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Integrated forward and reverse supply chain: A tire case study

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This paper attempts to integrate both a forward and reverse supply chain to design a closed-loop supply chain network (CLSC). The problem in the design of a CLSC network is uncertainty in demand, return products and the quality of return products. Scenario analyses are generated to overcome this uncertainty. In contrast to the existing supply chain network design models, a new application of a CLSC network was studied in this paper to reduce waste. A multi-product, multi-tier mixed integer linear model is developed for a CLSC network design. The main objective is to maximize profit and provide waste management decision support in order to minimize pollution. The result shows applicability of the model in the tire industry. The model determines the number and the locations of facilities and the material flows between these facilities.

1. Introduction

With the rapid changes in technology and the subsequent reduction in the life cycle of products, consumers produce more wastes and disposable products. This has led to serious environmental problems, such as rapid depletion of resources, production of more toxic and non-toxic waste, air and water pollution, and climate change. To highlight the waste and environmental problems and propose a solution for such problems, tires are used as one of the main sources of waste generation. Statistics show that over 1,000,000 tons of scrap tires are disposed off annually throughout the world; for instance over 600,000 tons per year in Germany (Lebreton and Tuma, 2006) and the equivalent to 250,000 tons per year in France (Ferrer, 1997), which indicates the potential for an enormous disposal problem that causes health hazards and environmental damage (Jang et al., 1998). The carbon black and rubber, which are part of tire contents, make tires unfit for landfill disposal.

A deeper look into the tire structure reveals great opportunities for retreading. A generic tire is composed of two parts: the casing and tread (Fig. 1). With prolonged usage, the surface of tire or tread wears out and tends to become flat as a result of being in contact with the road surface. This makes the tire unsuitable for road use because of reduction of brake performance and adherence. The casing of returned tires is less likely to have significant damage. Thus, there are opportunities for replacing the worn tread with a new one and reducing waste. In addition, a life cycle assessment of new tire production and tire retreading highlights the fact that production of new tires consumes four times more materials than the production of retreaded tires. Furthermore, energy usage for producing a new tire is three times higher than that for a retreaded tire (see Table 1). Therefore, retreading is a key to reducing waste and consumption of non-renewable raw material.

Managing new tires and used tires effectively as well as harmonizing the forward and reverse logistic networks are challenging tasks in a value chain for the tire industry. Therefore, an appropriate logistic network is a must for this type of industry. Designing an economically optimized CLSC network is a prerequisite for tire manufacturers not only to earn profit, but also to decrease waste, with the ultimate goal of sustainable development.

In addition, nowadays companies in the competitive market are seeking optimal configuration of their supply chains (Christopher, 2007). In fact, supply chain network design, i.e. defining number, size and location of supply nodes (Abdallah et al., 2012), has attracted great importance and companies are trying to have a robust and agile logistics network, which can be configured or redesigned easily and precisely (Creazza et al., 2012).

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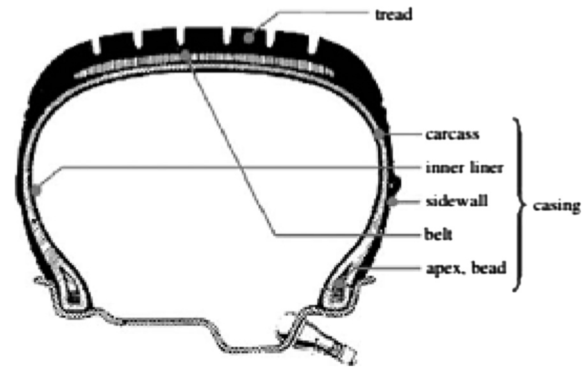

Fig. 1. Tire structure. Source: Lebreton and Tuma (2006).

Table 1
Energy and material usage for the manufacture of a car tire. Source: Ferrer (1997).

Type of tire	Materials consumption (in kg)	Energy usage (in kJ)
New tire	8	72,000
Retreaded tire	1.9	19,000

1.1. Product recovery and life cycle analysis

Product recovery is a process aiming at reusing the collected used products from the user with the purpose of minimizing the amount of waste that is sent to landfills. One type of product recovery process is remanufacturing, which provides a situation in which old products can be used as new, by means of carrying some necessary operations such as disassembly, refurbishing and replacement operations. In this context, Thierry et al. (1995) studied strategic production and operations management to determine recovery options such as repair, refurbishing, remanufacturing, and recycling. Their product recovery management model provided a system to recover economic value of the used products as reasonably as possible to reduce the quantity of waste as much as possible. Jayaraman (2006) suggested that manufacturers need to have a clearly thought-out strategy to collect products from the end-user. He proposed Remanufacturing Aggregate Production Planning (RAPP) in the form of a linear programming model to minimize the total remanufacturing cost taking into cognizance the incoming distribution of nominal quality. Boyer et al. (2013) developed a mathematical model for hazardous material. Dehghanian and Mansour (2009) designed a recovery network for end of life tires and addressed life cycle analysis (LCA) in order to highlight the environmental impact factors of different end of life options. Ferrer (1997) studied retreading of the tire for remanufacturing process and provided a simple rule to decide how many times a tire can be retreaded to reach its maximum utilization. Torretta et al. (2015) provided a review and compared the ways used tires were disposed and recovered in Europe, particularly in Italy and Romania which are two countries with high rate of waste disposal. In their study, various aspects of waste and their potential recovery options, such as the reconstruction of tires and material recovery, were taken into account. In addition, life cycle analysis has been used as a decision supporting tool in the literature. Dhouib (2014), for instance, proposed multi-criteria decision analysis to choose among different reverse logistics options for waste tires. Guide et al. (2008) provided an analytical model to help managers decide which products should be accepted for remanufacturing. In line with Guide et al. (2008), Jayaraman et al. (2008) identified the challenges in the collection of the used products and discussed how information technology can ameliorate many of these difficulties. de Souza and D'Agosto (2013) provided value chain analysis to assess the likelihood of distributing financial benefits for scrap tire reverse logistics.

1.2. Network design

Salema et al. (2008) developed a both strategic location-allocation and tactical decision model for CLSC. Easwaran and Üster (2010) developed a multi-product CLSC network design model to minimize the total cost of the model. They formulated the model as a mixed-integer linear programming problem, where hybrid manufacturing/remanufacturing facilities and a hybrid distribution/collection center with limited capacity was considered to serve retailers. Shekarian et al. (2016) developed a reverse logistics inventory model for a recoverable manufacturing process. Pishvaee et al. (2010) presented a bi-objective mixed-integer linear programming model for CLSC with a similar concept to that of Easwaran and Üster (2010). However, their model contained a disposal center. They maximized the responsiveness of the logistic network in addition to the total costs. Later, Pishvaee et al. (2011) solved the CLSC model given in Pishvaee et al. (2010) with robust optimization methods.

Amin and Zhang (2011) proposed a mixed-integer linear programming model to configure CLSC. They maximized profit by determining parts and products in the CLSC network. Pishvaee and Torabi (2010) proposed a CLSC network to minimize total costs including opening, transportation and processing cost and minimizing total tardiness. Gomes et al. (2011) developed a mixed-integer linear programming model for recovery of waste electrical and electronic equipment (WEEE).

Abdallah et al. (2012) presented an un-capacitated closed-loop location -inventory model with the assumption that a single plant shipped one type of product through the distribution center to the retailers, and the retailer, in turn, has the responsibility to collect the returned products. The remanufacturing center is an intermediary facility between recovery and market.

Zhou et al. (2007) studied the battery recycling and reverse logistics practice in China. They identified the obstacle and the weakness of the existing system in China and proposed a solution for the battery recycling logistics. Next, Kannan et al. (2010) provided a single objective, multi-echelon, multi-period, and multi-product CLSC network model for secondary or "rechargeable" (Zhou et al., 2007) lead/acid batteries. The proposed mixed integer linear programming model used genetic algorithm to determine the optimum cost. Moreover, the solution was comparable with that from GAMS optimization software. Sasikumar and Haq (2011) designed a multi-echelon, multi-product CLSC network and also included the best third party reverse logistics provider into their model to achieve cost efficiency and delivery schedule in reverse logistic. Jayant et al. (2014) provided simulation modeling and analysis of CLSC network design for the battery industry. Their model calculated cycle time, transfer cost, resource utilization, and transfer time. Subulan et al. (2014b) developed a fuzzy multi-objective, multi echelon, and multi-product mixed integer linear programming model for a CLSC network. However, their model is subject to minimization of cost, maximization of coverage and maximization of flexibility. Ene and Ozturk (2015) developed a reverse network for end of life vehicles. They proposed a mixed-integer linear programming model in order to determine the numbers and locations of facilities in the network and the material flows between these facilities.

1.3. Uncertainty

Most of the real life applications involve uncertainty. Similarly, uncertainty is embedded in the supply chain. Uncertainties contribute adversely to the quality of decisions made in the strategic, tactical and operational levels of the supply chain. Because CLSC simultaneously involves both the forward and reverse supply chain, it is more uncertain and complex. The uncertainty in some parameters of CLSC, e.g. demand, rate of return, and recovery rate, makes the estimation of the parameters a challenging task and an important issue for CLSC management. Although uncertainty has been investigated by relatively few studies, developing these types of models with uncertainty is a future trend (Subulan et al., 2015a). Wang and Hsu (2010) noted that there is a lack of CLSC models which handle uncertainty.

Fallah-Tafti et al. (2012) proposed a CLSC network design with typical forward supply chain including a supplier, a manufacturer (referred to by them as "assembler"), a distribution center, along with customer and reverse supply chain including a collection center, a recovery center and a recycling center. They provided a possibilistic solution approach with the STEP method to solve their multi-objective mixed-integer linear programming model. Their model targeted minimizing total cost and total delivery time of product, as well as maximizing supplier ranks.

Another study carried out by Subulan et al. (2014a), used the stochastic and possibilistic mixed integer programming for CLSC. Their proposed model minimized the total cost, but maximized the coverage of collected batteries. Subulan et al. (2015c) developed a fuzzy mixed integer linear programming (MILP) model to deal with uncertainty in CLSC. Vahdani et al. (2012b) developed a bi-objective MILP model for CLSC, where a combination of robust and fuzzy optimization methods was used to tackle uncertainty.

Although many scholars and researchers have studied various aspects of CLSC from different industries and case studies i.e. battery (Jayant et al., 2014; Kannan et al., 2010; Ramkumar et al., 2011; Sasikumar and Haq, 2011; Subulan et al., 2015a, 2015c), iron and steel (Vahdani et al., 2012a, 2012b), plastic water cane (Soleimani et al., 2013), cartridge (Chen et al., 2014), and glass (Devika et al., 2014), only a few researchers (see Table 2) focused on the development of a model for CLSC in the tire industry. It could be highlighted that there has been no attempt to deal with uncertainty in the tire industry. In order to fill this gap in the literature, this study presents a mathematical model for CLSC. The model consider uncertainty in demand and return rate and quality of return product which has significant impact on network configuration.

Moreover, a meticulous overview of the literature shows that most of the previous studies investigated the optimal tire supply chain configuration problem in either the forward or reverse supply chain, one at a time. Considering them separately caused sub-optimal results, because developing a CLSC network is an interdependent decision in forward and reverse supply chain networks (Pishvaee and Torabi, 2010). To cover the identified research gap, in this paper, we developed a mathematical model for optimizing the forward and reverse supply chain network simultaneously. A mathematical model provides a decision support tool for the tire supply chain with retreading and recycling options to choose the best alternative network configuration. Most of the real life applications involve different type of uncertainties, both environmental uncertainties and system uncertainty (Mula et al., 2006). This paper, taking into consideration environmental uncertainties, strives to design an efficient CLSC network to better represent the practical features of real-world problems. The present model aims to maximize profit with respect to energy saving and waste management.

2. Problem definition

This study extends the model developed by Creazza et al. (2012), which is a conventional forward supply chain. Our model differs from that of Creazza et al. (2012) and therefore extends this

Table 2
Characteristics of various models in the tire case study.

	Network structure			Demand		Return rate		Variable cost		Commodity		Period		Objective		Solution methodology
	Forward	Reverse	CLSC	Deterministic	Non-deterministic	Deterministic	Non-deterministic	Deterministic	Non-deterministic	Single	Multi	Single	Multi	Single	Multi	
Dehghanian and Mansour (2009)		×		×		×		×		×		×			×	Multi objective goal programming
Sasikumar et al. (2010)		×		×		×		×		×			×	×		Lingo
Creazza et al. (2012)	×			×		×		×			×	×		×		Lindo
Subulan et al. (2015b)			×	×		×		×			×		×		×	Fuzzy goal programming - GAMS
Proposed model			×		×		×	×			×	×		×		Scenario analysis - GAMS

model to better represent cases in real practice. First, we linked the forward supply chain in their model to the reverse logistics concept by adding a reverse path. The reverse path has collection, retreading, and recycling centers. The integrated network, called closed-loop supply chain (CLSC), is modified for the tire industry to help decision makers to make decisions such as expanding the capacity of facilities, selecting the location of facilities among potential locations, and creating flow between each facility. Second, our model considers uncertainty in some parameters of the mathematical model to account for the effect of uncertainty on the network configuration. Uncertainty is involved in the demand and collection of return products.

The proposed network (Fig. 2), involving three-echelon forward supply chain, consists of a manufacturer (M), a distribution center (DC) and a customer (k). The reverse supply chain involves a collection center (CC), a retreading center (RM), and a recycling center (RC).

Manufacturers produce different types of tires. The distribution centers receive new tires from the manufacturing plant and retreaded tires from the retreading center. Each type of new and retreaded product can be handled by all the distribution centers. The new and retreaded tires are shipped from distribution centers to the customers in order to fulfill demand. There is a likelihood of demand shortage for each customer. It is assumed that a certain portion of the demand, such as the used tires, is collected from customers and sent to the collection centers.

In the reverse flow, the collected used products at the retailer shop are shipped to the collection center. Through checking and inspecting of the tires at the collection center, those products that meet the quality level for remanufacturing will be sent to the retreading center, while the rest of the tires are sent to the recycling center. At the retreading center, the tires are retreaded and reconditioned and then moved to the distribution center.

A mixed integer linear programming model is designed for the CLSC to maximize total profit. The proposed model determines the optimum number of distribution, collection, retreading, and recycling centers. Determining the number and location of each facility and its capacity is a strategic decision because any change in the number of active facilities may result in additional cost. Additionally, facility locations and the flow between each facility are determined. The obstacle in designing a CLSC network is uncertainty in parameters such as demand, returned product and the number of products to meet the quality for remanufacturing. In fact, uncertainty is embedded in the optimization model. To overcome this problem, a scenario-based model is developed considering three scenarios of optimistic, most likely and pessimistic. In this model some assumptions are made which are listed below:

- Manufacturers have limited capacity of production.
- The capacity of distribution centers, retailers, and collection centers, and also the retreading and recycling center are given.
- Demand for new products is given.

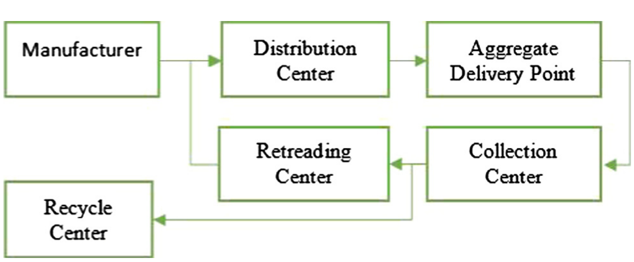

Fig. 2. Proposed closed-loop supply chain.

- The rates of collection, recycling and remanufacturing are identified.
- Location of manufacturers, distribution centers, retailers, customers, collection centers, retreading centers, recycling centers, are fixed and predefined.
- Tires can only be retreaded once.

In addition, the cost of manufacturing, the distribution center, the collection center and the retreading center are given. To calculate cost there are many factors involved. For instance, retreading cost contains labor cost, inspection cost, etc. At the retreading center inspection is a major source of cost because worn tires need to be inspected before starting the process in order to verify that the casing is acceptable for retreading. And at the end of the process, the tires need to be inspected again with some sophisticated instruments such as X-ray, shearographie/high pressure tester to ensure the quality is maintained.

3. Model formulation

The sets, the parameters and the decision variables are defined as follows.

Indices	
i	Set of manufacturers $i \in I$
j	Set of distribution centers $j \in J$
k	Set of aggregate delivery points $k \in K$
c	Set of collection centers $c \in C$
r	Set of retreading centers $r \in R$
b	Set of recycling centers $b \in B$
n	Set of new products $n \in N$
u	Set of retreaded products $u \in U$
s	Set of scenarios $s \in S$
Parameters	
odc_j	Fixed opening cost of distribution center j
occ_c	Fixed opening cost of collection center c
orm_r	Fixed opening cost of retreading center r
km_i	Production capacity of manufacturer i
kdc_j	Holding capacity of distribution center j
kr_k	Holding capacity of delivery point k
kcc_c	Holding capacity of collection center c
krm_r	Capacity of retreading center r
krc_n	Capacity of recycling center b
pn_{kn}	Penalty cost for unsatisfied demand of delivery point k for product n
pu_{ku}	Penalty cost for unsatisfied demand of retailer k for retreated product u
pn_n	Selling price for new product n
pu_u	Selling price for retreaded product u
dn_{kns}	Demand of aggregate delivery point k for new product n in scenario s
du_{kus}	Demand of aggregate delivery point k for retreaded product u in scenario s
cm_{in}	Production cost of manufacturer i for new product n
cdc_j	Distribution cost of distribution center j
ccc_{cn}	Collection cost of collection center c for product n
crm_{rn}	Retreading cost of retreading center r for product n
$t1_{ij}$	Distance between manufacturer i and distribution center j
$t2_{jk}$	Distance between distribution center j and delivery point k

(continued on next page)

$t3_{kc}$	Distance between delivery point k and collection center c
$t4_{cr}$	Distance between collection center c and retreading center r
$t5_{cb}$	Distance between collection center c and recycling center b
$t6_{rj}$	Distance between retreading center r and distribution center j
q	Unit transportation cost
α_{ns}	Return rate of new product n for scenario s
β_{ns}	Return rate of new product n to recycling center for scenario s
ps_s	Occurrence probability of scenario s

Variables

mdc_{ijns}	Quantity of product n shipped from manufacture i to distribution center j for scenario s
dcr_{jkns}	Quantity of product n shipped from distribution center j to delivery point k for scenario s
$dcrp_{jkus}$	Quantity of retreaded product u shipped from distribution center j to delivery point k for scenario s
rcc_{kcns}	Quantity of product n shipped from delivery point k to collection center c for scenario s
$ccrm_{crns}$	Quantity of product n shipped from collection center c to retreading center r for scenario s
$ccrc_{cbns}$	Quantity of product n shipped from collection center c to recycling center b for scenario s
$rmdc_{rjus}$	Quantity of product n shipped from remanufacturing center r to distribution center j for scenario s
δn_{kns}	Quantity of unsatisfied demand of new product n at delivery point k for scenario s
δu_{kus}	Quantity of unsatisfied demand of retreaded product u at delivery point k for scenario s
rem_{rns}	Retreading quantity of retreading center r for product n for scenario s

Binary variables

bdc_j	If distribution center j is open 1; otherwise 0
bcc_c	If collection center c is open 1; otherwise 0
brm_r	If remanufacturing center r is open 1; otherwise 0

3.1. Mathematical formulation

The objective of the mathematical formulation of the model is to maximize profit. It calculates by deducting total cost, which is the summation of fixed facility opening costs (FFOC) (Eq. (2)), transportation cost (TC) (Eq. (3)), manufacturing cost (MC) (Eq. (4)), distribution cost (DC) (Eq. (5)), collection cost (CC) (Eq. (6)), retreading cost (RC) (Eq. (7)) and penalty cost of unsatisfied demand (PCD) (Eq. (8)), from total revenue (TR) (Eq. (1)).

$$\text{Min } Z = \text{TR} - \text{FFOC} - \text{TC} - \text{MC} - \text{DC} - \text{CC} - \text{RC} - \text{PCD}$$

Objective Function: profit maximization

$$\begin{aligned}\text{TR} = &\sum_k\sum_n\sum_s (ps_s \cdot (dn_{kns} - \delta n_{kns}) \cdot pn_n) \\ &+ \sum_k\sum_u\sum_s (ps_s \cdot (du_{kus} - \delta u_{kus}) \cdot pu_u)\end{aligned} \tag{1}$$

$$\text{FFOC} = -\sum_j bdc_j \cdot odc_j - \sum_c bcc_c \cdot occ_c - \sum_r brm_r \cdot orm_r \tag{2}$$

$$\begin{aligned}TC = &-\sum_i\sum_j\sum_n\sum_s ps_s \cdot mdc_{ijns} \cdot t1_{ij} \cdot q \\ &-\sum_j\sum_k\sum_n\sum_s ps_s \cdot dcr_{jkns} \cdot t2_{jk} \cdot q \\ &-\sum_j\sum_k\sum_u\sum_s ps_s \cdot dcrp_{jkus} \cdot t2_{jk} \cdot q \\ &-\sum_k\sum_c\sum_n\sum_s ps_s \cdot rcc_{kcns} \cdot t3_{kc} \cdot q \\ &-\sum_c\sum_r\sum_n\sum_s ps_s \cdot ccrm_{crns} \cdot t4_{cr} \cdot q \\ &-\sum_c\sum_r\sum_n\sum_s ps_s \cdot ccrc_{cbns} \cdot t5_{cb} \cdot q \\ &-\sum_r\sum_j\sum_n\sum_s ps_s \cdot rmdc_{rjus} \cdot t6_{rj} \cdot q\end{aligned} \tag{3}$$

$$\text{MC} = -\sum_i\sum_j\sum_n\sum_s ps_s \cdot mdc_{ijns} \cdot cm_{in} \tag{4}$$

$$\text{DC} = -\sum_j\sum_k\sum_n\sum_u\sum_s ps_s \cdot (dcr_{jkns} + dcrp_{jkus}) \cdot cdc_j \tag{5}$$

$$\text{CC} = -\sum_c\sum_r\sum_b\sum_n\sum_s ps_s \cdot (ccrm_{crns} + ccrc_{cbns}) \cdot ccc_{cn} \tag{6}$$

$$\text{RC} = -\sum_r\sum_n\sum_s ps_s \cdot rem_{rns} \cdot crm_{rn} \tag{7}$$

$$\text{PCD} = -\sum_k\sum_n\sum_s ps_s \cdot pn_{kn} \cdot \delta n_{kns} - \sum_k\sum_u\sum_s ps_s \cdot pu_{ku} \cdot \delta u_{kus} \tag{8}$$

Subject to

$$\sum_j mdc_{ijns} \leqslant km_i \quad \forall i, n, s \tag{9}$$

$$\sum_i mdc_{ijns} + \sum_r rmdc_{rjus} \leqslant bdc_j * kdc_j \quad \forall j, n, u, s \tag{10}$$

$$\sum_j dcr_{jkns} + \sum_j dcrp_{jkus} \leqslant kr_k \quad \forall k, n, u, s \tag{11}$$

$$\sum_r ccrm_{crns} + \sum_b ccrc_{cbns} \leqslant bcc_c \cdot kcc_c \quad \forall c, r, n, s \tag{12}$$

$$\sum_j rmdc_{rjus} \leqslant brm_r \cdot krm_r \quad \forall r, u, s \tag{13}$$

$$\sum_c ccrc_{cbns} \leqslant krc_b \quad \forall b, n, s \tag{14}$$

$$\sum_j dcr_{jkns} + \delta n_{kns} \geqslant dn_{kns} \quad \forall k, n, s \tag{15}$$

$$\sum_j dcrp_{jkus} + \delta u_{kus} \geqslant du_{kus} \quad \forall k, u, s \tag{16}$$

$$\sum_i mdc_{ijns} = \sum_k dcr_{jkns} \quad \forall j, n, s \tag{17}$$

$$\sum_r rmdc_{rjus} = \sum_k dcrp_{jkus} \quad \forall j, n, u, s \tag{18}$$

$$\alpha_{ns} \cdot \sum_j dcr_{jkns} = \sum_c rcc_{kcns} \quad \forall k, n, s \tag{19}$$

$$\beta_{ns} \cdot \sum_k rcc_{kcns} = \sum_b ccrc_{cbns} \quad \forall c, n, s \tag{20}$$

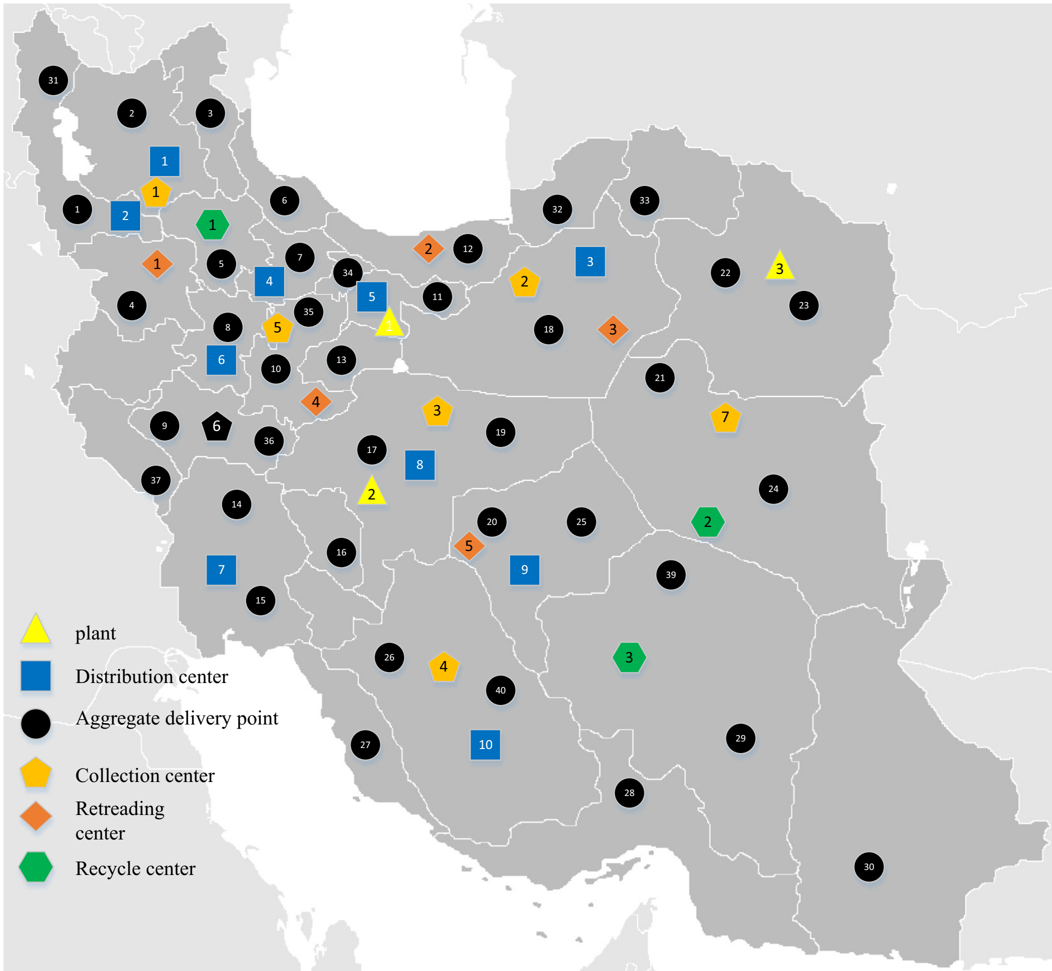

Fig. 3. Potential facility location and network.

$$(1-\beta_{ns})\cdot\sum_{k} rcc_{kcns} = \sum_{r} ccrm_{crns} \quad \forall c,n,s \tag{21}$$

$$rem_{rns} = \sum_{c} ccrm_{crns} \quad \forall r,n,s \tag{22}$$

$$\sum_{j} rmdc_{rjus} = rem_{rns} \quad \forall r,n,u,s \tag{23}$$

$$\begin{aligned} & mdc_{ijns}, dcr_{jkns}, dcrp_{jkus}, rcc_{kcns}, ccrm_{crns} \\ & ccrc_{cbns}, rmdc_{rjus}, \delta n_{kns}, \delta u_{kus}, rem_{rns} \geqslant 0 \end{aligned} \tag{24}$$

$$bdc_j, bcc_c, brm_r \in \{0,1\} \tag{25}$$

Table 3
Fixed opening cost (in millions $).

Opening cost	Range of values
DC	1.2–2
CC	0.9–2.1
RM	5–5.8

Table 4
Capacity.

Capacity	Range (per unit)
M	300,000–400,000
DC	250,000–300,000
K	100,000–150,000
CC	200,000–230,000
RM	170,000–200,000
RC	255,000–280,000

Table 5
Value of parameters used in the model.

Penalty	Range
Penalty for unsatisfactory new tire	\$20–50
Penalty for unsatisfactory retreaded tire	\$20–50
Price of new tire	\$450–550
Price of retreaded tire	\$150–250
Manufacturing cost	\$100–140
Distribution cost	\$2–5
Collection cost	\$3–8
Retreading cost	\$20–30

Table 6
Value of stochastic parameters used in the model.

	Pessimistic range	Expected range	Optimistic range
Demand for new tire	10,000–10,100	10,100–10,300	10,300–10,500
Demand for retreaded tire	1800–2020	2020–2060	2060–2100
alpha	0.4	0.5	0.8
beta	0.2	0.15	0.1

Table 7
Scenario probability.

Scenario	Probability	Scenario	Probability	Scenario	Probability
S1	0.006	S10	0.01	S19	0.004
S2	0.015	S11	0.025	S20	0.01
S3	0.009	S12	0.015	S21	0.006
S4	0.036	S13	0.06	S22	0.024
S5	0.09	S14	0.15	S23	0.06
S6	0.054	S15	0.09	S24	0.036
S7	0.018	S16	0.03	S25	0.012
S8	0.045	S17	0.075	S26	0.03
S9	0.027	S18	0.045	S27	0.018

Table 8
Summary of optimum result.

	Model
Number of variables	210,807
Number of constraints	82,136
CUP time	3.791 s
Number of open DCs	5
Number of open CCs	5
Number of open RMs	3
Profit	8.6465E+8

Constraints (9)–(13) are capacity constraints. Constraint (9) assures production does not exceed production capacity. Constraint (10) guarantees distribution centers have enough holding capacity for distribution of products. Constraint (11) shows aggregate delivery point has enough capacity to respond to the demand. Constraint (12) assures collected products do not exceed the capacity of collection centers. Constraint (13) assures return products will not exceed the capacity of the retreading centers. Constraint (14) assures scrap products that are sent to the recycling center meet capacity limitations of the recycling center. Constraint (15) and constraint (16) guarantee each customer receives his demand. Constraint (17)–(23) are equilibrium constraints, which assure the flow balance at the distribution center, retailer, collection center, and retreading center. Constraint (24) ensures that the quantity of production, retreaded products, and quantity of product that is shipped between each facility is non-negative. Constraint (25) represents the binary variables to provide decisions for opening of distribution centers, collection centers, and retreading centers.

4. Case study

An Iranian tire industry has been used to illustrate the performance of the proposed mixed integer linear programming (MILP) model for real life application. It is considered that the retreaded tire and the brand new tire have different demand. The objective of a CLSC network formation is to determine a maximal-profit formation of logistics network in order to be able to fulfill demands.

ABC is a domestic automobile tire manufacturer with headquarter in Tehran, Iran. It produces different type of tires with specific characteristics such as size and quality. Its products could be divided into two sub categories of car and truck tires. ABC

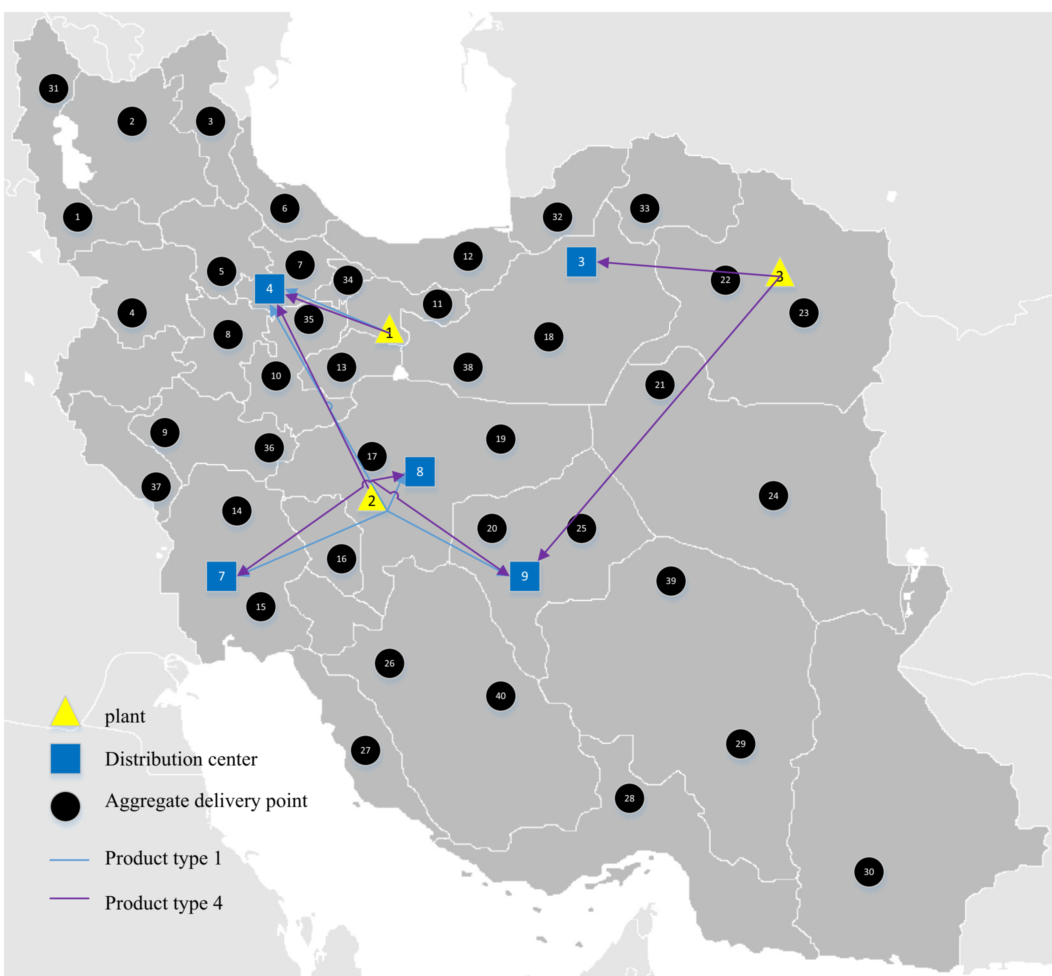

Fig. 4. Flow between DCs and manufacturing plants.

customers range from an original equipment automobile manufacturer (Bing et al., 2012), which produces cars in Iran and car fixed shop customers who do replacement of tires for individual customers. Original Equipment Manufacturer (OEM) customers receive tires directly from plants, basically under the made to order policy. OEM, due to its direct shipment, is not in the scope of our research. Apart from OEM customers, replacement customers receive 70% of annual production volume, which is a significantly high amount of production, and it requires great effort to satisfy customers in terms of demand and quality. Although, ABC produces both car and truck tires, their policy is to develop a reverse logistic network and retreading process for truck tiers alone because car passenger tires are not demand for some reasons such as customer perception with regard to safety matters (Lebreton and Tuma, 2006). Therefore, to serve these customers, ABC has built a logistics network to serve demand throughout the chain of local distribution centers. The ABC supply chain network is a three-echelon supply chain which involves production plants, regional distribution centers, and a set of delivery points. ABC is aiming to increase the efficiency of supply chain network in terms of cost, in order to achieve higher competitive advantage. This issue comes up with cost reduction and increased service level. Consequently, ABC is challenged by increasing profit and remanufacturing as well as reverse logistics opportunities.

Our illustrative example of the ABC Company has 6 types of products, 3 production plants, 10 regional distribution centers, and 40 aggregated delivery points for a particular region. Since in reality several fixed shop and delivery points might be in a region, considering that all of these delivery points in the model make the model complicated, therefore an aggregated delivery point is used as a summation of all the demand of each particular region. ABC has targeted to choose suitable distribution centers among the DCs. In addition, ABC has targeted to open collection centers to collect used tires, and to open retreading centers to recondition the tires and thereafter move them to regional distribution centers. ABC has a limited budget and machinery for its expansion program. Therefore, ABC wants to select 5 out of 7 potential collection centers and 3 out of 5 potential retreading centers. This, therefore, requires the addition of two constraints (26) and (27) which are written as:

$$\sum_c bcc_c \leqslant 5 \tag{26}$$

$$\sum_r brm_r \leqslant 3 \tag{27}$$

Particularly with regard to the network formation problem, ABC needs to optimize the set of aggregate delivery points, collection centers, and retreading facilities in terms of number, location and size in addition to the network linkages (i.e. the linkages between plants, distribution centers and aggregate delivery points). The potential network configuration of the model is shown in Fig. 3 for the tire case study in Iran.

It is assumed the collection centers should be located where there is high demand. Collection centers should be distributed throughout the region uniformly. Based on this assumption 7 potential sites have been selected for collection centers.

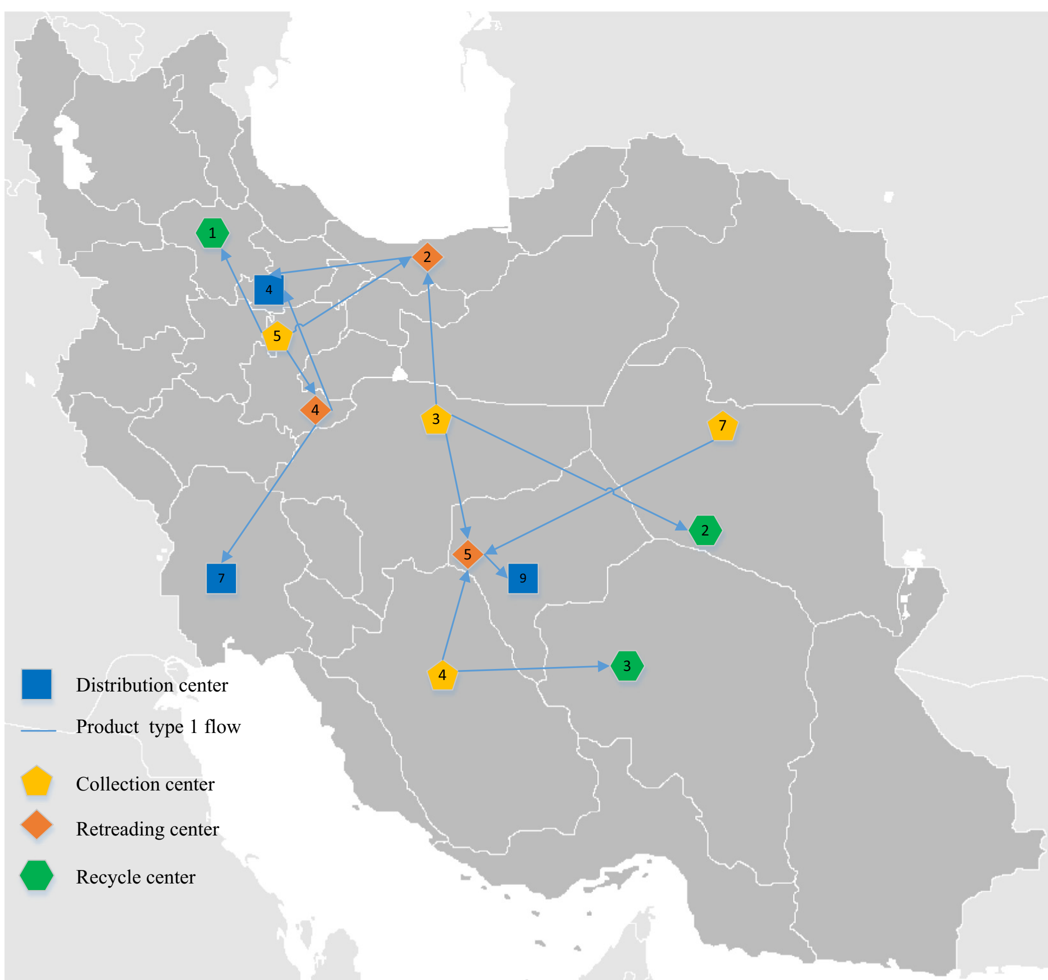

Fig. 5. Reverse network for product type 1.

It is assumed that the opening cost includes technology and equipment purchasing, cost of land, and set up cost. Table 3 presents the opening cost of the DC, CC and retreading center. Table 4 indicates capacity for each facility.

Other parameters of the model are presented in Tables 5 and 6. Moreover, it is assumed that the transportation cost between facilities is based on full truck load cost of 0.02$ per kilometer distance. The distance between each facility is calculated based on direct distance.

In the network model, the number of end-of-life tires returned to each collection center is required. To obtain this, the scenario values must be distributed among all center locations in the region. For this purpose, considering that the number of end-of-life tires in each location is proportional to the demand of that region, the scenario values were distributed among the locations in the region proportionally to the demand of that region (see Table 6).

In the solution phase of the problem, to address the uncertainty in the number of end-of-life tires returned to collection centers, the pessimistic, expected and optimistic scenarios were defined for three planning periods and integrated into the model. The probabilities of occurrence of the pessimistic, expected and optimistic scenarios were 0.15, 0.50 and 0.35, respectively Details of the scenarios are presented in Table 7.

As shown in the scenario table, scenario number 14 has the highest probability. Therefore, this paper analyses the network based on this scenario.

The models were run through optimization software GAMS rev 140 including CPLEX 9.0 production on personal computer with 2.5 GHz CPU and 8 GB main memory. The result for the objective function is shown in Table 8. The result indicates optimum profit of 8.6465E+8 for a developed network. In addition, the result shows in order to have optimum network configuration, some facilities should shut down. Although the number of variables is high, the computation time for problems of this size are sufficiently fast for making strategic decisions.

Fig. 4 shows active DCs and the flow of product between manufacturing plants and DCs for product type 1 and type 4 simultaneously. It highlights that manufacturing plant 1 sent product type 1 and type 4 to distribution center number 4. Moreover, it shows that product type 1 is not served by manufacturing plant number 3.

Figs. 5 and 6 show optimum reverse configuration network of product type 1 and 4 respectively. Fig. 5 reveals four collection centers are used to serve product type 1. In both Figs. 5 and 6, distribution center number 4, 7 and 9 are selected among 10 available DCs. Fig. 5 also shows which CCs are assigned to which retreading facilities.

4.1. Sensitivity analysis

To see how the changes in the problem parameters can affect the optimal solution and to gain more insights from the model, sensitivity analyses is performed. We study sensitivity of the solutions to the changes in the capacity of the DC. For this analyses, the capacities of the DCs increased by 20%. Table 9 shows the effect of this analysis on the objective function value and number of open

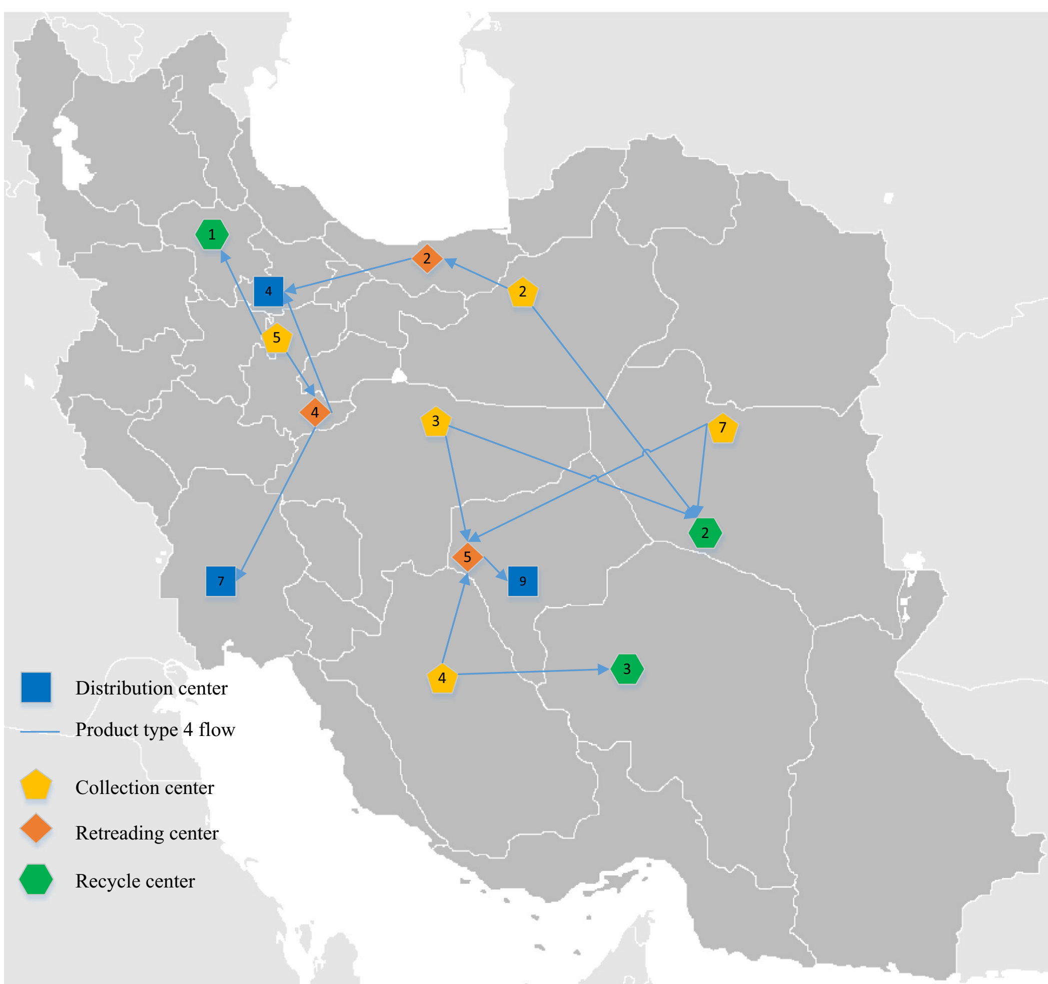

Fig. 6. Reverse network for product type 4.

Table 9
Effect of 20% change in capacity of DCs on network.

	Objective function	Open facilities		
		dc	cc	rm
Base case	8.6465E+8	3, 4, 7, 8, 9	2, 3, 4, 5, 7	2, 4, 5
20% increase	8.7234E+8	1, 4, 9	4, 5	4, 5

Table 10
Effect of 20% change in capacity of CCs on network.

	Objective function	Open facilities		
		dc	cc	rm
Base case	8.6465E+8	3, 4, 7, 8, 9	2, 3, 4, 5, 7	2, 4, 5
20% increase	8.1491E+8	4, 9	5	4, 5

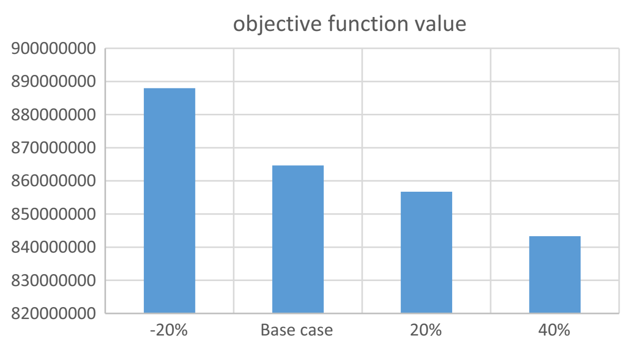

Fig. 7. The effect of change of transportation cost on objective function value.

facilities. It can be observed from the results that, when capacity of the DC increases, the objective function value increases and the number of open facilities decreases. Increase in objective function is as a result of reduction of the number of open facilities which reduces opening cost.

Table 10 indicate effect of 20% increase in capacity of CC on the number of open facilities. It can be seen that when capacity increase number of open facilities decreases. Increase in capacity of CCs has a significant effect on the number of open CCs, which can be seen as only CC number 5 is selected.

Fig. 7 shows how change in transportation affects objective function value. It can be seen that a rise in transportation cost has a significant effect on objective function value which increase in cost leads to reduced profit. It illustrates that with 20% reduction of transportation cost objective value increased about 3%.

5. Conclusions

A closed-loop supply chain is becoming increasingly important for researchers and practitioners as a result of stringent environmental regulations concerning product recovery and waste management. This study develops a mathematical model for a closed-loop supply chain network which provides decision support to practitioners of end-of-life tire recovery as well as determines the numbers and the locations of facilities and the material flows between these facilities. This study addresses the paucity of research on the design of an entire product recovery network for used tires. An important characteristic of closed loop flow networks is the uncertainty in the flow of demand, returned products and quality of returned product. This study addressed this problem with a scenario-based model. The modeling approach used in this study can be adapted for other industries. The main objective of product recovery and waste management is to minimize waste and pollution. This study shows that a well-designed closed-loop supply chain network model may not only benefit the environment, it may also provide economic benefits and incentives to manufacturers. For future work, a multi objective optimization model can be considered for the total profit and collection coverage simultaneously. Additionally, life cycle assessment and environmental damage indicator such as eco-indicator 99 also can be scheduled for future research.

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