \sum_{k} C_{as} QF^{sk}_{a} + \sum_{p} \sum_{i \in K \cup L} \sum_{x \in \{x2,x3\}} \sum_{j \in M \cup L} CP^{x}_{pi} \, QF^{ij}_{px} + \sum_{p} \sum_{g \in L \cup M} \sum_{x \in \{x4,x6,x9\}} \sum_{h \in K \cup L} \beta C^{x}_{ph} \, QB^{gh}_{px} + \sum_{p} \sum_{y \in L \cup K} \times \sum_{x \in \{x5,x7,x8\}} \sum_{z \in S \cup K \cup L} C^{x}_{pz} \, QB^{yz}_{px} \tag{A.51}$$

(3) Transportation cost

$$Z_t = \sum_{a} \sum_{s} \sum_{k} C_{at} d_{sk} QF^{sk}_{a} + \sum_{p} \sum_{i \in K \cup L} \sum_{x \in \{x3,x9\}} \times \sum_{j \in M \cup L} C_{pt} \, d_{ij} QF^{ij}_{px} + \sum_{p} \sum_{g \in K \cup L \cup M} \sum_{x \in \{x4,x5,x6,x7,x8,x9\}} \times \sum_{h \in K \cup L \cup M} C_{pt} \, d_{gh} QB^{gh}_{px} \tag{A.52}$$

(4) Handling emission

$$E_h = \sum_{a} \sum_{s} \sum_{k} EP_{as} QF^{sk}_{a} + \sum_{p} \sum_{i \in K \cup L} \sum_{x \in \{x2,x3\}} \times \sum_{j \in M \cup L} EP^{x}_{pi} \, QF^{ij}_{px} + \sum_{p} \sum_{g \in g \in L \cup M} \sum_{x \in \{x4,x6,x9\}} \times \sum_{h \in K \cup L} \gamma EP^{x}_{ph} \, QB^{gh}_{px} + \sum_{p} \sum_{y \in L \cup K} \sum_{x \in \{x5,x7,x8\}} \times \sum_{z \in S \cup K \cup L} EP^{x}_{pz} \, QB^{yz}_{px} \tag{A.53}$$

(5) Transportation emission

$$E_t = \sum_{a} \sum_{s} \sum_{k} ET^{t} d_{sk} QF^{sk}_{a} + \sum_{p} \sum_{i \in K \cup L} \sum_{x \in \{x2,x3\}} \times \sum_{j \in M \cup L} ET^{t} \, d_{ij} QF^{ij}_{px} + \sum_{p} \sum_{g \in K \cup L \cup M} \sum_{x \in \{x4,x5,x6,x7,x8,x9\}} \times \sum_{h \in K \cup L \cup M} ET^{t} d_{gh} QB^{gh}_{px} \tag{A.54}$$

B.2 Constraints

(1) Balance constraints

Constraints (A.55) and (A.56) are the flow balance in plant and distribution centers for forward logistics. Constraints (A.57) and (A.58) ensure the flow balance in plant and distribution centers for reverse logistics. Constraints (A.59) and (A.60) ensure that the new and reprocessed products would be shipped to customers under their requirement. Constraints (A.61) ensures that all the returned products would be collected.- Constraints (A.62) promises the returned products would be shipped to the facilities for further process, where RX_p represents RR_p, RM_p,RC_p,RD_p, respectively for different returned products. In equation (A.62), x∈{x5,x6,x8,x9} and $i \in K \cup S$.

$$\sum_s QF_a^{sk} = \sum_p \sum_l Num_{pa} QF_{p,x2}^{kl} \ \forall a,k \tag{A.55}$$

$$\sum_k QF_{p,x2}^{kl} = \sum_m QF_{p,x3}^{lm} \ \forall p,l \tag{A.56}$$

$$\sum_l \left(QB_{p,x6}^{lk} + QB_{p,x5}^{lK} \right) = \sum_l QB_{p,x7}^{kl} \ \forall p,k \tag{A.57}$$

$$\sum_k QB_{p,x7}^{kl} = \sum_m QB_{p,x3}^{lm} \ \forall p,l \tag{A.58}$$

$$\sum_l QF_{p,x3}^{lm} = DM_{mp} \ \forall p,m \tag{A.59}$$

$$\sum_l QB_{p,x3}^{lm} \le RT_p DM_{mp} \ \forall p,m \tag{A.60}$$

$$DM_{mp} RT_p = \sum_l QB_{p,x4}^{ml} \ \forall p,m \tag{A.61}$$

$$\sum_m QB_{p,x4}^{ml} RX_p = \sum_i QB_{p,x}^{li} \ \forall p,l \tag{A.62}$$

(2) Capacity constraints

Constraints (A.63) – (A.65) are the handling capacity constraints in forward logistics. Constraints (A.66)-(A.71) are the handling capacity constraints in reverse logistics.

$$\sum_a \sum_k QF_a^{sk} CPU_a \le f_s CP_s \ \forall s \tag{A.63}$$

$$\sum_p \sum_l QF_{p,x2}^{kl} CPU_p \le f_k CP_k^{x1} \ \forall k \tag{A.64}$$

$$\sum_p \sum_m CPU_p \ QF_{p,x3}^{lm} \le f_l CP_l^{x2} \ \forall l \tag{A.65}$$

$$\sum_p \sum_l CPU_p QB_{p,x8}^{ls} \le CP_s^{x8} \ \forall s \tag{A.66}$$

$$\sum_p \sum_l CPU_p \ QB_{p,x5}^{lk} \le f_k CP_k^{x5} \ \forall k \tag{A.67}$$

$$\sum_p \sum_l CPU_p QB_{p,x6}^{lk} \le f_k CP_k^{x6} \ \forall k \tag{A.68}$$

$$\sum_p \sum_l CPU_p \ QB_{p,x9}^{lk} \le f_k CP_k^{x9} \ \forall k \tag{A.69}$$

$$\sum_p \sum_k CPU_p \ QB_{p,x7}^{kl} \le f_l CP_l^{x7} \ \forall l \tag{A.70}$$

$$\sum_p \sum_m CPU_p \ QB_{p,x4}^{ml} \le f_l CP_l^{x4} \ \forall l \tag{A.71}$$

(4) Binary and the non-negativity restrictions

$$f_i \in \{0,1\} \ \forall \ i \in K \cup L \tag{A.72}$$

$$Q_a^{sk} \ge 0 \ \forall a,s,k \tag{A.73}$$

$$QF_p^{ij} \ \ge 0, QB_p^{ij} \ \ge 0 \ \forall i \in K \cup L \cup M \cup S, j \in K \cup L \cup M \cup S \tag{A.74}$$

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