International Journal of Applied Operational Research
Vol. 4, No. 4, pp. 49-76, Autumn 2014

Journal homepage: ijorlu.liau.ac.ir

Cost minimization model for reducing carbon footprints from different transportation modes

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Received: 3 March 2014 ; **Accepted:** 29 July 2014

Abstract Recovery of used products is receiving much attention recently due to growing environmental concerns.In this paper, we address the carbon footprint basedon problem arising in closed-loop supply chain where returned products are collected from customers. These returned products can either be disposed or be remanufactured to be sold as new ones again. Here, we formulate a comprehensive closed-loop model for the logistics planning considering profitability and ecological goals. In this way, we can achieve the ecological goalreducing the overall amount of CO_2 emitted from journeys. Moreover, the profitability criterion can be supported in the cyclic network with the minimum costs and maximum service level. To validate the model a numerical experiment is worked out.

Keywords: Closed-loop Supply Chain, Mixed Integer Linear Programming, Carbon Emissions, Transport Mode Selection.

1 Introduction

The issue of supply chain management has received increasing attention among the researchers over the last few decades or so. Nowadays, due to the existence of global and competitive market, it is necessary that enterprises work together to enhance their adaptive ability and viability in the market. Hereby, these achieve common goals such as minimizing the total costs and the delay of deliveries in the whole chain [1-3]. A supply chain is a network containing of suppliers, manufacturers, distribution centers (DCs), retailers, and customers, in which raw materials are received, transformed, produced, and delivered to the end-customer [4]. Three main flows exist in the chain; the material flow, the information flow, and the fund flow. Coordination and integration of these flows across from the enterprises is called a supply chain management (SCM) [5].

The global economic growth from the 20th to the 21st century has led to rise in consumption of goods. Consequently, large streams of goods all over the world have been founded. In this way, the production and all aspects of logistics such as transportation,

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warehousing and inventories have created large environmental problems such as global warming and climate changes [6].

Integration of the SCM concept with the issue of environment protection confirms sharp decline in pollution problem. Research on this approach has received considerable attention recently and led to create new research agenda, green supply chain management (GSCM). So, GSCM is a new paradigm where the supply chain will have a direct relation to the environment.

In the reverse logistics/closed-loop supply chain systems, a product returns to the manufacturer after use and can be repaired or remanufactured to be delivered again to the end consumers. A top environmental issue for an enterprise is how to reduce the utilization of the materials by reusing and remanufacturing the used products. This brings about the GSCM concept and has led to a problem of the closed-loop supply chain management.

With well-managed reverse logistics, the environment protection can be achieved with minimizing of total costs in the whole closed-loop supply chain.Most of the previous studies focused on reverse logistics and only formulated models corresponding to this field. Some researchers presented the closed-loop models, but they did not consider the relation between forward and reverse flows in their proposed models [7-9]. These models often assumed the unlimited capacities for the reverse logistics which is not valid assumption for representing the real situations. There exist a few studies in which closed-loop models were proposed with realistic assumption. In these studies, researchers shared the same capacity for the reverse logistics and stated the relation between forward and reverse flows [10]. In this study, we designeda closed-loop supply chain network in which not only the relation between forward and reverse flows is met but also capacity for the reverse logistics is supposed to be restricted.

Reviewing the above-mentioned literature on closed-loop supply chain, it is concluded that a few studies consider the relations between forward and reverse logistics. In this study, we extend the Wang and Hsu's model [10] doing more to protect the environment. First of all, in addition to manage properly reverse logistics to reduce negative impact of greenhouse gases emissions, we suggest another strategy for achieving an expected goal, simultaneously. Here, we focus on a different and important aspect of green supply chains: We focus on transport mode selection as a way to reduce emissions.

In the transport mode selection literature, the approach of the previous studies is very different because the focus is on accurately describing transport and inventory models [11]. Some studies considered emissions come from freight transport. Bauer et al[12] developed an integer linear programming model to optimize a service network design with theaim to minimize the emissions. An overview of all available literature on transportation mode selection given by Meixell and Norbis [13] indicated that none of the studies they reviewed included emissions. Studies are available in the transport choice literature in which a simple inventory model was formulated and the effect of regulation mechanisms to drive down carbon emissions on transport mode selection decision was investigated [14]. Their work differs from our work because they analyzed a situation in which a single transport mode was to be selected by a decision-maker to conduct all transport. Moreover, they only discussed forward flow for their chain with presentation of a simple inventory model.

Incorporation of transport mode selection into a closed-loop model with aim to protect environment is a main contribution of our study. For this, in addition to minimizing the total cost in the whole closed-loop chain, we consider a regulation to reduce carbon emissions come from freight transport. This mechanism specifies a cost for carbon emissions. In this study, we pursue a scenarioand develop problem formulation for this scenario corresponding to this regulation. This scenario is given below:

- Model with emissions (Emission cost-minimization problem)

Here, we use an empirical data to estimate the carbon emissions for various transport modes accurately. The carbon emissions are taken into account for the scenario where a trade-off exists between lead time, unit transportation cost, and unit emissions for transport mode. For example, air transport has a shorter lead time, higher unit transportation costs and carbon emissions than water transport.

The remainder of our works is organized as follows. In section 2, we present the literature review regarding GSCM and closed-loop supply chain. The proposed problem is fully explained and justified in section 3. The methodology based on empirical data to estimate the carbon emissions for different modes of transport is also discussed. Next, the mathematical formulation for the scenario is developed. In section 5, the numerical experiment to illustrate the effectiveness of the proposed methodology is given. Finally, conclusions are presented.

2 Literature Review

Below, the review of previous studies on GSCM and reverse logistics/ closed-loop supply chain systems is discussed and divided into two sections which are GSCM and closed-loop supply chain.

Green Supply Chain Management (GSCM)

The roots of environmentalism come from the period of World War II when the shortages of materials took place worldwide. Subsequently, people were forced to become creative and reuse or recycle many different materials. Recently, many enterprises are undertaken to restructure their supply chain processes to minimize the environmental impact in reaction to increasing public concern of the environment pollution. Supply chain is central to do environmentally friendly practices and supply chain managers play a key role in implementing this issue since they are responsible for the entire flow of materials throughout the supply chain. Moreover, they are who change in making decisions about the procurement and disposition of materials.

The green supply chain was first introduced by Kelle and Silver [15]. They designed an optimal system to forecast products that can be potentially reused.

Green Design: Green design is an important issue in the GSCM literature which deals with designing a product or a service considering environmental concerns. The first green design study was done by Navin-Chandra [16].The author considered a green design with the aim of reducing the impact of product waste. After that, an expansion of framework of green design can be found in the literature. See for example Ashley [17], Allenby and Richards [18], and Zhang et al[19].One of the frameworks emerged from green design was life-cycle analysis. This was proposed for measuring environmental and resources related products to the production process. Also, it quantifies the used and wasted energy and materials and assesses the impact of the product on the environment. A Discussion on life-cycle analysis as a framework was given by Arena et al [20], Beamon [21], and De Ron and Penev [22].

Green Operations: Reverse logistics came out of green operations and was known as an important concept in the GSCM literature. This sets against the forward logistics concept and is known as a process in which a manufacturer accepts shipped products from end-consumers for recycling and remanufacturing. There exist many case studies on reverse logistics in the literature. See for example Kelle and Silver [16], Pohlen and Farris [23], Stock [24], Tibben-Limbke [25].Srivastava and Srivastava [26] and Min et al [27] probed a reverse logistics concept from academic's viewpoint.

Waste Management: Another topic extracted from GSCM literature was waste management. This was first argued by Roy and Whelan [28]. The authors designed a model to reduce electronic waste without harming the environment. Sarkis and Cordeiro [29], and Nagorney and Toyasaki [30] investigated waste management issues around recycling and remanufacturing.

Green Manufacturing: In 1993, Crainic et al[31] conceptualized the green manufacturing concept for the first time. They formulated a comprehensive green supply chain model in which transporting containers from land to sea was considered. Moreover, dynamic and stochastic models for the allocation of empty containers were investigated. After that, the ideas of green manufacturing were extended in the literature. See for example Guide and Srivastava [32].

There are comprehensive reviews on GSCM literature. For example, Bras and McIntosh [33] presented an overview of GSCM from the green production and planning and manufacturing's viewpoint. An overview of GSCM from the perspective of product recovery was done by Gungor and Gupta [34].

Closed-loop Supply Chain

All those activities corresponding to the transformation and flows of products and services with their information from the sources of the materials to the end-consumers are defined as a closed-loop logistics [35]. That aclosed-loop supply chain is a network containing manufacturers, retailers, with logistics service providers in the forward channel and in contrast with this structure, existence of a backward channel which contains the material recovery facilities was pointed out by Fleischmann et al [36].A proper management of closed-loop logistics makes improvement on economic and environmental performance throughout the chain.

These objectives are obtained when the long-term relationships between buyers and suppliers are established [37]. Few studies in the literature have considered the closed-loop logistics where is the integration of the forward and reverse logistics. Fleischmann et al [7] proposed a model in which both the forward and reverse logistics have been considered. The authors assumed unlimited capacities for designing their reverse logistics. Salemaet al[8] extendedthe Fleischmann et al [7]model and formulated the general model for the case study conducted in Iberian Company. Both the proposed models by Fleischmann et al and Salemaet al did not considersupplier side and the relations between forward and reverse flows.

In real life situations, the DC also plays such role as a collector in a recovery system. So, the capacity of DC is restricted to both distribution and collection. Now, there is an interaction between amounts of the distribution and the collection so that when the amounts of the collection are larger, then the amounts of distribution must decrease under the same capacity. Similarly, it can also occur in the manufactory where the flow of materials from both forward and reverse is under the same capacity. Suppliers and dismantlers are responsible for delivering materials to the manufactory in forward and reverse flows, respectively. The closed-loop supply chain is characterized with these interactions. With the lack of such kind of relations, the model can be separated into two parts independently and become a supply chain including forward and reverse chains but not a loop. Solving the closed-loop network design problem using Benders decomposition was done by Uster et al[9]. The authors formulated the simple assignment model for the proposed problem which was not proper for representing the real situations. Wang and Hsu [10] proposed a generalized closed-loop model for the logistics planning. They formulated an integer linear programming model in which the integration between forward and reverse logistics and the decisions for selecting the places such as DCs was considered. Due to NP-hard nature of their model, a Genetic algorithm based on spanning tree structure was developed.

Thinking about the structure of closed-loop supply chain, whether or not, reminds us of the concept of network. Many procedures are available in this field. One of these is related to Traveling Salesman Problem (TSP) concept which having N cities, a salesman should start from home city, visit all customers once and comes back to the home city finding a minimal route. While there are several salesmen who all start and return to a single home city somehow all customers are visited exactly once is known as multiple Traveling Salesman Problem (mTSP).

Now, we suppose that there are multi DCs in a supply network. Any of them has a number of salesmen. Multiple DCs, Multiple Traveling Salesmen Problem (MDMTSP) finds tours for all salesmen such that all customers are visited exactly once and the total cost of the tours are minimized. The point that salesmen depart from DCs and arrive to the single destination is called as multiple departures single destination multiple TSP. This concept has several applications which one of them is for modeling school bus routing. In such problems, buses depart from DCs and arrive to the single destination (school). All passengers are serviced exactly once and the total cost of all the tours is minimized, [38].

Reviewing the above-mentioned literature on closed-loop supply chain, it is concluded that a few studies consider the relations between forward and reverse logistics. In this study, we extend the Wang and Hsu's model doing more to protect the environment. Embedding the transport mode selection, MDMTSP and time window concepts in a closed-loop system with respect to the overall amount of CO_2 emitted from journeys, it is noted that our closed-loop network design is more precisely planned with aim to protect environment. Here, we use a regulation mechanism to reduce carbon emissions come from freight transport. To our knowledge, this study is the first paper which considers these concepts in the closed-loop supply chain.

3 Problem description

In this section, we categorize our problem description into three. The first one wants to have a discussion about our proposed closed-loop chain; the second clarifies the transportation concept especially mode choice, and the third is emission calculations.

The proposed closed-loop chain

There are essentially five stages along a green logistic network: suppliers, manufacturers, DCs, customers, and dismantlers. Here, we consider multiplemanufactories, DCs, dismantlers, and customers being serviced with one supplier, various transport modes, and one commodity with deterministic demands. The initial problem is making decisions for choosing the proper places of manufactories, DCs, and dismantlers among candidates set while pursuing minimal operations cost, carbon emission, maximal profits, considering inventory constraints and satisfying customer demands. Distribution of product from DCs to customers playsa critical role. The MDMTSP approach can be appropriate for this problem. Any salesman located at

DC must depart and visit customers and then go back to the similar or dissimilar DC. In this problem, we suppose that any customer is supplied by only one DC. Meanwhile, the total demands are satisfied. We use the basic conditions for our closed-loop chain and consider them as our assumptions in modeling.These basic conditions are given below:

- The customers' demands must be satisfied.
- The flow transferred between two inconsecutive stages must be prevented.
- The number of opened facilities and their capacities are limited.

Recycling rate issue is only discussed in the closed-loop logistics literature. This contains the recovery and landfilling rates. In our model, the recovery amount is assumed to be a percentage of the customer demand corresponding to the Laan et al [39]assumption based on the dependence of the amounts of returned products on the demand of the products. So, the following assumption is considered by our model.

- The recovery and landfilling rates are given.

One of the main advantages of our proposed model is integrating the transport mode selection and closed-loop logistics in the supply network. In this study, we design a closed-loop supply chain with aim both to minimize the total cost and to reduce the environmental impact in the whole chain by choosing the optimal locations of the facilities, the flows of operation units, and the transportation modes along each capacity-constrained stage when the demand of customers and the recycling rates are given.

Transportation

Transportation has a significant impact on air pollution so that the overall amount of CO_2 emitted from it is about 14% of total emissionsat global level [40, 41]. Transportationmodeis one of the main choices in transport. There is a variety of transportation modes in our closed-loop chain such as transport by plane, ship, truck, or rail. Costs, transit time, and environmental performance are factors by which each mode is distinguished from other modes. Here, the transport mode is chosen using financial and environmental considerations. Besides, the time window constraints play a key role in selecting the transport mode.Due to the air pollution impacts resulting from freight transportation, this paper pays a special attention to this issue from CO_2 emission's viewpoint.

Emission calculations

There are several methodologies to measure carbon emissions accurately: Greenhouse Gas protocol (GHG) [42], Artemis [43], EcoTransIT [44], NTM [45], and STREAM [46]. Here, we use the NTM method which specifies emissions for four types of transport: air, rail, road, and water. The NTM method has a high level of detail and focuses on Europe. In this section, we describe the calculation method for the total emissions for each type of transport. This method calculates the total emissions for an average-loaded vehicle and allocates part of the emissions to one unit of product. Below, emissions calculated for four types of transport based on NTM method are given.

Air Transport: The emission factor and the distance are the two main elements determining the total emissions come from the air transport. The emission factor is in two parts; a constant emission factor (*CEF*) and a variable emission factor (*VEF*). Estimation of the emission factors from aircraft is based on aircraft type, engine type, and maximum load. With respect to this type of transport, the flight distance (D_a) is considered to calculate the distance between the origin and destination location. The bend of the earth is taken into account when we need to calculate the flight distance. The total emissions for an aircraft are calculated by the following equation:

$$EM_{total} = CEF + VEF \cdot D_a \qquad (1)$$

Defining the equation (1), the total emissions for an average-loaded vehicle have been calculated. If we want to allocate part of the emissions to one unit of product (e_a), we also have to define the dimensional weight (w_d) which is determined by the density (ρ) times volume (v) of one unit of product. Corresponding to the [47], if a product has a higher density than 167 (kg/m^3), the actual weight is considered to calculate the dimensional weight. In contrast to this, the volume times 167 (kg/m^3) is substituted for the actual weight when a product has a low density. Then,

$$w_d = \max(w, 167v) = \max(\rho v, 167v) = v \max(\rho, 167) \qquad (2)$$

Since the amount of goods carried by a vehicle depends on the weight and the volume of the load, the emissions allocated to one unit of the product (e_a in kg) are calculated as follows:

$$e_a = EM_{total} \frac{w_d}{Lo_{\max} LF} \qquad (3)$$

where, $LO_{\max}$ and LF are the maximum load of an aircraft (in kg) and the average load factor of the aircraft, respectively.

Railway transport:Here, the emission calculation method for only diesel engine in railway transportation is described [48]. The unit emissions are calculated (e_d) based on the emission factor, the distance, and the weight of the product. The amount of CO_2 emitted when transporting 1 net tonne over 1 km in wayis known as the emission factor (EF in $kg\, CO_2$ / net tonne km). It depends on several factors outlined below:

- The gross weight of the train (W_{gr} in tonne): includes the weight of the locomotive and the carriages.
- An emission constant (T): determines the fuel consumption for a way.
- A correcting factor for the terrain (ξ_t): is different based on the topography of the way. For example, the factor for *hilly* and *mountainous* terrain is greater than for *flat*. Hence, $\xi_f = 1$ and $\xi_m > \xi_h > 1$, where $t \in \{flat, mountainous, hilly\}$.
- The load factor (LF): equals the ratio of net and gross weight of the train.
- The fuel emissions (FE): denotes the emissions per liter of fuel burnt.

The emission factor for the diesel rail transport (EF_d in ($kg\, CO_2$ / net tonne km)) is defined by the following equation:

$$EF_d = \frac{\xi_t \cdot T \cdot FE}{10^6 \sqrt{W_{gr}} \cdot LF} \qquad (4)$$

The emissions allocated to one unit of the product (e_d in kg) is a function of the distance (D in km), the weight of the product(w in tonne), and the emission factor. The formula for the unit emissions for the diesel engine in railway transportation is then:

$$e_d = EF_d \cdot D \cdot w \qquad (5)$$

Road transport: In this section, the fuel consumption, the fuel emissions and the distance are three main factors to calculate the total emissions of the vehicle. Below, each factor is given in more detail.

- The fuel consumption(FC in l/km) is based on two factors, load factor (LF) and the type of vehicle and is calculated as follows:

$$FC = FC_{empty} + \left(FC_{full} - FC_{empty}\right) \cdot LF \tag{6}$$

where, FC_{full} and FC_{empty} are the fuel consumption for a full loaded vehicle and the fuel consumption for an unloaded vehicle, respectively.

- The fuel emissions (FE) is defined as gram of CO_2 emitted per liter of fuel.
- The Distance (D in km) is the distance between the locations.

Combining these factors yields the following equation for the total emissions of the vehicle for road transport (EM_{total} in g):

$$EM_{total} = FE \cdot FC \cdot D \tag{7}$$

Defining the equation (7), the emissions of the entire vehicle have been calculated. If we want to allocate part of the emissions to one unit of product (e_r), we also have to define the dimensional weight (w_d) of one unit of product, which is defined as:

$$w_d = \max(w, 250v) = \max(\rho v, 250v) = v \max(\rho, 250) \tag{8}$$

where, 250 is a default density used by transport companies [49]. So, if a product has a higher density than 250 (kg/m^3), the actual weight is considered to calculate the dimensional weight. In contrast to this, the volume times 250 (kg/m^3) is substituted for the actual weight when a product has a low density. The emissions allocated to one unit of the product (e_r in g) are calculated as follows:

$$e_r = EM_{total} \frac{w_d}{Lo_{\max} LF} \tag{9}$$

where, $LO_{\max}$ and LF are the maximum load of a vehicle (in kg) and the average load factor of the vehicle, respectively.

Water transport: Short-sea transport with diesel oil-powered vessels is known as a water transport [50]. Here, the total emissions(EM_{total} in kg) depend on three factors, the fuel consumption (FC), the fuel emissions (FE) and the distance (D_w). The fuel consumption FC (in l per km) is given in [50] for a given both vessel type and average load factor. The distance D_w (in km) is the distance between two locations over waterways which is larger than the distance over road. The fuel emissions factor FE (in kg) is also the amount of CO_2 emitted when 1 l of diesel is burnt. The total emissions (EM_{total} in kg) of the vessel are calculated by the following equation:

$$EM_{total} = FE \cdot FC \cdot D_w \tag{10}$$

The unit emissions for the vessel in waterway transportation are obtained defining of the allocation fraction $\alpha \in (0,1]$ as follows:

$$\alpha = \frac{\text{unit capacity}}{\text{total capacity}} \tag{11}$$

where, the type of ship plays a critical role in determining the unit of capacity,here, it can be weight for bulk vessels. The formula for the unit emissions (e_w in kg) of the vessel is then:

$$e_w = \alpha \cdot EM_{total} = \alpha \cdot FE \cdot FC \cdot D_w \tag{12}$$

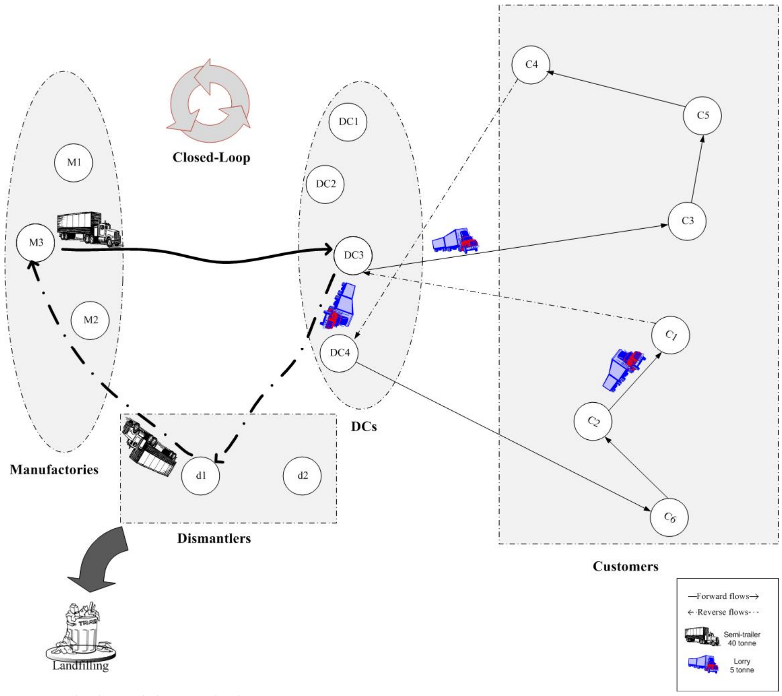


Fig. 1 Framework of proposed closed-loop chain

4 Mathematical formulation

Here, we describe how the carbon emissions are incorporated into our model and the methodology to calculate the emissions. In the following section, we define the Emission cost-minimization problem in which a unit cost for emission is charged.

Emission cost-minimization Model

The objective of the proposed model is to minimize the total construction and operations costs and the total cost of the carbon emissions allocated to whole units of the product while considering structural, product flow, capacity, customers' demands, and time windows constraints. In the Emission Trading Scheme the carbon cost is expressed in €/(metric) tonne emissions. We therefore specify a carbon emission cost $CE(CE > 0)$ per tonne of CO_2 emitted.

For any transportation mode, let $EM\_total\_MD_{ij}$ and $e\_u\_MD_{ij}$ denote its total carbon emissions and the emissions allocated to one unit of the product for transportation from the *i*-th manufactory to the *j*-th DC, respectively. Let $EM\_total\_DC_{jK}$ and $e\_u\_DC_{jk}$ denote its total carbon emissions and the emissions allocated to one unit of the product for transportation from the *j*-th DC to the *k*-th customer, respectively.Let $EM\_total\_CC_{Kl}$ and $e\_u\_CC_{kl}$ denote its total carbon emissions and the emissions allocated to one unit of the product for transportation from the *k*-th customer to the *l*-th customer, respectively. Let $EM\_total\_CD_{Kj}$ and $e\_u\_CD_{kj}$ denote its total carbon emissions and the emissions allocated to one unit of the product for transportation from the *k*-th customer to the *j*-th DC, respectively. Let $EM\_total\_DD_{jm}$ and $e\_u\_DD_{jm}$ denote its total carbon emissions and the emissions allocated to one unit of the product for transportation from the *j*-th DC to the *m*-th dismantler, respectively. Let $EM\_total\_DM_{mi}$ and $e\_u\_DM_{mi}$ denote its total carbon emissions and the emissions allocated to one unit of the product for transportation from the *m*-th dismantler to the *i*-th manufactory, respectively.

In order to formulate this Emission cost-minimization model mathematically, the following notations are necessary:

Notations:

I	= set of candidate manufactories
J	= set of candidate DCs
K	= set of customers
M	= set of candidate dismantlers
V	= set of transport mode types
V_I	= set of transport mode types at manufactory; $V_I \subset V$
V_J	= set of transport mode types at DC; $V_J \subset V$
V_M	= set of transport mode types at dismantler; $V_M \subset V$

Parameters:

Cm_i	Capacity of manufactory *i*
Tc_j	Total capacity of DC *j* (forward & reverse)
Cd_m	Capacity of dismantler *m*
Pc_j	The percentage of total capacity for reverse logistics in DC *j*
pr_k	The percentage of recovery of customer *k*
Pl_m	The percentage of land filling of dismantler *m*
dc_k	Demand of customer *k*
$P\_\cos t_i$	Unit cost of production in manufactory *i*
CMD_{v_i}	Unit cost of transportation from manufactory to DC by vehicle v_i per km
CDC_{v_j}	Unit cost of transportation from DC to customer by vehicle v_j per km
CDM_{v_m}	Unit cost of transportation from dismantler to manufactory by vehicle v_m per km
FM_i	Fixed cost for operating manufactory *i*
FDC_j	Fixed cost for operating DC*j*
FD_m	Fixed cost for operating dismantler *m*
Cl	Fixed cost for land filling per unit
dis_MD_{ij}	Distance between manufactory *i* and DC *j*
dis_DC_{jk}	Distance between DC *j* and customer *k*
dis_CC_{kl}	Distance between customer *k* and customer *l*
dis_DD_{jm}	Distance between DC *j* and dismantler *m*
dis_DM_{mi}	Distance between dismantler *m* and manufactory *i*
$t\_DC_{jkv_j}$	The time of transportation from DC *j* to customer *k* using vehicle v_j
$t\_CC_{klv_j}$	The time of transportation from customer *k* to customer *l* using vehicle v_j
a_c_k	The lower bound of expected time for delivering product at customer *k*
b_c_k	The upper bound of expected time for delivering product at customer *k*
Rc_{kj}	The recovery cost in DC *j* from customer *k*

NVM_{iv_i}	Number of vehicle v_i at manufacture i
NVD_{jv_j}	Number of vehicle v_j at DC j
$NVDi_{mv_m}$	Number of vehicle v_m at dismantler m
CVM_{v_i}	Capacity of vehicle v_i
CVD_{v_j}	Capacity of vehicle v_j
$CVDi_{v_m}$	Capacity of vehicle v_m
$LO_{\max}\_M_{v_i}$	Maximum load for vehicle v_i
$LO_{\max}\_D_{v_j}$	Maximum load for vehicle v_j
$LO_{\max}\_Di_{v_m}$	Maximum load for vehicle v_m
$LF\_M_{v_i}$	Average load factor for vehicle v_i
$LF\_D_{v_j}$	Average load factor for vehicle v_j
$LF\_Di_{v_m}$	Average load factor for vehicle v_m
vol	Volume of product
ρ_{v_i}	Density of product for vehicle v_i
wp	Weight of product
$capw$	Total capacity of cargo vessel
Q	The maximum number of nodes a salesman may visit
L	The minimum number of nodes a salesman must visit
M	A large number
CEF	Constant emission factor
VEF	Variable emission factor
$FC\_D_{v_j}$	The fuel consumption for vehicle v_j
$FE\_D_{v_j}$	The fuel emissions for diesel fuel for vehicle v_j
FC_M	The fuel consumption for semi-trailer stated in manufactory
FE_M	The fuel emissions for diesel fuel for semi-trailer stated in manufactory
FC_Di	The fuel consumption for semi-trailer stated in dismantler
FE_Di	The fuel emissions for diesel fuel for semi-trailer stated in dismantler
T	The fuel consumption factor for diesel train
FER	The fuel emissions for diesel train
W_gr	The gross weight of the train
FEW	The fuel emissions for cargo vessel
FCW	The fuel consumption for cargo vessel
CE	The price of carbon emission (expressed in €/(metric) tonne emissions)

Decision variables:

$$x\_MD_{ijv_i} \quad \begin{cases} 1, & \text{if a product can be shipped by vehicle } v_i \text{ from manufactory } i \text{ to DC } j \\ 0, & \text{o.w.} \end{cases}$$

$x\_DC_{jkv_j}$ $\begin{cases}1, & \text{if a product can be shipped by vehicle } v_j \text{ from DC } j \text{ to customer } k \\ 0, & \text{o.w.}\end{cases}$

$x\_DD_{jmv_j}$ $\begin{cases}1, & \text{if a recovered product can be shipped by vehicle } v_j \text{ from DC } j \text{ to dismantler } m \\ 0, & \text{o.w.}\end{cases}$

$x\_CD_{kjv_j}$ $\begin{cases}1, & \text{if a vehicle } v_j \text{ returned from customer } k \text{ to DC } j \\ 0, & \text{o.w.}\end{cases}$

$x\_DM_{miv_m}$ $\begin{cases}1, & \text{if a reused product can be shipped by vehicle } v_m \text{ from dismantler } m \text{ to manufactory } i \\ 0, & \text{o.w.}\end{cases}$

α_i $\begin{cases}1, & \text{if production takes place on manufactory } i \\ 0, & \text{o.w.}\end{cases}$

β_j $\begin{cases}1, & \text{if DC } j \text{ is opened} \\ 0, & \text{o.w.}\end{cases}$

γ_m $\begin{cases}1, & \text{if dismantler } m \text{ is opened} \\ 0, & \text{o.w.}\end{cases}$

$z\_CC_{klv_j}$ $\begin{cases}1, & \text{if a product can be shipped by vehicle } v_j \text{ from customer } k \text{ to customer } l \\ 0, & \text{o.w.}\end{cases}$

$y\_MD_{ijv_i}$ amount shipped by vehicle v_i from manufactory i to DC j

$y\_DC_{jkv_j}$ amount shipped by vehicle v_j from DC j to customer k

$y\_DD_{jmv_j}$ amount recovered product shipped by vehicle v_j from DC j to dismantler m

$y\_CD_{kjv_j}$ recovered amount shipped by vehicle v_j from customer k to DC j

$y\_DM_{miv_m}$ reused amount shipped by vehicle v_m from dismantler m to manufactory i

$y\_CC_{klv_j}$ recovered amount shipped by vehicle v_j from customer k to customer l

PM_i quantity produced at manufactory i

u_k the number of nodes visited by travelers from DC to node k

$congR_k$ amount of congested product at customer k

$congF_k$ amount of congested recovered product at customer k

S_k the arrival time of product at customer k

$EM\_total\_MD_{ij}$ total emissions of the vehicle from manufactory i to DC j

$EM\_total\_DC_{jk}$ total emissions of the vehicle from DC j to customer k

$EM\_total\_CD_{kj}$ total emissions of the vehicle from customer k to DC j

$EM\_total\_CC_{kl}$ total emissions of the vehicle from customer k to customer l

$EM\_total\_DD_{jm}$ total emissions of the vehicle from DC j to dismantler m

$EM\_total\_DM_{mi}$ total emissions of the vehicle from dismantler m to manufactory i

$e\_u\_MD_{ij}$ unit emissions of the vehicle from manufactory i to DC j

$e\_u\_DC_{jk}$ unit emissions of the vehicle from DC j to customer k

$e\_u\_CD_{kj}$ unit emissions of the vehicle from customer k to DC j

$e\_u\_CC_{kl}$ unit emissions of the vehicle from customer k to customer l

$e\_u\_DD_{jm}$	unit emissions of the vehicle from DC j to dismantler m
$e\_u\_DM_{mi}$	unit emissions of the vehicle from dismantler m to manufactory i

Using these definitions, the model for the proposed closed-loop chain can be described as follows:

Objective function:

$$\begin{aligned} f = & \sum_{i\in I}\alpha_i \cdot FM_i + \sum_{j\in J}\beta_j \cdot FDC_j + \sum_{m\in M}\gamma_m \cdot FD_m + \sum_{i\in I}\sum_{j\in J}\sum_{v_i\in V_I} y\_MD_{ijv_i} \cdot dis\_MD_{ij} \cdot CMD_{v_i} \\ & + \sum_{j\in J}\sum_{k\in K}\sum_{v_j\in V_J} y\_DC_{jkv_j} \cdot dis\_DC_{jk} \cdot CDC_{v_j} + \sum_{k\in K}\sum_{l\in K}\sum_{v_j\in V_J} y\_CC_{klv_j} \cdot dis\_CC_{kl} \cdot CDC_{v_j} \\ & + \sum_{k\in K}\sum_{j\in J}\sum_{v_j\in V_J} y\_CD_{kjv_j} \cdot dis\_DC_{jk} \cdot CDC_{v_j} + \sum_{j\in J}\sum_{m\in M}\sum_{v_j\in V_J} y\_DD_{jmv_j} \cdot dis\_DD_{jm} \cdot CDC_{v_j} \\ & + \sum_{m\in M}\sum_{i\in I}\sum_{v_m\in V_M} y\_DM_{miv_m} \cdot dis\_DM_{mi} \cdot CDM_{v_m} + \sum_{i\in I} PM_i \cdot P\_\mathrm{cost}_i + \\ & \sum_{k\in K}\sum_{j\in J}\sum_{v_j\in V_J} y\_CD_{kjv_j} \cdot Rc_{kj} + CL \cdot \sum_{m\in M}\left\lfloor Pl_m \cdot \sum_{j\in J}\sum_{v_j\in V_J} y\_DD_{jmv_j}\right\rfloor + \\ & \sum_{i\in I}\sum_{j\in J} e\_u\_MD_{ij} \cdot CE + \sum_{j\in J}\sum_{k\in K} e\_u\_DC_{jk} \cdot CE + \sum_{k\in K}\sum_{l\in K} e\_u\_CC_{kl} \cdot CE \\ & + \sum_{k\in K}\sum_{j\in J} e\_u\_CD_{kj} \cdot CE + \sum_{j\in J}\sum_{m\in M} e\_u\_DD_{jm} \cdot CE + \sum_{m\in M}\sum_{i\in I} e\_u\_DM_{mi} \cdot CE \end{aligned} \tag{13}$$

Constraints:

$$\sum_{i\in I}\alpha_i \ge 1, \tag{14}$$

$$\sum_{j\in J}\beta_j \ge 1, \tag{15}$$

$$PM_i \ge 1 - M(1-\alpha_i), \qquad \forall i \in I, \tag{16}$$

$$\sum_{v_i\in V_I}\sum_{j\in J} x\_MD_{ijv_i} \ge 1 - M(1-\alpha_i), \qquad \forall i \in I, \tag{17}$$

$$\sum_{v_i\in V_I}\sum_{i\in I} x\_MD_{ijv_i} \ge 1 - M(1-\beta_j), \qquad \forall j \in J, \tag{18}$$

$$y\_MD_{ijv_i} \ge 1 - M(1 - x\_MD_{ijv_i}) \qquad \forall i \in I, \forall j \in J, \forall v_i \in V_I, \tag{19}$$

$$\sum_{v_i\in V_I}\sum_{j\in J} y\_MD_{ijv_i} \le Cm_i, \qquad \forall i \in I, \tag{20}$$

$$\sum_{j\in J} x\_MD_{ijv_i} \le NVM_{iv_i} \qquad \forall i \in I, \forall v_i \in V_I, \tag{21}$$

$$\sum_{v_i\in V_I} x\_MD_{ijv_i} \le 1, \qquad \forall i \in I, \forall j \in J, \tag{22}$$

$$wp \cdot y\_MD_{ijv_i} \le CVM_{v_i} \cdot LF\_M_{v_i}, \qquad \forall i \in I, \forall j \in J, \forall v_i \in V_I, \tag{23}$$

$$\sum_{v_j\in V_J}\sum_{k\in K} x\_DC_{jkv_j} \ge 1 - M(1-\beta_j), \qquad \forall j \in J, \tag{24}$$

$$\sum_{v_j \in V_J} \sum_{k \in K} x\_CD_{kjv_j} \geq 1 - M(1-\beta_j), \qquad \forall j \in J, \tag{25}$$

$$\sum_{v_j \in V_J} \sum_{j \in J} x\_DC_{jkv_j} + \sum_{v_j \in V_J} \sum_{j \in J} x\_CD_{kjv_j} \leq 1, \qquad , \qquad \forall k \in K, \tag{26}$$

$$\sum_{v_j \in V_J} \sum_{j \in J} x\_DC_{jkv_j} + \sum_{v_j \in V_J} \sum_{l \in k} z\_CC_{lkv_j} = 1, \qquad \forall k \in K, \tag{27}$$

$$\sum_{v_j \in V_J} \sum_{j \in J} x\_CD_{kjv_j} + \sum_{v_j \in V_J} \sum_{l \in k} z\_CC_{klv_j} = 1, \qquad \forall k \in K, \tag{28}$$

$$\sum_{l \in K} z\_CC_{klv_j} + \sum_{j \in J} x\_CD_{kjv_j} = \sum_{e \in K} z\_CC_{ekv_j} + \sum_{j \in J} x\_DC_{jkv_j}, \quad \forall k \in K, \forall v_j \in V_J, \tag{29}$$

$$u(k) - u(l) + (Q \cdot z\_CC_{klv_j}) + ((Q-2) \cdot z\_CC_{lkv_j}) \leq Q - 1, \quad \forall k, l \in K, \forall v_j \in V_J, \tag{30}$$

$$u(k) + \left((Q-2) \cdot \sum_{v_j \in V_j} \sum_{j \in J} x\_DC_{jkv_j} \right) - \sum_{v_j \in V_J} \sum_{j \in J} x\_CD_{kjv_j} \leq Q - 1, \qquad \forall k \in K, \tag{31}$$

$$\sum_{v_j \in V_J} \sum_{j \in J} x\_DC_{jkv_j} + \left((2-L) \cdot \sum_{v_j \in V_J} \sum_{j \in J} x\_CD_{kjv_j} \right) \geq 2, \qquad , \qquad \forall k \in K, \tag{32}$$

$$congR_k = \left(\sum_{v_j \in V_J} \sum_{l \in k} z\_CC_{klv_j} \cdot congR_l \right) + dc_k, \qquad \forall k \in K, \tag{33}$$

$$y\_DC_{jkv_j} \geq 1 - M(1 - x\_DC_{jkv_j}), \qquad \forall k \in K, \forall v_j \in V_J, \forall j \in J, \tag{34}$$

$$y\_DC_{jkv_j} \geq congR_k, \qquad \forall k \in K, \forall v_j \in V_J, \forall j \in J, \tag{35}$$

$$wp \cdot y\_DC_{jkv_j} \leq CVD_{v_j} \cdot LF\_D_{v_j}, \qquad \forall k \in K, \forall v_j \in V_J, \forall j \in J, \tag{36}$$

$$\sum_{k \in K} x\_DC_{jkv_j} \leq NVD_{jv_j}, \qquad \forall v_j \in V_J, \forall j \in J, \tag{37}$$

$$\sum_{v_i \in V_I} \sum_{i \in I} y\_MD_{ijv_i} = \sum_{v_j \in V_J} \sum_{k \in K} y\_DC_{jkv_j}, \qquad \forall j \in J, \tag{38}$$

$$congF_k = \left(\sum_{v_j \in V_J} \sum_{l \in k} z\_CC_{lkv_j} \cdot congF_l \right) + \lceil pr_k . dc_k \rceil, \qquad \forall k \in K, \tag{39}$$

$$y\_CD_{kjv_j} \geq 1 - M(1 - x\_CD_{kjv_j}), \qquad \forall k \in K, \forall v_j \in V_J, \forall j \in J, \tag{40}$$

$$y\_CD_{kjv_j} \geq congF_k, \qquad \forall k \in K, \forall v_j \in V_J, \forall j \in J, \tag{41}$$

$$y\_CC_{klv_j} \geq \left(\sum_{j \in J} y\_DC_{jkv_j} + \sum_{h \in K} y\_CC_{hkv_j} \right) - \lceil (1 - pr_k) \cdot dc_k \rceil - M(1 - z\_CC_{klv_j}), \qquad \forall k, l \in K, \forall v_j \in V_J \tag{42}$$

$$\sum_{v_j \in V_J} \sum_{j \in J} x\_DD_{jmv_j} \geq 1 - M(1 - \gamma_m), \qquad \forall m \in M, \tag{43}$$

$$\sum_{v_j \in V_J} x\_DD_{jmv_j} \leq 1, \qquad \forall j \in J, \forall m \in M, \tag{44}$$

$$\sum_{v_j \in V_J} \sum_{m \in M} x\_DD_{jmv_j} \geq 1 - M(1 - \beta_j), \qquad \forall j \in J, \tag{45}$$

$$y\_DD_{jmv_j} \geq 1 - M(1 - x\_DD_{jmv_j}), \qquad \forall j \in J, \forall m \in M, \forall v_j \in V_J, \tag{46}$$

$$\sum_{v_j \in V_J} \sum_{k \in K} y\_CD_{kjv_j} = \sum_{v_j \in V_J} \sum_{m \in M} y\_DD_{jmv_j}, \qquad \forall j \in J, \tag{47}$$

$$\sum_{v_j \in V_J} \sum_{k \in K} y\_DC_{jkv_j} + \sum_{v_j \in V_J} \sum_{m \in M} y\_DD_{jmv_j} \le Tc_j \cdot \beta_j, \qquad \forall j \in J, \tag{48}$$

$$\sum_{m \in M} x\_DD_{jmv_j} \le NVD_{jv_j}, \qquad \forall j \in J,\ \forall v_j \in V_J, \tag{49}$$

$$wp \cdot y\_DD_{jmv_j} \le CVD_{v_j} \cdot LF\_D_{v_j}, \quad \forall j \in J, \forall m \in M, \forall v_j \in V_J, \tag{50}$$

$$\sum_{v_j \in V_J} \sum_{m \in M} y\_DD_{jmv_j} \le \lfloor Pc_j \cdot Tc_j \cdot \beta_j \rfloor, \qquad \forall j \in J, \tag{51}$$

$$\sum_{v_m \in V_m} \sum_{i \in I} x\_DM_{miv_m} \ge 1 - M(1-\gamma_m), \qquad \forall m \in M, \tag{52}$$

$$\sum_{v_m \in V_M} x\_DM_{miv_m} \le 1 \qquad \forall m \in M, \forall i \in I, \tag{53}$$

$$\sum_{v_m \in V_m} \sum_{m \in M} x\_DM_{miv_m} \ge 1 - M(1-\alpha_i), \qquad \forall i \in I, \tag{54}$$

$$y\_DM_{miv_m} \ge 1 - M\left(1 - x\_DM_{miv_m}\right), \qquad \forall m \in M, \forall i \in I,\ \forall v_m \in V_M, \tag{55}$$

$$\sum_{v_m \in V_M} \sum_{m \in M} y\_DM_{miv_m} + PM_i = \sum_{v_i \in V_i} \sum_{j \in J} y\_MD_{ijv_i}, \qquad \forall i \in I, \tag{56}$$

$$\sum_{v_j \in V_J} \sum_{j \in J} y\_DD_{jmv_j} = \left\lfloor Pl_m \cdot \sum_{v_j \in V_J} \sum_{j \in J} y\_DD_{jmv_j} \right\rfloor + \sum_{v_m \in V_M} \sum_{i \in I} y\_DM_{miv_m}, \qquad \forall m \in M, \tag{57}$$

$$\sum_{v_m \in V_M} \sum_{i \in I} y\_DM_{miv_m} + \left\lfloor Pl_m \cdot \sum_{v_j \in V_J} \sum_{j \in J} y\_DD_{jmv_j} \right\rfloor \le \gamma_m \cdot Cd_m, \qquad \forall m \in M, \tag{58}$$

$$\sum_{i \in I} x\_DM_{miv_m} \le NVDi_{mv_m}, \qquad \forall m \in M, \forall v_m \in V_M, \tag{59}$$

$$wp \cdot y\_DM_{miv_m} \le CVDi_{v_m} \cdot LF\_Di_{v_m}, \qquad \forall m \in M, \forall i \in I,\ \forall v_m \in V_M, \tag{60}$$

$$S_k \ge a\_c_k, \qquad \forall k \in K, \tag{61}$$

$$S_k \le b\_c_k, \qquad \forall k \in K, \tag{62}$$

$$S_k + t\_CC_{klv_j} - M\left(1 - z\_CC_{klv_j}\right) \le S_l, \qquad \forall k, l \in K, \forall v_j \in V_J, \tag{63}$$

$$S_k + t\_CC_{klv_j} + M\left(1 - z\_CC_{klv_j}\right) \ge S_l, \qquad \forall k, l \in K, \forall v_j \in V_J, \tag{64}$$

$$t\_DC_{jkv_j} - M\left(1 - x\_DC_{jkv_j}\right) \le S_k, \qquad \forall k \in K, \forall v_j \in V_J, \forall j \in J, \tag{65}$$

$$t\_DC_{jkv_j} + M\left(1 - x\_DC_{jkv_j}\right) \ge S_k, \qquad \forall k \in K, \forall v_j \in V_J, \forall j \in J, \tag{66}$$

$$\begin{aligned} &EM\_total\_MD_{ij} \ge y\_MD_{ija} \cdot \left(CEF + \left(VEF.0.801 dis\_MD_{ij}\right)\right) - \\ &M\left(1 - x\_MD_{ija}\right) - M\left(x\_MD_{ijr} + x\_MD_{ijt} + x\_MD_{ijw}\right), \ \forall i \in I, \forall j \in J, \end{aligned} \tag{67}$$

$$\begin{aligned} &e\_u\_MD_{ij} \ge \left(\left(v \cdot \rho_a \cdot EM\_total\_MD_{ij}\right) \big/ \left(LO_{\max}\_M_a \cdot LF\_M_a\right) \right) - \\ &M\left(1 - x\_MD_{ija}\right) - M\left(x\_MD_{ijr} + x\_MD_{ijt} + x\_MD_{ijw}\right), \quad \forall i \in I, \forall j \in J, \end{aligned} \tag{68}$$

$$\begin{aligned} &EM\_total\_MD_{ij} \ge y\_MD_{ijr} \cdot \left(FE\_M \cdot FC\_M \cdot \left(dis\_MD_{ij}\right)\right) - \\ &M\left(1 - x\_MD_{ijr}\right) - M\left(x\_MD_{ija} + x\_MD_{ijt} + x\_MD_{ijw}\right), \forall i \in I, \forall j \in J, \end{aligned} \tag{69}$$

$$e\_u\_MD_{ij} \geq \left(\left(v \cdot \rho_r \cdot EM\_total\_MD_{ij} \right) \Big/ \left(LO_{\max}\_M_r \cdot LF\_M_r \right) \right) - M\left(1 - x\_MD_{ijr}\right) - M\left(x\_MD_{ija} + x\_MD_{ijt} + x\_MD_{ijw}\right), \ \forall i \in I, \forall j \in J, \quad (70)$$

$$EM\_total\_MD_{ij} \geq y\_MD_{ijt} \cdot \left(10^{-3} \cdot \left(\xi_f \cdot T \cdot FER \right) \Big/ 10^6 \left(\sqrt{W\_gr} \cdot LF\_M_t \right) \right) - M\left(1 - x\_MD_{ijt}\right) - M\left(x\_MD_{ija} + x\_MD_{ijr} + x\_MD_{ijw}\right), \ \forall i \in I, \forall j \in J, \quad (71)$$

$$e\_u\_MD_{ij} \geq \left(EM\_total\_MD_{ij} \cdot dis\_MD_{ij} \cdot wp \right) - M\left(1 - x\_MD_{ijt}\right) - M\left(x\_MD_{ija} + x\_MD_{ijr} + x\_MD_{ijw}\right), \forall i \in I, \forall j \in J, \quad (72)$$

$$EM\_total\_MD_{ij} \geq y\_MD_{ijw} \cdot \left(FCW \cdot FEW \cdot 1.2 dis\_MD_{ij} \right) - M\left(1 - x\_MD_{ijw}\right) - M\left(x\_MD_{ija} + x\_MD_{ijr} + x\_MD_{ijt}\right), \forall i \in I, \forall j \in J, \quad (73)$$

$$e\_u\_MD_{ij} \geq \left(\left(wp \cdot EM\_total\_MD_{ij} \right) \Big/ \left(capw \cdot 1000 \right) \right) - M\left(1 - x\_MD_{ijw}\right) - M\left(x\_MD_{ija} + x\_MD_{ijr} + x\_MD_{ijt}\right), \ \forall i \in I, \forall j \in J, \quad (74)$$

$$EM\_total\_DC_{jK} \geq y\_DC_{jkv_j} \cdot \left(FE\_D_{v_j} \cdot FC\_D_{v_j} \cdot \left(dis\_DC_{jk} \right) \right) - M\left(1 - x\_DC_{jkv_j}\right), \quad \forall k \in K, \forall j \in J, \forall v_j \in V_J, \quad (75)$$

$$e\_u\_DC_{jk} \geq \left(\left(v \cdot \rho_r \cdot EM\_total\_DC_{jk} \right) \Big/ \left(LO_{\max}\_D_{v_j} \cdot LF\_D_{v_j} \right) \right) - M\left(1 - x\_DC_{jkv_j}\right), \ \forall k \in K, \forall j \in J, \forall v_j \in V_J, \quad (76)$$

$$EM\_total\_CC_{Kl} \geq y\_CC_{klv_j} \cdot \left(FE\_D_{v_j} \cdot FC\_D_{v_j} \cdot \left(dis\_CC_{kl} \right) \right) - M\left(1 - z\_CC_{klv_j}\right), \qquad \forall k, l \in K, \forall v_j \in V_J, \quad (77)$$

$$e\_u\_CC_{kl} \geq \left(\left(v \cdot \rho_r \cdot EM\_total\_CC_{kl} \right) \Big/ \left(LO_{\max}\_D_{v_j} \cdot LF\_D_{v_j} \right) \right) - M\left(1 - z\_CC_{klv_j}\right), \ \forall k, l \in K, \forall v_j \in V_J, \quad (78)$$

$$EM\_total\_CD_{Kj} \geq y\_CD_{kjv_j} \cdot \left(FE\_D_{v_j} \cdot FC\_D_{v_j} \cdot \left(dis\_DC_{jk} \right) \right) - M\left(1 - x\_CD_{kjv_j}\right), \qquad \forall k \in K, \forall j \in J, \forall v_j \in V_J, \quad (79)$$

$$e\_u\_CD_{kj} \geq \left(\left(v \cdot \rho_r \cdot EM\_total\_CD_{kj} \right) \Big/ \left(LO_{\max}\_D_{v_j} \cdot LF\_D_{v_j} \right) \right) - M\left(1 - x\_CD_{kjv_j}\right), \forall k \in K, \forall j \in J, \forall v_j \in V_J \quad (80)$$

$$EM\_total\_DD_{jm} \geq y\_DD_{jmv_j} \cdot \left(FE\_D_{v_j} \cdot FC\_D_{v_j} \cdot \left(dis\_DD_{jm} \right) \right) - M\left(1 - x\_DD_{jmv_j}\right), \quad \forall m \in M, \forall j \in J, \forall v_j \in V_J, \quad (81)$$

$$e\_u\_DD_{jm} \geq \left(\left(v \cdot \rho_r \cdot EM\_total\_DD_{jm} \right) \Big/ \left(LO_{\max}\_D_{v_j} \cdot LF\_D_{v_j} \right) \right) - M\left(1 - x\_DD_{jmv_j}\right), \ \forall m \in M, \forall j \in J, \forall v_j \in V_J \quad (82)$$

$$EM\_total\_DM_{mi} \geq y\_DM_{mir'} \cdot \left(FE\_Di \cdot FC\_Di \cdot \left(dis\_DM_{mi} \right) \cdot 1.05 \right) - M\left(1 - x\_DM_{mir'}\right) - M\left(x\_DM_{mit'}\right), \ \ \forall m \in M, \forall i \in I, \quad (83)$$

$$e\_u\_DM_{mi} \geq \left(\left(v \cdot \rho_r \cdot EM\_total\_DM_{mi} \right) \Big/ \left(LO_{\max}\_Di_{r'} \cdot LF\_Di_{r'} \right) \right) - M\left(1 - x\_DM_{mir'}\right) - M\left(x\_DM_{mit'}\right), \ \ \forall m \in M, \forall i \in I, \quad (84)$$

$$EM\_total\_DM_{mi} \geq y\_DM_{mit'} \cdot \left(10^{-3} \cdot {(\xi_h \cdot T \cdot FER)} \Big/ {10^6 \left(\sqrt{W\_gr} \cdot LF\_Di_{t'} \right)} \right) - M(1 - x\_DM_{mit'}) - M(x\_DM_{mir'}), \forall m \in M,\ \forall i \in I, \tag{85}$$

$$e\_u\_DM_{mi} \geq (EM\_total\_DM_{mi} \cdot dis\_DM_{mi} \cdot wp) - M(1 - x\_DM_{mit'}) - M(x\_DM_{mir'}), \quad \forall m \in \tag{86}$$

$$x\_MD_{ijv_i}, x\_DC_{jkv_j}, x\_DD_{jmv_j}, x\_CD_{kjv_j}, x\_DM_{miv_m}, z\_CC_{klv_j}, \alpha_i, \beta_j, \gamma_m \in \{0,1\}, \quad \forall i \in I, \forall j \in J, \forall k,l \in K, \forall m \in M, \forall v_i \in V_I, \forall v_j \in V_J, \forall v_m \in V_M, \tag{87}$$

$$y\_MD_{ijv_i}, y\_DC_{jkv_j}, y\_DD_{jmv_j}, y\_CD_{kjv_j}, y\_DM_{miv_m}, y\_CC_{klv_j}, PM_i, u_k, congR_k, congF_k, S_k, EM\_total\_MD_{ij}, EM\_total\_DC_{jk}, EM\_total\_CD_{kj}, EM\_total\_CC_{kl}, EM\_total\_DD_{jm}, EM\_total\_DM_{mi}, e\_u\_MD_{ij}, e\_u\_DC_{jk}, e\_u\_CD_{kj}, e\_u\_CC_{kl}, e\_u\_DD_{jm}, e\_u\_DM_{mi} \geq 0, \forall i \in I, \forall j \in J, \forall k,l \in K, \forall m \in M, \forall v_i \in V_I, \forall v_j \in V_J, \forall v_m \in V \tag{88}$$

Equation (13) is the objective function which minimizes cost of opening manufactory, distribution center and dismantler, minimizes the total cost of both forward and backward distance, minimizes the total cost of operations and minimizes the total cost of the carbon emissions allocated to whole units of the product.

The Constraints (14) and (15) show that there exists at least one activated manufactory and DC in the chain, respectively. The Constraint (16) ensures that each manufactory can produce an amount of product just after it is selected. Each activated manufactory covers at least one DC, and the Constraints (17) represent this goal. On the contrary, each DC receives at least one link from manufactories just after it is selected (Constraints (18)).

The Constraint (19) represents the amount of flow between manufactory and DC. The Constraint (20) represents the limit of the capacity for manufactories in forward logistics. The Constraint (21) imposes that the number of traveled vehicles from manufactory would not exceed the existing vehicles. The Constraint (22) prevents the route between manufactory and DC from accepting its vehicle more than once. The capacity constraint of each vehicle traveled from manufactory to DC is shown by Constraint (23).The Constraint (24) guarantees that each activated DC covers at least one customer. Each activated DC receives at least one link from customers, and the Constraint (25) represents this goal. The Constraint (26) represent a salesman from DC must visit at least two customers. The Constraint (27) requires that any customer be supplied by either DC or other customer. As well as, it either comeback to DC or supply other customer. This concept is represented by constraint (28).Each customer is supplied and supplies by the same vehicle. This is represented by Constraint (29). The Constraints (30), (31) and (32) prevent any sub-tour in the network. The Constraint (33) indicates the amount of congested product for supplying other customers by each customer. The Constraint (34) represents the amount of flow between DC and customer. The Constraint (35) is to satisfy the customer demand. The capacity constraint of each vehicle traveled from DC to customer is shown by Constraint (36).

The Constraint (37) imposes that the number of traveled vehicles from DC would not exceed the existing vehicles. The Constraint (38) satisfies the law of the flow conservation by in-flow equal to out-flow. The amount of congested product for recovering from other customers by each customer is indicated by Constraint (39). The Constraints (40- 41) represent the amount of flow between customer and DC. The amount of flow among customers is represented by Constraint (42). The Constraint (43) guarantees that each activated dismantler receives at least one link from DCs. The Constraint (44) prevents the route between DC and dismantler from accepting its vehicle more than once. The Constraint (45) guarantees that each activated DC covers at least one dismantler. The amount of flow between DC and dismantler is shown by Constraint (46). The Constraint (47) satisfies the law of the flow conservation by in-flow equal to out-flow. The Constraint (48) indicates that the total flows of forward and backward cannot exceed the total capacity of DC.

The Constraint (49) imposes that the number of traveled vehicles from DC to dismantler would not exceed the existing vehicles. The capacity constraint of each vehicle traveled from DC to dismantler is shown by Constraint (50). The Constraint (51) means the reverse limit of the capacity for DCs. The Constraint (52) ensures that each activated dismantler covers at least one manufactory. The Constraint (53) prevents the route between dismantler and manufactory from accepting its vehicle more than once. The Constraint (54) guarantees that each activated manufactory receives at least one link from dismantlers. The amount of flow between dismantler and manufactory is shown by Constraint (55). The Constraints (56) and (57) satisfy the law of the flow conservation by in-flow equal to out-flow. The Constraint (58) means the reverse limit of the capacity for dismantlers. The Constraint (59) imposes that the number of traveled vehicles from dismantler to manufactory would not exceed the existing vehicles. The capacity constraint of each vehicle traveled from dismantler to manufactory is shown by Constraint (60). The Constraints (61- 66) satisfy time windows. The Constraints (67-74) show the emissions allocated to one unit of the product for transportation from the i-th manufactory to the j-th DC. where, $x\_MD_{ija} \dots x\_MD_{ijw}$ are the binary variables to link carbon emissions constraints to the related types of transport. The Constraints (67-68), (69-70), (71-72), and (73-74) measure carbon emissions of the aircraft, vehicle, diesel train, and vessel based on NTM method for air transport, road transport, rail transport, and water transport.

The Constraints (75) and (76) show the emissions allocated to one unit of the product for transportation from the j-th DC to the k-th customer. The Constraints (77) and (78) show the emissions allocated to one unit of the product for transportation from the k-th customer to the l-th customer. The Constraints (79) and (80) show the emissions allocated to one unit of the product for transportation from the k-th customer to the j-th DC. The Constraints (81) and (82) show the emissions allocated to one unit of the product for transportation from the j-th DC to the m-th dismantler. The Constraints (75-82) measure carbon emissions of the vehicle based on NTM method for road transport. The Constraints (83-86) show the emissions allocated to one unit of the product for transportation from the m-th dismantler to the i-thmanufactory where, $x\_DM_{mir'}$ and $x\_DM_{mit'}$ are the binary variables to link carbon emissions constraints to the related types of transport. The Constraints (83-84) and (85-86) measure carbon emissions of the vehicle and diesel train based on NTM method for road transport and rail transport. The Constraint (87) denotes the binary variables, and the Constraint (88) restricts all other variables from taking non-negative values.

Linearization

To improve the performance of the proposed mathematical model we act out the following linearization for the nonlinear equations. As Constraint (33) is nonlinear, we turn it into the following equations,

$$\text{Equation (33)} \rightarrow \quad congR_k \geq M \cdot \left(z\_CC_{klv_j} - 1\right) + \left(dc_k + congR_l\right), \quad \forall v_j \in V_J, \forall l, k \in K, \tag{89}$$

$$congR_k \leq (-M) \cdot \left(z\_CC_{klv_j} - 1\right) + \left(dc_k + congR_l\right), \quad \forall v_j \in V_J, \forall l, k \in K, \tag{90}$$

$$congR_k \le \left(\sum_{v_j \in V_J} \sum_{l \in k} z\_CC_{klv_j} \right) \cdot M + dc_k, \qquad \forall k \in K, \tag{91}$$

$$congR_k \ge \left(\sum_{v_j \in V_J} \sum_{l \in k} z\_CC_{klv_j} \right) \cdot (-M) + dc_k, \qquad \forall k \in K, \tag{92}$$

As Constraint (39) is nonlinear, we turn it into the following equations,

Equation (39) →

$$congF_k \ge M \cdot \left(z\_CC_{klv_j} - 1\right) + \left(\left(pr_k \cdot dc_k\right) + congF_l\right), \ \forall v_j \in V_J, \forall l, k \in K, \tag{93}$$

$$congF_k \le (-M) \cdot \left(z\_CC_{klv_j} - 1\right) + \left(\left(pr_k \cdot dc_k\right) + congF_l\right), \ \forall v_j \in V_J, \forall l, k \in K, \tag{94}$$

$$congF_k \le \left(\sum_{v_j \in V_J} \sum_{l \in k} z\_CC_{klv_j} \right) \cdot M + \left(pr_k \cdot dc_k\right), \qquad \forall k \in K, \tag{95}$$

$$congF_k \ge \left(\sum_{v_j \in V_J} \sum_{l \in k} z\_CC_{klv_j} \right) \cdot (-M) + \left(pr_k \cdot dc_k\right), \qquad \forall k \in K, \tag{96}$$

5 Numerical experiments

Here, we propose a numerical example to indicate the effectiveness of the proposed mathematical models. Our models are tested in small scale of data. Tables 1-10 are the given data. The number of potential locations for the manufactory, DC, and dismantler are three, four, and two, respectively. Manufactories, DCs, and dismantlers are selected to secure 57 customers having definite demands. While the applied optimization software is not able to provide solutions for 57 customers in a reasonable time, we categorized the customers into 7more comprehensive zones with aggregated demands. There are four types of transportation mode (air, rail, road, and water) used to transfer product from manufactories to DCs, one type of transportation mode (road) used to transfer product from DCs to customers and dismantlers, and two types of transportation mode (rail and road) used to transfer product from dismantlers to manufactories.
For each of the four transport classes used to transfer product from manufactories to DCs, we select a representative vehicle to which we apply the NTM method.

Air transport
We select a cargo aircraft whose emission factors are most similar to the average values [47]. For the cargo aircraft we select the maximum load ($LO_{\max}\_M_a$) is 29029 kg. We note that the distance over road (D_r) between two locations is always more than the air distance (D_a) and we find the following value $D_a = 0.801 D_r$ on average in Google Maps [51].

Road transport
We assumed that a semi-trailer is used, because it is a common type to use for longer distance. The road type is supposed to be a motorway. We assume a load factor of 70%, which is typical for transport via integrating terminals [49]. The maximum load ($LO_{\max}\_M_r$) is 40 tonne.

Rail transport

It is supposed that the rail network is designed for only diesel trains. All constants below are taken from NTM Rail [48]. We assume that the gross weight (W_gr) of the train is 1000 tonne, which is the average value specified by NTM Rail [48]. The entire track from manufactories to DCs is flat, and we find the following value $\xi_f = 1$ in NTM Rail [48]. We assume that the rail distance between two locations is equal to the road distance. For a diesel train we take the following parameter values.

Water transport

We assume that inland waterways are used for transport and that a general cargo vessel is used. For inland waterways NTM assumes a load factor of 50% [50]. The cargo capacity (maximum load) of a general cargo vessel for inland waterways is 1920 tonne. We assume that the distance between two locations over inland waterways is larger than the distance over road. The distance (D_w) is therefore 1.2 times the road distance (D_r). For a general cargo vessel we take the following parameter values.

Table 1 Emission factors for representative vehicle from manufactories to DCs

Cargo Aircraft		Semi-Trailer (40 tonne)		Diesel Train		Cargo Vessel	
Load Factor (%) (LF_M_a)	80	Load Factor (%) (LF_M_r)	70	Load Factor (%) (LF_M_t)	50	Load Factor (%) (LF_M_w)	50
CEF (kg)	4139.6	FC (l/km) (FC_M)	0.3198	T	122.46	FEW (kg/tonne)	3178
VEF (kg)	15.353	FE (kg/l) (FE_M)	2.621	FER (g/l)	3175	FCW (tonne/km)	0.007

For one type transport mode used to transfer product from DCs to customers and dismantlers, we select two representative vehicles to which we apply the NTM method.

Road transport

We assumed that two Lorries are used, 5 tonne Lorry and 40 tonne Lorry. The road type is supposed to be a motorway. For two Lorries we take the following parameter values.

Table 2 Emission factors for representative vehicle from DCs to customers and dismantlers

	5 tonne Lorry	40 tonne Lorry
Load Factor (%) ($LF\_D_{v_j}$)	75	90
$FC\_D_{v_j}$ (l/km)	0.245	0.369
$FE\_D_{v_j}$ (kg/l)	2.63	2.63

For each of the two transport classes used to transfer product from dismantlers to manufactories, we select a representative vehicle to which we apply the NTM method.

Road transport
We assumed that a semi-trailer is used, because it is a common type to use for longer distance. The road type is supposed to be a hilly terrain. We assume a load factor of 50%. The maximum load ($LO_{\max}\_Di_{r'}$) is 40 tonne. To account for hilly terrain we add 5% [49] to the total emissions.

Rail transport
It is supposed that the rail network is designed for only diesel trains. All constants below are taken from NTM Rail [48]. We assume that the gross weight (W_gr) of the train is 1000 tonne, which is the average value specified by NTM Rail [48]. The entire track from dismantlers to manufactories is hilly and we find the following value $\xi_h = 1.25$ in NTM Rail [48]. We assume that the rail distance between two locations is equal to the road distance. For a diesel train we take the following parameter values.

Table 3 Emission factors for representative vehicle from dismantlers to manufactories

Semi-Trailer (40 tonne)		Diesel Train	
Load Factor (%) ($LF\_Di_{r'}$)	50	Load Factor (%) ($LF\_Di_{t'}$)	50
FC (l/km) (FC_Di)	0.293	T	122.46
FE (kg/l) (FE_Di)	2.621	FER (g/l)	3175

There are five types of connection links in the proposed closed-loop chain. Possible connection links are as below:

- Connection link between the manufactory and DC
- Connection link between the DC and customer
- Connection link among customers
- Connection link between the DC and dismantler
- Connection link between the dismantler and manufactory

Table 4 shows distances related to the defined connection links and transfer times between DCs and customers and among customers using variety of vehicles. Maximum and minimum waiting time for customers are set to be 500 and 2500 unit of time, respectively. Manufactory, distribution center, customer, and dismantler are involved with the respective numbers (capacity, demand, fixed cost, production cost, and rate) as shown in Table 5 and three rates are assumed to be different with respect to each DC, customer, and dismantler, respectively. Table 6 lists the unit cost of transportation. The recovery cost in DC is given in Table 7 and are assumed to be equal for each DC with respect to each customer. Table 8 shows the vehicle properties. The weight and volume of the product are assumed to be 40 (kg) and 0.5 (m^3), respectively. The maximum (Q) and minimum (L) number of customers a salesman must visit are supposed to be 4 and 1, respectively. The fixed cost for landfilling is set to be €2 per unit. Since the establishment of the carbon market price has varied between €1 and €30/tonne, we consider the average cost of carbon emission (i.e. €15/tonne).

Table 4 Distance and transfer times

DC	Customers 1 Distance	Customers 1 Transfer times using 5 tonne lorry	Customers 1 Transfer times using 40 tonne lorry	Customers 2 Distance	Customers 2 Transfer times using 5 tonne lorry	Customers 2 Transfer times using 40 tonne lorry	Customers 3 Distance	Customers 3 Transfer times using 5 tonne lorry	Customers 3 Transfer times using 40 tonne lorry	Customers 4 Distance	Customers 4 Transfer times using 5 tonne lorry	Customers 4 Transfer times using 40 tonne lorry	Customers 5 Distance	Customers 5 Transfer times using 5 tonne lorry	Customers 5 Transfer times using 40 tonne lorry	Customers 6 Distance	Customers 6 Transfer times using 5 tonne lorry	Customers 6 Transfer times using 40 tonne lorry	Customers 7 Distance	Customers 7 Transfer times using 5 tonne lorry	Customers 7 Transfer times using 40 tonne lorry
1	85	500	800	149	380	430	75	780	1020	123	270	560	174	660	900	100	984	1329	250	654	780
2	328	300	450	187	280	403	98	857	1220	257	370	460	400	720	950	278	284	629	189	354	870
3	198	1500	1850	447	850	1430	280	780	1470	378	670	1060	260	760	987	315	1084	1629	92	947	1280
4	270	200	705	360	480	830	200	1180	1780	420	770	960	338	1050	1800	173	884	1330	290	554	856

Customer - Customer	1 Distance	1 Transfer times using 5 tonne lorry	1 Transfer times using 40 tonne lorry	2 Distance	2 Transfer times using 5 tonne lorry	2 Transfer times using 40 tonne lorry	3 Distance	3 Transfer times using 5 tonne lorry	3 Transfer times using 40 tonne lorry	4 Distance	4 Transfer times using 5 tonne lorry	4 Transfer times using 40 tonne lorry	5 Distance	5 Transfer times using 5 tonne lorry	5 Transfer times using 40 tonne lorry	6 Distance	6 Transfer times using 5 tonne lorry	6 Transfer times using 40 tonne lorry	7 Distance	7 Transfer times using 5 tonne lorry	7 Transfer times using 40 tonne lorry
1	0	0	0	58	180	203	128	65	120	117	37	60	68	72	95	150	28	75	249	35	87
2	58	180	203	0	0	0	123	78	147	130	67	106	88	76	98	125	108	162	270	94	128
3	128	65	120	123	78	147	0	0	0	317	77	96	146	105	180	300	88	133	210	55	85
4	117	37	60	130	67	106	317	77	96	0	0	0	190	66	90	250	98	132	315	65	78
5	68	72	95	88	76	98	146	105	180	190	66	90	0	0	0	190	67	97	320	57	110
6	150	28	75	125	108	162	300	88	133	250	98	132	190	67	97	0	0	0	279	85	111
7	249	35	87	270	94	128	210	55	85	315	65	78	320	57	110	279	85	111	0	0	0

DC	Manufactories 1			Manufactories 2			Manufactories 3			Dismantlers 1			Dismantlers 2			Manufactories - Dismantlers 1			Manufactories - Dismantlers 2		
1	75	-	-	38	-	-	54	-	-	50	-	-	88	-	-	168	-	-	90	-	-
2	50	-	-	46	-	-	36	-	-	110	-	-	90	-	-	200	-	-	178	-	-
3	24	-	-	25	-	-	68	-	-	155	-	-	182	-	-	138	-	-	119	-	-
4	17	-	-	63	-	-	96	-	-	122	-	-	80	-	-						

Table 5 Capacity, demand, fixed cost, production cost, and rate

Manufactory			DC			Customer		Dismantler		
Capacity (Cm)	Fixed cost (€) (FM)	Pro. Cost (€) (P_cost)	Total Capacity (Tc)	Fixed cost (€) (FDC)	Pc (%)	Demand (dc)	pr (%)	Capacity (Cd)	Fixed cost (€) (FD)	Pl (%)
1000000	200000	326	3000	80000	40	20	10	1600	20000	30
1000000	180000	400	5000	50000	20	18	30	2400	25000	38
1000000	150000	300	1500	23000	50	10	50			
			2000	30000	50	12	20			
						20	80			
						14	10			
						10	40			

Table 6 Unit cost (€)of transportation per km

	DC			
Manufactory	Cargo aircraft	Semi-trailer	Diesel train	Cargo vessel
	0.25	0.16	0.2	0.3
	Customer & Dismantler			
DC	5 tonne Lorry		40 tonne Lorry	
	0.13		0.18	
	Manufactory			
Dismantler	Semi-trailer		Diesel train	
	0.15		0.25	

Table 7 The recovery cost (€) in DC from customer

Rc	1	2	3	4
1	1.5	2.3	1.8	0.8
2	1.5	2.3	1.8	0.8
3	1.5	2.3	1.8	0.8
4	1.5	2.3	1.8	0.8
5	1.5	2.3	1.8	0.8
6	1.5	2.3	1.8	0.8
7	1.5	2.3	1.8	0.8

Table 8 The vehicles' properties

Vehicle	Number of vehicle (unit)				Maximum load (kg)	Capacity (kg)	Density of product
	Manufactory (NVM)				($LO_{\max}\_M$)	(CVM)	(ρ)
	1	2	3				
Cargo aircraft	2	1	2		29029	29029	167
Semi-trailer	5	3	6		40000	40000	250
Diesel train	1	0	1		1000000	1000000	-
Cargo vessel	3	2	2		1920000	1920000	-
	DC (NVD)				($LO_{\max}\_D$)	(CVD)	
	1	2	3	4			
5 tonne Lorry	5	3	10	4	5000	5000	250
40 tonne Lorry	3	6	6	1	40000	40000	250
	Dismantler ($NVDi$)				($LO_{\max}\_Di$)	($CVDi$)	
	1		2				
Semi-trailer	4		3		40000	40000	250
Cargo vessel	1		2		1000000	1000000	-

So far, we present the required data for processing the results. To facilitate the computations in our mixed integer programming (MIP) models, GAMS 22.9 software package is applied. After solving the proposed model(Emission cost-minimization) using this software, we have found that the total carbon emissions for this problem is 1242.89 (kg). We have reported the results in Table 9 along with the optimal solution obtained for this problem. The validity of model is measured for numerical experiment as seen in Figure 2, schematically. The results are summarized in Table 9. Table 9 presents objective function of this case. Product flow rates and amount of CO_2 (kg) emitted from journeys of selective paths are shown in Table 9. There are five types of connection links in the selective path column:

- Links connected between the manufactory and DC is indicated by a-b: $[n]$ format; where, a and b are numbers which indicate selective manufactory and DC, respectively. n is a number which indicates a selective path on the figure. $[\ ]$ is a symbol related to this kind of connection links.
- Links connected between the DC and customer is indicated by c-d: (n) format; where, c and d are numbers which indicate selective DC and customer, and vice versa. $(\ )$ is a symbol related to this kind of connection links.
- Links connected among the customers is indicated by e-f: $\{n\}$ format; where, e and f are numbers which indicate selective customers. $\{\ \}$ is a symbol related to this kind of connection links.
- Links connected between the DC and dismantler is indicated by g-h: $\langle n\rangle$ format; where, g and h are numbers which indicate selectiveDC and dismantler, respectively. $\langle\ \rangle$ is a symbol related to this kind of connection links.
- Links connected between the dismantler and manufactory is indicated by i-j: $\|n\|$ format; where, i and j are numbers which indicate selectivedismantler and manufactory, respectively. $\|\ \|$ is a symbol related to this kind of connection links.

From Table 9, it is concluded that:

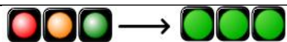
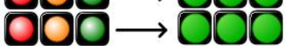
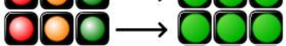
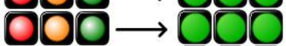
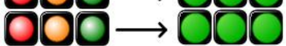
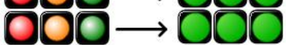
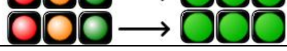
1. For this case, only one manufactory (No. 3) and one DC (No. 3) are selected to secure and transport the total sum of customers' demands. Besides, only one dismantler (No. 1) is selected to transport the recovered product to the manufactory.
2. For this case, one route exit from the manufactory (No. 3).
3. The aggregate value of product flow in exiting paths a manufactory is equivalent to the total sum of customers' demands. That means the whole of customers' demands in the network are met.
4. The value of product flow in exiting path a DC is equivalent to the total sum of demands of customers which belongs to the same tour. That means, the whole of customers' demands in the each tour are met.
5. The value of product flow in exiting path a customer is equivalent to the total sum of demands of remaining customers which belongs to the same tour plus the amount of recovered product obtained from customer.
6. In the reverse flow, the aggregate value of returned product flow in exiting paths a DC is equivalent to the total sum of customers' demands of recovered product.

For cost-based case, an optimal closed-loop chain is shown in Figures 2. In this figure, we consider a particular color for each tour in which a salesman depart from selective DCs and arrive to the customers. So, the selective path given in Table 9 is indicated by different colors. The objective functions for cost-based case is 233765.9units in 1380seconds. Note that this computation time is needed to be spent for solving a problem with three, four, and two potential locations for the manufactory, DC, and dismantler and seven customers. The suitable paths to deliver product to customers from manufactories and DCs in the forward flows, to deliver recovered product to dismantlers from DCs and customers, and to deliver reused product to manufactories from dismantlers in the reverse flows for Emission cost minimization model is shown by Figure 2. As well as, the selected vehicles for carrying product and the corresponding amount of product are illustrated in it which also includes the amount of CO_2 (kg) emitted from journeys and the amount of landfills. The arrival time of product at each customer for this model is reported in Table 10.The traffic light turned green in all shows the time window of each customer is satisfied and the arrival time of product is within the allowed range ([500 2500]).

Table 9 Results for cost-based case

Selective path	Amount of product flow	Amount of CO_2 (kg)
3-3: $[1]$	104	26.46
3-3: (1)	30	180.42
3-6: (2)	26	175.9
3-7: (3)	48	94.85
3-5: $\{1\}$	25	78.4
6-4: $\{2\}$	13.4	71.95
7-2: $\{3\}$	42	243.56
2-1: $\{4\}$	29.4	36.62
5-3: (4)	21	117.27
4-3: (5)	3.8	30.85
1-3: (6)	11.4	48.48
3-1: $\langle 1 \rangle$	36.2	120.51
1-3: $\lVert 1 \rVert$	25.34	17.62
Landfill	10.86	-
	objective	
	233765.9	

Table 10 The time windows

Customer	Time Windows (S_k)	Status
1	1221	
2	1041	
3	780	
4	1182	
5	885	
6	1084	
7	947	

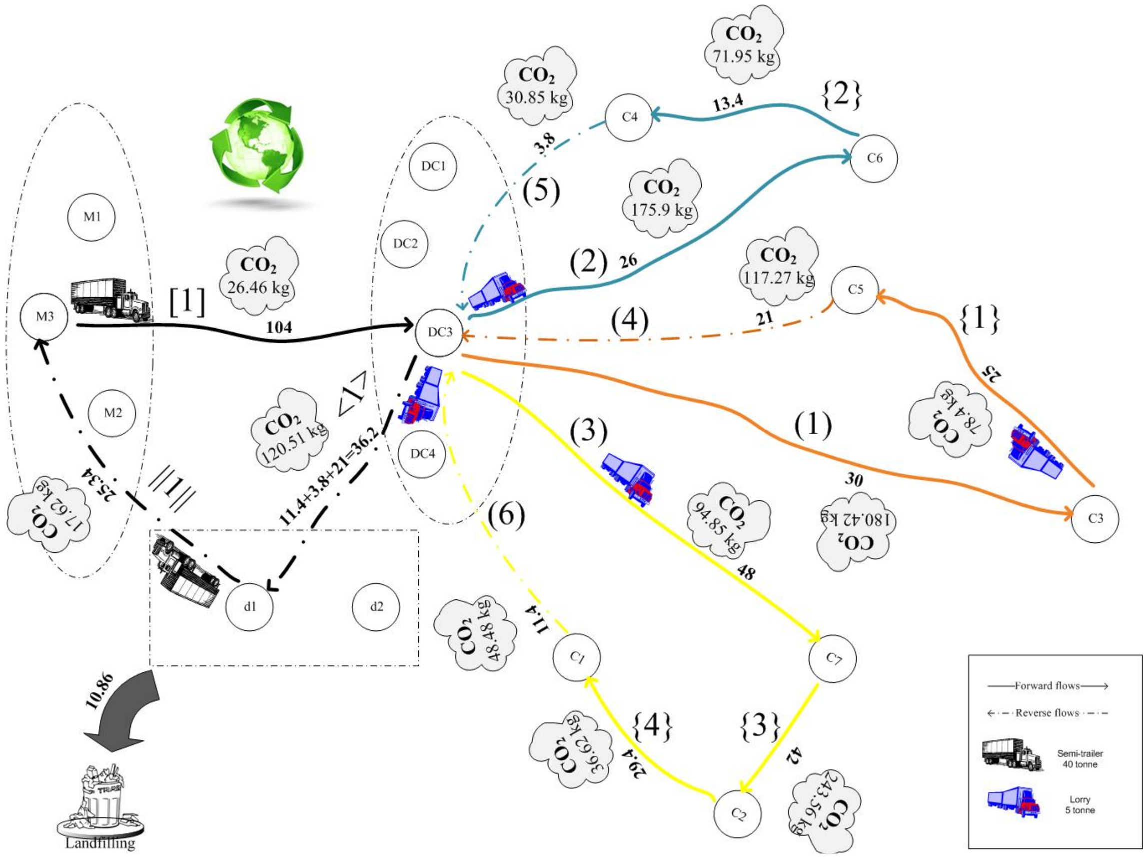


Fig. 2 Optimal closed-loop chain of the numerical experiment

6 Conclusion

In this work, we presented an extended closed-loop supply chain network to integrate the environmental issues into a traditional logistic system. Our proposed chain contained four layers (manufacturers, DCs, customers, and dismantlers). Finding optimal locations of manufacturers, DCs, and dismantlers and distribution of product satisfying time windows were our purposes that are attained in a mixed integer linear programming approach. In this way, we proposed an approach as multiple DCs multiple traveling salesman problem (MDMTSP) between DCs and customers. In addition to manage properly reverse logistics to reduce negative impact of greenhouse gases emissions, we focused on transport mode selection as a way to reduce emissions. For this, a regulation to reduce carbon emissions come from freight transport was considered. This mechanism specified a cost for carbon emissions. Consequently, the model was formulated corresponding to this regulation.
The applicability and effectiveness of our proposed model was tested through numerical example.

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