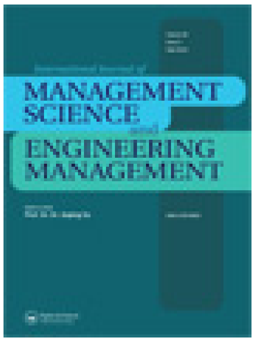

International Journal of Management Science and Engineering Management

ISSN: 1750-9653 (Print) 1750-9661 (Online) Journal homepage: http://www.tandfonline.com/loi/tmse20

An optimization model for network design of a closed-loop supply chain: a study for a glass manufacturing industry

Ehsan Pourjavad & Rene V. Mayorga

INTERNATIONAL JOURNAL OF MANAGEMENT SCIENCE AND ENGINEERING MANAGEMENT
https://doi.org/10.1080/17509653.2018.1512387

An optimization model for network design of a closed-loop supply chain: a study for a glass manufacturing industry

Ehsan Pourjavad and Rene V. Mayorga

Industrial Systems Engineering, University of Regina, Regina, Canada

ABSTRACT
Closed-Loop Supply Chain (CLSC) network design plays a significant role in supply chain performance. The CLSC network design is recognized as a strategic problem which ensures a useful and efficient supply chain management providing an optimal platform. The CLSC network design problem includes two types of decisions, strategic and tactical. This paper aims to determine the location of facilities which is recognized as a strategic decision. In addition, tactical decisions such as the amount of supplied raw material, the level of production, and shipments among the network entities are made through the proposed model. This paper is distinctive by introducing a Mixed Integer Linear Programming (MILP)-based model which simultaneously optimizes the both forward and reverse chains. The model is implemented on a glass manufacturing industry to highlight the importance and applicability of the framework. Moreover, the study provides a comprehensive sensitivity analysis to investigate the effect of parameters such as demand and return rates on strategic and tactical decisions in supply chain network.

ARTICLE HISTORY
Received 10 March 2018
Accepted 13 August 2018

KEYWORDS
Closed loop supply chain; mixed integer linear programming; network; design; optimization

1. Introduction

Increasing cost pressures force enterprises to investigate and arrange their logistics systems and strategies to diminish costs and enhance customer service strategies (Pourjavad & Mayorga, 2017). Supply Chain Management (SCM) is a tool to achieve these aims. SCM includes both strategic and tactical decisions, accomplished via forward and reverse Supply Chain Network Design (SCND) (Bowersox, Closs, & Cooper, 2002). In a forward supply chain, as conventional logistics, manufacturers receive raw material from suppliers and deliver the products to distributors and subsequently customers. The customer centers are defined as the end of the process. However, products are not used by customers forever. It is required to extend the supply chain's responsibilities until the end of products' life cycle.

In a reverse supply chain, end-of-life products are collected from customers by disassembly centers. Some of these returned products are redistributed after major repairs in disassembly centers. Some returned products are recognized to be delivered to the manufacturers to reproduce and resell to so-called the second customers. Also, some can be recycled and used partially as raw materials. Eventually, the non-reusable products will be sent to disposal centers. The factors that have effects on reverse strategies are divided into three categories; economic, environmental, and social. The main economic factors are; total manufacturing cost, recycling costs, recycled volumes, and an increase of sales volume for new products. Consumers environmental awareness, environmental regulations, pressures with stakeholders are recognized as important environmental factors that affect the reverse strategies. For social category, advertising promotion of image, corporate social responsibility, good recycling management system, and competitive pressures are four criteria that have a big effect on reverse strategies (Chiou, Chen, Yu, & Yeh, 2012).

The government plays an important role in the reverse supply chain. It can improve the reverse rates of products by adopting several strategies; creating incentives to encourage people for returning used products; issuing strict regulations to use raw material for producers, increasing environmental awareness of customers from the importance of returned products; establishing suitable recycling management systems; encouraging companies to use renewable raw materials.

A Closed-loop Supply Chain (CLSC) is achieved when forward and reverse supply chains are simultaneously taken into account (Soleimani & Kannan, 2015). Design and planning are identified as the most important decisions that should be made in coping with a CLSC. Strategic decisions such as network configuration, structure, capacity, and coordination are the main characteristics of all facilities in the design stage. However, at the planning level, one of the most important parameters adopted in supply chain network is to determine the number of shipped products between all supply chain network entities (Chopra & Meindl, 2007).

This paper presents a CLSC network design model (in the forward and reverse chains) for a glass manufacturing industry located in the center part of IRAN. The forward chain included raw material suppliers, producers, distributors, warehouses, and customer entities. The reverse chain considered collection & inspection, disposal, recycling, recovering, remanufacturing, redistributors, and second customer centers. A Mixed Integer Linear Programming (MILP) model is proposed to optimize the CLSC network design. The model determines the location of facilities, which is recognized as a strategic decision. In addition, tactical decisions, such as the amount of supplied raw material, the level of production, and shipments among the network entities are made. The objective of the model is to minimize

CONTACT Rene V. Mayorga Rene.Mayorga@uregina.ca Industrial Systems Engineering, University of Regina, 3737 Wascana Parkway, Regina, SK S4S 0A2, Canada

transportation, production, collection, reverse costs, and the fixed costs of establishment of new entities. Also, a comprehensive sensitivity analysis is carried out to investigate the effect of parameters, such as demand and return rates on the strategic and tactical decisions of supply chain network. In addition, the optimum solution for CLSC network design of this industrial case is compared with one non-optimized case to show the advantage of optimization.

2. Literature review

Table 1. summarizes the conducted studies for the supply chain network design problem. The studies are categorized based on network type, objective function, modeling type, finding solution approaches, and applications. Supply chain network design problems can be classified into three categories according to the underlying network structure: forward, reverse, and Closed-Loop Supply Chain (CLSC).

For forward supply chains networks, Tsiakis and Papageorgiou (2008) formulated a mixed integer linear programming model. They determined the optimal configuration of a production and distribution network considering financial and operational constraints. The objective function of this model was the minimization of the costs of fixed infrastructure, transportation, production, and material handling costs. Thanh, Bostel, and Peton (2008) employed a mixed integer linear programming model for the design of a production-distribution system for forward chains. They designed a multi-echelon network with deterministic demands. Sadjady and Davoudpour (2012) formulated a mixed integer programming model which aims to minimize total costs of network and opening and operating for facilities. The proposed model determined locations of plants and warehouses, best transportation method, and the best strategy for distributing the products. Balaman and Selim (2014) presented a mixed integer linear programming model to design a supply chain network for the production of biogas through anaerobic digestion of biomass. The model determined numbers, capacities, and locations of biogas plants and biomass storages and the biomass supply and product distribution.

For reverse chain networks, Kim, Song, and Jeong (2006) also developed a mathematical model to optimize the supply planning function for a reverse chain. Their model determines the number of purchased parts from the subcontractors and the number of parts to be processed at each remanufacturing facility. They used a set of experimental data to validate their model. Xanthopoulos and Iakovou (2009) proposed a model to design of the recovery processes of the end-of-life (EOL) electric and electronic products. Their model includes two phases; identifying components that need to be disassembled for recovery by a decision-making model and presenting a multi-period, multi-product mixed-integer linear programming model to design recovery processes. Achillas et al. (2010) presented a decision support tool for policy-makers and regulators in order to optimize reverse logistics network of electronic products. They formulated a Mixed Integer Linear Programming mathematical model in which the cost elements are considered for objective function of the model. Sasikumar, Kannan, and Haq (2010) formulated a Mixed Integer Non-linear Programming (MINLP) model to design a multi-echelon reverse logistics network with the aim of maximizing the profit. Their model determines the locations and required number of facilities and product flows between facilities in the reverse chain. They applied this model for network design of truck tire remanufacturing for the secondary market segment. Alumur, Nickel, Saldanha-da Gama, and Verter (2012) proposed a framework of profit maximization modeling to design a reverse logistics network. They presented a mixed-integer linear programming formulation to solve this problem. They applied this model for reverse network design of washing machines and tumble dryers in Germany. Alshamsi and Diabat (2015) presented a MILP model for designing a complex network of the reverse logistics system in which the model results provide decision elements on locations, capacities of inspection centers and remanufacturing facilities.

In a CLSC problem both forward and reverse supply chain decisions must be taken into account simultaneously (Lee & Dong, 2008). Fleischmann, Beullens, Bloemh of Ruwaard, and Wassenhove (2001) presented a mixed

Table 1. Summary of literature review.

Authors	Network type	Objective function	Modeling	Solution method: Software	Solution method: Metaheuristic	Application
Tsiakis and Papageorgiou (2008)	Forward	Cost	MILP	CPLEX	–	CE
Thanh et al. (2008)	Forward	Cost	MILP	Xpress Optimizer	–	CE
Sadjady and Davoudpour (2012)	Forward	Cost	MILP	LINGO	–	CE
Balaman and Selim (2014)	Forward	Cost	MILP	CPLEX	–	CE
Kim et al. (2006)	Reverse	Cost	MILP	CPLEX	–	CE
Xanthopoulos and Iakovou (2009)	Reverse	Cost	MILP	CPLEX	–	Electronic products
Achillas. et al. (2010)	Reverse	Cost	MILP	CPLEX	–	Electronic products
Sasikumar et al. (2010)	Reverse	Cost	MINLP	LINGO	–	Tire retreading
Alumur et al. (2012)	Reverse	Cost	MILP	CPLEX	–	Washing machine
Alshamsi and Diabat (2015)	Reverse	Cost	MILP	CPLEX	–	Washing machine
Fleischmann et al. (2001)	CLSC	Cost	MILP	CPLEX	–	Paper industry
Uster et al. (2007)	CLSC	Cost	MILP	CPLEX	–	CE
Jayaraman (2006)	CLSC	Cost	Linear programming	GAMS	–	CE
Kusumastuti et al. (2008)	CLSC	Cost	MILP	LINGO	–	Computer industry
Ozceylan and Paksoy (2013)	CLSC	Cost	MILP	CPLEX	–	CE
Ramezani et al. (2014)	CLSC	Cost	MILP	CPLEX	–	CE
Özceylan et al. (2014)	CLSC	Cost	MINLP	GAMS	–	CE
Gaur et al. (2017)	CLSC	Cost	MINLP	GAMS	–	CE
Lee and Dong (2008)	CLSC	Cost	Linear programing	CPLEX	Tabu search	CE
Aras et al. (2008)	Reverse	Cost	MINLP	GAMS	Tabu search	CE
Pishvaee et al. (2010)	Reverse	Cost	MILP	LINGO	SA	CE
Soleimani et al. (2013)	CLSC	Cost	MILP	CPLEX	GA	CE

CE: Computational Experiment.

integer linear programming model for designing a recovery network considering the forward flow. The proposed network includes un-capacitated disassembly and re-manufacturing facilities in the reverse channel. Suppliers and the relations between forward and reverse flows were not considered in designing network. Uster, Easwaran, Akcali, and Cetinkaya (2007) employed an MILP model for a closed-loop supply chain network design problem. The manufacturing and remanufacturing were considered separately. Also, they considered a single source for meeting customer demands. Jayaraman (2006) introduced an analytical Remanufacturing Aggregate Production Planning (RAPP) model, for aggregating production planning and controlling for closed-loop supply chains with product recovery and reuse. The output of that model included the number of units of core type with a nominal quality level which are to be disassembled, disposed, remanufactured, or acquired within a given time period. Kumar and Yamaoka (2007) presented a system dynamics modeling method to design a closed loop supply chain for the Japanese car industries. They also explored the relationship between reducing, reusing, recycling and disposal with base scenario analysis using consumption data and forecast. Kusumastuti, Piplani, and Lim (2008) developed a facility location-allocation model to redesign a closed-loop service network at a Singapore-based company, which provides after-sales service. They considered four repair facilities in the model: service providers (for the collection of faulty equipment), local sub hubs (for consolidation of faulty parts), regional distribution centers (for handling faulty and good parts), and part manufacturers and third-party repair vendors (as repair facilities for faulty parts). They considered the possibility of having the network span across several countries and multi-period planning horizons Ozceylan and Paksoy (2013) presented a mixed integer mathematical model for a CLSC network that contained both forward and reverse flows with multi-periods and multi-parts. The transportation amounts of manufactured and disassembled products and the location of plants and retailers were determined. Ramezani, Kimiagari, and Karimiz (2014) modeled a CLSC design considering a financial approach. Economic aspects were considered as exogenous variables in this study. They incorporated the financial aspects and a set of budgetary constraints representing balances of payment delays, discounts, securities, and cash in the supply chain planning. Özceylan, Paksoy, and Bekta (2014) described a MINLP model to optimize strategic decisions (amounts of goods flowing on the forward and reverse chains) and tactical decisions in the reverse chain. The objective function in this model minimizes costs of transportation, purchasing, refurbishing, and operating the disassembly workstations. Gaur, Amini, and Rao (2017) presented a CLSC model for new product and its reconditioned version. The model specified production plan and configuration of CLSC for new products. They applied the model for a battery manufacturer in India.

As seen from Table 1, most studies employed commercial software such as LINGO (Sasikumar et al., 2010), GAMS (Gaur et al., 2017), and CPLEX (Alshamsi & Diabat, 2015; Alumur et al., 2012; Achillas et al. 2010; Ozceylan & Paksoy, 2013; Ramezani et al., 2014; Tsiakis & Papageorgiou, 2008; Xanthopoulos & Iakovou, 2009). CLSC network design problem is identified as an NP-hard (Non-deterministic polynomial-time) problem, for which analytical methods and commercial software are not able to provide optimal solutions for large problem situations. Therefore meta-heuristics methods are used to solve such problems. Lee and Dong (2008) employed a deterministic programming model to optimize forward and reverse logistics flows for end-of-lease computer products recovery. They developed a Tabu Search (TS) algorithm to determine transportation amounts for returned products. The TS algorithm is a meta-heuristic algorithm that uses local search method for optimizing mathematical models. A mixed-integer nonlinear facility location-allocation model was proposed by Aras, Aksen, and Gonul Tanugˇur (2008) to explore the best locations for collection centers and the optimal incentive values for different return types. They employed a Tabu search solution procedure to solve this model. Pishvaee, Kianfar, and Karimi (2010) used a mixed integer linear programming model to design a multistage reverse logistics network in which both opening and transportation costs are taken in their model into consideration. They introduced a simulated annealing algorithm with special neighborhood search mechanisms. Soleimani, Seyyed-Esfahani, and Akbarpour Shirazi (2013) developed a multi-echelon, multi-product, and multi-period in a mixed integer linear programming framework for CLSC network, and employed a genetic algorithm to solve this problem. They validated the solution method by solving a number of large-size cases.

The main contributions and features that distinguish this study from the previous ones are as follows:

- In most studies, the only forward logistics networks are extended in CLSC design. But, in the proposed model the forward and reverse logistics are integrated. For this reason, three reverse strategies, recycling, recovering, and remanufacturing centers are taken in designing CLSC network into account.
- An integrated, multi-echelon, and multi-period MILP model is developed in order to determine facility locations and optimize the production and distribution planning for a CLSC network.
- The proposed model has been implemented for a real case study (glass manufacturing), while in most studies of CLSC network design a numerical example has been applied to validate the model.

3. Problem description

The CLSC model proposed in this paper is a multi-echelon and multi-period. This model integrates activities of purchase, production, distribution, collection, and return in a CLSC network, which is more complicated and needs more efforts to investigate than both forward and reverse networks. The general structure of the proposed closed-loop logistic network is shown in Figure 1. Not only does the proposed model consist of five layers in the forward logistics, which are suppliers, producers, distributors, warehouses, and customer centers, but it also has seven layers in the reverse logistics, which are collection & inspection, disposal, recycling, recovering, re-manufacturing centers, redistributors, and second-customer centers.

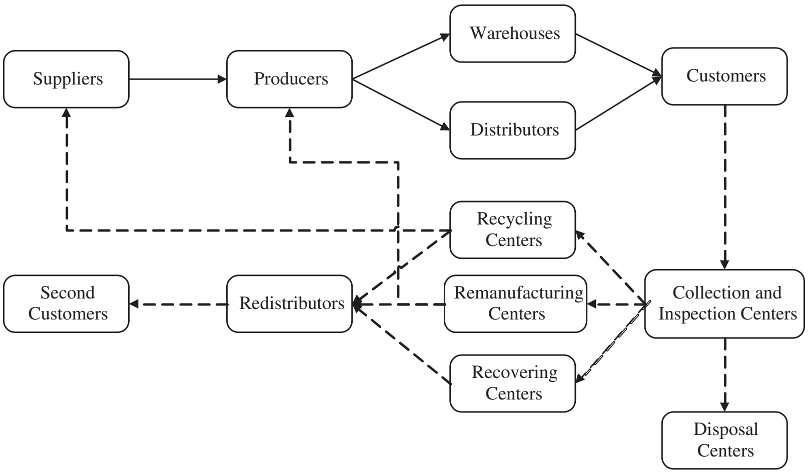

Figure 1. A conceptual framework for the CLSC network.

In the forward logistics, the suppliers provide raw materials to producers. The manufactured goods are forwarded from producers to customers via warehouses and distribution centers to satisfy customer demands. In the reverse logistics, the returned products are gathered from customers by collection & inspection centers to be examined. In the proposed model four treatment processes are taken into account for the returned goods in the reverse chain: (i) Recovering: the returned products are recovered and sent to redistributors for reuse; (ii) Remanufacturing: the returned products are remanufactured and provided for reuse; (iii) Recycling: the returned products are recycled and sent to suppliers; and (iv) Disposal: the returned products which have low quality for manufacturing are completely disposed. This approach helps supply chains to inhibit excessive transportations of returned products and transfer these products to the relevant facilities directly. The following assumptions and limitations are made in the network configuration:

- The locations of suppliers, customer, and second-customer centers are known and fixed.
- The potential locations of plants, warehouses, distributors, collection & inspection, disposal, recycling, remanufacturing, recovering centers, and redistributors are known.
- The flows are only allowed to be sent between two consecutive stages in forward and reverse logistics. Furthermore, there are not defined flows between facilities at the same layer.
- The quantities of all parameters are deterministic.
- The raw material cost includes the transportation cost of products from suppliers to the producers.
- The transportation cost of products between all layers remains fixed for all the periods.
- The inspection cost of the returned products is included in the transportation cost from customer zones to collection & inspection centers.
- All of the returned products from customer centers are gathered in the collection & inspection centers.
- All customer demands should be satisfied.
- The proposed model is multi-period and single-product.

4. Model formulation

The network can be formulated as a mixed-integer linear programming model. Sets, parameters, and decision variables are presented in Appendix.

4.1. *Objective function*

The objective function of the proposed CLSC model aims at the total cost:

Minimize Total Cost = fixed costs+producing cost+recycling cost+remanufacturing cost+recovering cost+disposal cost+transportation cost+material cost+shortage cost+collection cost

Fixed Costs

$$\sum_{p\in P}\sum_{t\in T}\mathrm{fc_p O_{pt}} + \sum_{w\in W}\sum_{t\in T}\mathrm{fc_w O_{wt}} + \sum_{d\in D}\sum_{t\in T}\mathrm{fc_d O_{dt}} + \sum_{i\in I}\sum_{t\in T}\mathrm{fc_i O_{it}} + \sum_{m\in M}\sum_{t\in T}\mathrm{fc_m O_{mt}} + \sum_{l\in L}\sum_{t\in T}\mathrm{fc_l O_{lt}} + \sum_{j\in J}\sum_{t\in T}\mathrm{fc_j O_{jt}} + \sum_{k\in K}\sum_{t\in T}\mathrm{fc_k O_{kt}} + \sum_{n\in N}\sum_{t\in T}\mathrm{fc_n O_{nt}} \quad (1)$$

$$\text{Manufacturing Costs} = \sum_{p\in P}\sum_{w\in W}\sum_{t\in T} mc_{pt}X_{pwt} + \sum_{p\in P}\sum_{d\in D}\sum_{t\in T} mc_{pt}X_{pdt} \quad (2)$$

$$\text{Recycling Cost} = \sum_{i\in I}\sum_{l\in L}\sum_{t\in T} rc_{lt}X_{ilt} \quad (3)$$

$$\text{Remanufacturing Cost} = \sum_{j\in J}\sum_{i\in I}\sum_{t\in T} ec_{jt}X_{ijt} \quad (4)$$

$$\text{Recovering Cost} = \sum_{k\in K}\sum_{i\in I}\sum_{t\in T} bc_{kt}X_{ikt} \quad (5)$$

$$\text{DisposalCost} = \sum_{m\in M}\sum_{i\in I}\sum_{t\in T} dc_{mt}X_{imt} \quad (6)$$

$$\begin{aligned}\text{Transportation Costs} = &\sum_{w\in W}\sum_{p\in P}\sum_{t\in T} tc_{pw}X_{pwt} \\ &+ \sum_{d\in D}\sum_{p\in P}\sum_{t\in T} tc_{pd}X_{pdt} + \sum_{w\in W}\sum_{c\in C}\sum_{t\in T} tc_{wc}X_{wct} \\ &+ \sum_{d\in D}\sum_{c\in C}\sum_{t\in T} tc_{dc}X_{dct} + \sum_{c\in C}\sum_{i\in I}\sum_{t\in T} tc_{ci}X_{cit} \\ &+ \sum_{i\in I}\sum_{m\in M}\sum_{t\in T} tc_{im}X_{imt} + \sum_{i\in I}\sum_{l\in L}\sum_{t\in T} tc_{il}X_{ilt} \\ &+ \sum_{i\in I}\sum_{j\in J}\sum_{t\in T} tc_{ij}X_{ijt} + \sum_{i\in I}\sum_{k\in K}\sum_{t\in T} tc_{ik}X_{ikt} \\ &+ \sum_{l\in L}\sum_{n\in N}\sum_{t\in T} tc_{ln}X_{lnt} + \sum_{j\in J}\sum_{n\in N}\sum_{t\in T} tc_{jn}X_{jnt} \\ &+ \sum_{k\in K}\sum_{n\in N}\sum_{t\in T} tc_{kn}X_{knt} + \sum_{f\in F}\sum_{n\in N}\sum_{t\in T} tc_{nf}X_{nft} \end{aligned} \quad (7)$$

$$\begin{aligned}\text{Material Costs} = &\sum_{s\in S}\sum_{p\in P}\sum_{t\in T} pc_{st}X_{spt} \\ &- \sum_{s\in S}\sum_{l\in L}\sum_{t\in T} (pc_{st} - rc_{lt})X_{lst}\end{aligned} \quad (8)$$

$$\text{Shortage Costs} = \left(\sum_{c\in C}\sum_{t\in T} \mathrm{de}_{ct} - \sum_{w\in W}\sum_{c\in C}\sum_{t\in T} X_{wct} - \sum_{d\in D}\sum_{c\in C}\sum_{t\in T} X_{dct}\right) sc \quad (9)$$

$$\text{Collection costs} = \sum_{c\in C}\sum_{i\in I}\sum_{t\in T} tc_{ci}X_{cit} \quad (10)$$

4.2. Constraints

The constraints of the model are represented as follows:

4.2.1. Capacity constraints

$$\sum_{p\in P} X_{spt} \le O_{st}\ ca_{st}\ \forall s \in S, t \in T \quad (11)$$

$$\sum_{w\in W} X_{pwt} + \sum_{d\in D} X_{pdt} \le O_{pt}\ ca_{pt}\ \forall p \in P,\ t \in T \quad (12)$$

$$\sum_{p\in P} X_{pwt} \le O_{wt}\ ca_{wt}\ \forall w \in W,\ t \in T \quad (13)$$

$$\sum_{p\in P} X_{pdt} \le O_{dt}\ ca_{dt}\ \forall d \in D,\ t \in T \quad (14)$$

$$\sum_{c\in C} X_{cit} \le O_{it}\ ca_{it}\ \forall i \in I,\ t \in T \quad (15)$$

$$\sum_{i\in I} X_{imt} \le O_{mt}\ ca_{mt}\ \forall m \in M,\ t \in T \quad (16)$$

$$\sum_{s\in S} X_{lst} + \sum_{n\in N} X_{lnt} \le O_{lt}ca_{lt}\ \forall l \in L,\ t \in T \quad (17)$$

$$\sum_{p\in P} X_{jpt} + \sum_{n\in N} X_{jnt} \le O_{jt}\ ca_{jt}\ \forall j \in J,\ t \in T \quad (18)$$

$$\sum_{n\in N} X_{knt} \le O_{kt}\ ca_{kt}\quad \forall\ k \in K,\ t \in T \quad (19)$$

$$\sum_{l\in L} X_{lnt} + \sum_{j\in J} X_{jnt} + \sum_{k\in K} X_{knt} \le O_{nt}\ ca_{nt}\quad \forall\ n \in N \quad (20)$$

The Constraint (11) guarantees that the sum of the flow exiting from suppliers to all producers does not exceed the capacity of suppliers. Constraint (12) shows that, in each period, the sum of shipped products from producers to warehouses and distributors is lower than the capacity of producers. Constraint (13) states that, in each period, the sum of the flow entering warehouses from producers does not exceed the holding capacity of warehouses. Constraint (14) ensures that in each period the sum of the flow entering from producers to distributors is not more than capacity of the relevant distributor. Constraint (15) states that the all collected products from customer centers which are entered to collection and inspection centers do not exceed the relevant capacity. Constraint (16) ensures that the sum of the flow entering from collection and inspection centers to disposal centers does not exceed the disposing capacity of disposal centers. Constraint (17) guarantees that the sum of recycled products which are sent to suppliers and redistributors is not more than of capacity of the relevant recycling center. Constraint (18) demonstrates that the sum of the flow exiting from remanufacturing centers to producers and redistributors does not exceed the remanufacturing capacity of remanufacturing centers. Constraint (19) guarantees that sum of recovered products which are shipped to redistributors from recovering centers are not more than the relevant capacity. Constraint (20) states that the sum of the flow entering to redistributors from recycling, remanufacturing, and recovering centers does not exceed the holding capacity of redistributors.

4.2.2. Balance constraints

$$\sum_{s\in S} X_{spt} + \sum_{j\in J} X_{jpt} = \sum_{w\in W} X_{pwt} + \sum_{d\in D} X_{pdt}\ \forall p \in P,\ t \in T \quad (21)$$

$$\sum_{p\in P} X_{pwt} = \sum_{c\in C} X_{wct}\ \forall w \in W,\ t \in T \quad (22)$$

$$\sum_{p\in P} X_{pdt} = \sum_{c\in C} X_{dct}\ \forall d \in D,\ t \in T \quad (23)$$

$$\sum_{c\in C} X_{cit} = \sum_{m\in M} X_{imt} + \sum_{l\in L} X_{ilt} + \sum_{j\in J} X_{ijt} + \sum_{k\in K} X_{ikt}\ \forall i \in I, t \in T \quad (24)$$

$$\sum_{c\in C} ry_t\ X_{cit} = \sum_{l\in L} X_{ilt}\ \forall i \in I,\ t \in T \quad (25)$$

$$\sum_{l\in L} X_{ilt} = \sum_{n\in N} X_{lnt} + \sum_{s\in S} X_{lst}\ \forall l \in L,\ t \in T \quad (26)$$

$$\sum_{c\in C} rm_t\ X_{cit} = \sum_{j\in J} X_{ijt}\ \forall i \in I,\ t \in T \quad (27)$$

$$\sum_{i\in I} X_{ijt} = \sum_{n\in N} X_{jnt} + \sum_{p\in P} X_{jpt} \ \forall j \in J,\ t \in T \tag{28}$$

$$\sum_{c\in C} rv_t\ X_{cit} = \sum_{k\in K} X_{ikt} \ \forall i \in I,\ t \in T \tag{29}$$

$$\sum_{i\in I} X_{ikt} = \sum_{n\in N} X_{knt} \ \forall k \in K,\ t \in T \tag{30}$$

$$\sum_{c\in C} rd_t\ X_{cit} = \sum_{m\in M} X_{imt} \ \forall i \in I,\ t \in T \tag{31}$$

$$\sum_{l\in L} X_{lnt} + \sum_{j\in J} X_{jnt} + \sum_{k\in K} X_{knt} = \sum_{f\in F} X_{nft} \ \forall n \in N,\ t \in T \tag{32}$$

Constraint (21) shows that the flow entering from suppliers and remanufacturing centers to producers is equal to sum of the existing from producers to warehouses and distributors at each period. Constraint (22) ensures that in each period, the sum of the flow entering from producers to warehouses is equal to sum of the existing from warehouses to customer centers. Constraint (23) guarantees that in each period, the sum of the flow entering from producers to distributors is equal to sum of the existing from distributors to customer centers. Constraint (24) states that in each period, the sum of the flow entering from customer centers to collection and inspection centers is equal to existing from collection and inspection centers to recycling, remanufacturing, recovering, and disposal centers. Constraints (25) and (26) ensures that in each period, all returned products from customer centers which are entered to recycling centers after a required inspection in collection and inspection centers are delivered to suppliers and redistributors. Constraints (27) and (28) ensures that in each period, all returned products from customer centers which are delivered to remanufacturing centers after a required inspection in collection and inspection centers are delivered to producers and redistributors. Constraints (29) and (30) states that in each period, all collected products from customer centers which are entered to recovering centers after a required inspection in collection and inspection centers are delivered to redistributors. Constraint (31) states that in each period, all returned products which are sent to disposal centers are disposed. Constraint (32) ensures that in each period, the sum of the flow entering from recycling, remanufacturing, recovering centers to redistributors is equal to existing from redistributors to second customer centers.

4.2.3. *Maximum number of allowable locations constraints*

$$\sum_{s\in S} O_{st} \leq S \ \forall t \in T \tag{33}$$

$$\sum_{p\in P} O_{pt} \leq P \ \forall t \in T \tag{34}$$

$$\sum_{w\in W} O_{wt} \leq W \ \forall t \in T \tag{35}$$

$$\sum_{d\in D} O_{dt} \leq D \ \forall t \in T \tag{36}$$

$$\sum_{i\in I} O_{it} \leq I \ \forall t \in T \tag{37}$$

$$\sum_{m\in M} O_{mt} \leq M \ \forall t \in T \tag{38}$$

$$\sum_{l\in L} O_{lt} \leq L \ \forall t \in T \tag{39}$$

$$\sum_{j\in J} O_{jt} \leq J \ \forall t \in T \tag{40}$$

$$\sum_{k\in K} O_{kt} \leq K \ \forall t \in T \tag{41}$$

$$\sum_{n\in N} O_{nt} \leq N \ \forall t \in T \tag{42}$$

Constraints (33)–(42) limit the maximum number of allowable locations. In fact, these constraints do not allow the supply chain to have more nodes than relative possible limitations.

$$\sum_{w\in W} X_{wct} + \sum_{d\in D} X_{dct} = de_{ct} \ \forall c \in C,\ t \in T \tag{43}$$

$$\sum_{n\in N} X_{nft} = de_{ft} \ \forall f \in F,\ t \in T \tag{44}$$

$$\sum_{i\in I} X_{cit} = de_{ct} \ \forall c \in C,\ t \in T \tag{45}$$

$$X_{spt},\ X_{pwt},\ X_{pdt}, X_{wct},\ X_{dct},\ X_{cit},\ X_{imt},\ X_{ilt},\ X_{ijt},\ X_{ikt}, X_{jpt},\ X_{jnt},\ X_{nft},\ X_{lnt},\ X_{lst},\ X_{knt},\ X_{kdt} \geq 0 \tag{46}$$

$$O_{st},\ O_{pt},\ O_{wt},\ O_{dt},\ O_{it},\ O_{mt},\ O_{jt},\ O_{lt},\ O_{nt},\ O_{kt}, \in \{0,1\} \tag{47}$$

Constraints (43) and (44) ensure that all customer demands should be met in customer and second-customer centers, respectively. Constraint (45) guarantees that all products should be collected from customer centers. Constraints (46) and (47) represent the non-negativity and integrality of variables.

5. Computational case study

In this section, the application of the proposed MILP model for CLSC network design is investigated through an actual case study. The selected company for this study is a glass manufacturing industry located in the center part of IRAN. In the supply chain network of the glass industry, the producers provide the main raw materials, such as Silica Sand, Dolomite, and Feldspar for producing glass from suppliers. Then glass manufacturers produce glass bottles during three main operations; the batch house, the hot end, and the cold end. The produced glass bottles are delivered to customers by distributors. The collection & inspection centers collect the glass bottles from bar-restaurants and home depot garbage. Finally, three approaches are defined for returned glass bottles. (i) broken glasses are separated based on their end use, capability, and colors, and are crushed in recycling centers and delivered to suppliers to use as raw material; (ii) unbroken glasses are washed at recovering centers and redistributed trough redistributors for second customers; (iii) a percentage of returned products which are not reusable are disposed.

The entities of considered CLSC network for the glass manufacturing industry consisted of: (1) three given suppliers which for the flow of material between suppliers and producers should be determined; (2) one producer which is currently operative and one identified potential location to establish new producer; (3) two considered selected locations for building required warehouses; (4) one active distribution center and one candidate location to meet demands of customers (it should be noted that these distributors work for other companies as well); (5) four customer centers that use the products; (6) two candidate locations to collect and inspect returned products; (7) one active disposal center and two candidate places in order to dispose defective products; (8) two considered positional locations to establish recycling centers to convert recyclable products into reusable materials and send to suppliers; (9) two candidate locations to establish recovering centers; (10) two considered locations to establish redistributors.

One of the most usable optimization software packages, CPLEX 12.6, is implemented to solve the proposed CLSC mixed-integer linear programming model for this case study. All computational work was accomplished on a personal computer (32-bit operating system, 2.53 GHz CPU, and 4.00 GB). The presented case study involved 369 variables and 180 constraints and took approximately 2.37 seconds to solve using commercial solver.

5.1. *Description data*

The used data for the considered case study is illustrated in Table 2. As regards to this issue that reverse logistics is included in the business process of this company, the information related to demand for new and returned products are predicted based on historical data of sales to the customer centers. Distributors can calculate exact demands of customers in terms of their records for selling new and recovered goods or similar products from other companies. It should be noted that distributors in the forward chain are used to distribute recovered products in the reverse chain.

The collection and inspection costs of the returnable products consist of encouragements for motivating customers to turn back products to collection centers and storage costs, required activities to collect products, as well as their margins. The road-based transportation is implemented to carry out the shipping operation in this company. The transportation costs of products include operating costs and service provided such as salaries, wages, costs of fuel, insurance and depreciation. One important point that should be mentioned here is, the raw material is transferred from suppliers to producers based on 'kg', but transportation cost for this shipping is calculated based on one product. In addition to the input parameters shown in Table 2, the fixed costs for establishing producers, opening warehouses, contractual arrangement with collection & inspection centers for collecting returned products, contractual arrangement with disposal, recycling, and recovering centers to treat with returned products are taken into account. It is worth noting that fixed costs are same for all time periods.

5.2. *Results*

The optimal results for the proposed case study during any period (in four periods) are illustrated in Table 3. The results (Table 3) are provided by solving proposed mathematical model in Section 3 for a glass manufacturing industry with CPLEX solver. The calculated total cost for CLSC network of this company is found to be \$265,347 for all periods.

The purchased raw materials from suppliers are shown in the first three rows in Table 3. The results indicate two of three considered suppliers can be chosen to provide raw materials. As indicated in Table 3, plants did not purchase raw materials from supplier 3. The condition is found for

Table 2. Capacities, costs, demands, return rates parameters.

	Period					Period			
	t_1	t_2	t_3	t_4		t_1	t_2	t_3	t_4
pc_{st}	22	22	22	22	ca_{st}	1000	1500	2000	1000
	24	24	24	24		1000	1500	2000	2000
	26	26	26	26		1000	1500	2000	3000
mc_{pt}	6	6	7	7	ca_{pt}	3000	3000	3000	3000
	4	4	6	6		4000	4000	4000	4000
de_{ct}	300	400	300	300	ca_{wt}	1000	1000	1000	1000
	300	250	200	300		1500	1500	1500	1500
	300	300	400	300	ca_{dt}	1000	1000	1000	1000
	300	250	400	300		2000	2000	2000	2000
bc_{kt}	5	5	4	4	ca_{it}	1000	1000	1000	1000
	4	4	4	4		2000	2000	2000	2000
dc_{mt}	5	5	4	4	ca_{mt}	2000	2000	2000	2000
	4	4	4	4		3000	3000	3000	3000
	3	3	3	3		1500	1500	1500	1500
rc_{lt}	4	4	4	4	ca_{lt}	2000	2000	2000	2000
	4	4	4	4		1000	1000	1000	1000
ry_t	0.2	0.15	0.3	0.1	ca_{kt}	1500	1500	1500	1500
rv_t	0.4	0.35	0.3	0.3		2000	2000	2000	2000
rd_t	0.4	0.5	0.4	0.6	ca_{nt}	1000	1000	1000	1000
de_{ft}	200	250	100	100		2000	2000	2000	2000
	100	50	100	100					
	100	100	100	100					

Table 3. Distribution flow of between utilities.

	Time Periods			
Utility	t_1	t_2	t_3	t_4
Suppliers	900	1200	1300	800
	300	0	0	400
	0	0	0	0
Producers	0	0	0	0
	1200	1200	1300	1200
Warehouse	0	0	0	0
	1200	1200	0	1200
Distributors	0	0	0	0
	0	0	1300	0
Collection & Inspection	900	950	1000	900
	300	250	300	300
Disposal	0	0	0	0
	0	0	0	0
	480	600	520	720
Recycling	0	180	0	0
	240	0	390	120
Recovering	200	420	390	360
	280	0	0	0
Redistributors	100	150	200	200
	300	250	100	100

suppliers 2 in periods 2 and 3. For this case study, one producer was operative and one potential location was identified to establish new producer. The results demonstrate that only one producer is needed to manufacture products in all periods. This means, in terms of customer demands and other conditions of this case study, that one producer would suffice to meet the required customer demands.

One of the most important strategic decisions for this case study is determining the needed warehouses to distribute final products. The supply chain managers of this case study wanted to decide which potential locations are suitable for a contractual arrangement for the warehouse. The obtained results indicate that this company needs to make a contract with one of these warehouses to distribute products. According to Table 3, 73% of customers' demands are met via a warehouse. This company also was looking for the required distributors to distribute products. They had one active distributor and considered one extra distributor on a contract basis if needed. As it can be inferred from the results, one active distributor suffices for the supply chain of the company. It should be mentioned that 27% of final products are forwarded from producers to customers via a distributor.

Two centers were identified to collect the returned products from customer zones. The obtained results show these two collections & inspection centers are needed for this company. In all periods, these centers are occupied to gather the returned products. For the defined supply chain for this case study, two potential and one active disposal centers were considered, with the results demonstrating the sufficiency of the active disposal center for study. In fact, it is not required to have a contractual arrangement with candidate disposal centers for the company. As indicated Table 3, disposal center 3 has been used to dispose returned products in all periods.

Another strategic decision to be made by the supply chain managers of the company is to determine the required recycling centers for the returned products. They identified two potential locations for recycling centers. With reference to Table 3, both of these centers are needed for the company. Recycling center 1 is implemented in period 2 and center 2 is used in periods 1, 3, and 4. It should be mentioned that 930 of the returned products were recycled by the two predetermined recycling centers. However, the results indicate that the two recycling centers are used through this supply chain. However, this company can make a contractual arrangement with only recycling center 2 since recycling center 1 is applied to 180 items in one period. By using recycling center 2 for all returned products, this company does not need to pay the extra fixed cost. These results also help supply chain managers determine how many recovering centers is needed to repair returned products. As it can be seen from Table 3, these two potential recovering centers are required. Recovering center 1 is used to repair 1370 items in all periods and recovering center 2 is applied to recover 280 of returned products in period 1.

6. Sensitivity analysis

A sensitivity analysis is carried out to measure the performance of presented CLSC network of this company under different operational conditions. The performed sensitivity analysis included the effect of changing demands, reverse rates, changing the capacity of suppliers, and reverse utilities on total costs.

6.1. *Effect of changing demands*

The effect of increasing customer demands on the total costs of the supply chain was analyzed. Products demands were increased eight times with a 5%. Table 4, demonstrates the increase in total costs of the supply chain by changing demands.

As expected, increase in demand results in an increase in the total costs of the supply chain. For instance, when customer demands increased by 5%, the total costs of supply chain increased by 2.9% and reached $ 273,145. It can be easily implied from Table 4 that the total costs of supply chain increased by about roughly 2.9% for a 5% increase in demands at each time. However, when customers' demands increase by 35%, the total cost of supply chain increased by 61% and reached $427,453. The total costs increased by 39% when demands of customers grew from 6370 to 6615 while it was expected to have 3.5% increases for the total costs of the supply chain. The main reason for this drastic increase is using two producers to meet the customers' demands. Initial results indicated that one producer is enough to meet 4900 products. This number of opened entities supports the demands of customers if they increase to 30%. That is, if customer demands increase from 4900 to 6370, one producer will be needed. On the other hand, if customer demands increase by 35%, the another producer should be established by this company to meet demands. Fixed costs of opening new entities increase the costs dramatically. The obtained results of sensitivity analysis of changing demands help managers to find maximum demands that they can meet at minimum cost.

6.2. *Effect of changing reverse rates*

The effect of changing disposal rate, recycling rate, recovering rate on total costs were investigated. Hence, different *rd*, *ry*, *rv*, where the sum of them equals to 1 are generated to the analyze total costs of supply chain. The associated results of these investigations are shown in Table 5.

Table 5 includes changing disposal rate, recycling rate, and recovering rate. The effect of changing disposal rate on total cost is analyzed first. For instance, 0.3 was taken into consideration for the disposal rate and 0.35 for recycling and recovering rates for all periods in the first scenario. The obtained results indicate increasing disposal rate and decreasing recycling and recovering rates simultaneously increase the total costs of the supply chain. The increasing of total costs is normally followed until the third scenario. The total costs increase drastically while disposal rate

Table 4. The impact of changing demand on total cost.

	Demand	Total cost	%
5	5145	273,145	2.9
10	5390	284,875	7.4
15	5635	292,485	10.2
20	5880	301,214	13.5
25	6125	311,441	17.4
30	6370	319,450	20.4
35	6615	427,453	61.1
40	6860	439,544	65.7

Table 5. The impact of changing reverse rates on total cost.

Scenario		1	2	3	4	5	6
Disposal	*rd*	***0.3***	***0.4***	***0.5***	***0.6***	***0.7***	***0.8***
	ry	0.35	0.3	0.25	0.2	0.15	0.1
	rv	0.35	0.3	0.25	0.2	0.15	0.1
	Total Cost	245,412	258,475	264,839	364,587	371,105	379,845
Recycling	*rd*	0.35	0.3	0.25	0.2	0.15	0.1
	ry	***0.3***	***0.4***	***0.5***	***0.6***	***0.7***	***0.8***
	rv	0.35	0.3	0.25	0.2	0.15	0.1
	Total Cost	247,462	247,436	249,875	230,112	222,874	218,756
Recovering	*rd*	0.35	0.3	0.25	0.2	0.15	0.1
	ry	0.35	0.3	0.25	0.2	0.15	0.1
	rv	***0.3***	***0.4***	***0.5***	***0.6***	***0.7***	***0.8***
	Total Cost	246,875	250,115	328,452	321,423	317,463	311,010

changes from 0.5 to 0.6. The second section of Table 5 shows the effect of recycling rate variations on the total cost. For this analysis, the rate value of recycling increases and disposal and recovering rates decrease simultaneously. The calculated results demonstrate the increasing recycling rate continuously reduces the total costs. The last part of Table 5 shows the effect of changing recovering rate on total costs. The calculated results display two different trends for total costs by increasing the recovering rates. At first, when the recovering rate soars from 0.3 to 0.4, the total cost decreased. On the other hand, for the next scenario where the recovering rate increased from 0.4 to 0.5, an intense increase in the total cost is incurred. Consequently, these costs started to decline by increasing the recovering rate.

6.3. *Effect of changing the capacity of suppliers and reverse utilities (disposal, recycling, recovering centers)*

The effect of changing suppliers' capacities on links in the supply network and the total costs of the supply chain was examined. The changing of reverse utilities' capacity was also analyzed in this section. Five scenarios were generated: (1) increasing the capacity of disposal centers; (2) increasing the capacity of recycling centers; (3) increasing the capacity of recovering; (4) increasing the capacity of reverse utilities simultaneously and increasing the capacity of suppliers. The capacities of suppliers and reverse utilities were gradually increased in increments of 5% to 40%. The achieved results from changing suppliers' capacities are demonstrated in Table 6.

As indicated in Table 6, increasing the supplier capacity leads to decrease of the total costs of supply chain whose decline continues until the supplier capacity increases by 20%. Based on the results, when supplier capacity increased from 20% to 25%, the total cost does not change. Also, the obtained results from other scenarios show the increasing the capacity of reverse utilities does not effect on the total costs. The existing capacity of reverse utilities covers all returned products.

7. Discussion

In Section 3, a mixed integer linear programming model was applied for a glass manufacturing industry. The optimal distribution flow of between utilities is summarized in Table 3, giving the best supply chain network for this industry. The optimum distribution determined the best supplier for raw material procurement, the best plant to produce the products, the best distributor to distribute the products to customer centers, the best collection centers to collect returned products, the best disposal centers to dispose the useless products, the best recovering center to recover returned products, and the best recycling centers in the reverse chain.

The optimum solution also determines how many products are to be transferred from suppliers to producers, from plants to distributors, from distributors to customer centers, from customer centers to collection centers, from collection centers to disposal, recycling, and recovering centers. The optimum solution minimizes the objective function (cost) while respecting all the constraints (capacity, balance, etc.). The optimum solution meets the customer demands, which is one of the main aims of supply chain network design. The optimum solution (Table 3) for this network is compared to the non-optimized current (at the time of writing) operating conditions (from the glass manufacturing industry). This comparison is summarized in Table 7.

In the current operating system, 1,100 products are requested from supplier #1 to be delivered to producer # 1, while the optimum value, as shown in Table 3, is 900. Based on defined utility capacities in Table 1, the maximum capacity of supplier # 1 is 1,000. That means, supplier # 1 cannot meet the current order on time, which leads to producer #1 receiving the products with delay. Consequently, the current network faces challenges in responding to customers demand in a timely fashion. The optimum solution guarantees to find the best network with the minimum total costs. The obtained value of an objective function based on optimum solution was CAD $ 265,347, while meeting the same customers demand with the current conditions will be around CAD $ 330,810. In the current operating system, one collection and inspection center is utilized to collect the returned products, while the optimum results showed (Table 3) that two centers are needed. The current operating conditions lead to failure in collecting all the returned products. The optimum solution (Table 3) shows that supplier #3 was not selected to supply the raw material in this network, while the company currently procures the raw material from this supplier. Supplying the raw material by supplier #3, results in extra costs.

Table 6. The impact of changing supplier capacity on the total cost.

	0%	5%	10%	15%	20%	25%	30%	35%	40%
Total Cost	271,987	271,687	271,387	271,087	270,787	270,787	270,787	270,787	270,878

Table 7. Comparison optimized case and current operating system for a studied case study.

	Optimized case	Current operating system
Objective function value	CAD 265,347	CAD 330,810
Capacity constraints	Satisfied	Not satisfied
Balance constraints	Satisfied	Not satisfied
Customer demands	On-time	Backlogged

8. Conclusions & future research

A Mixed Integer Linear Programming model was formulated to design a CLSC network for a glass manufacturing industry, where the location of facilities and the material flows in the entire network were determined. The model incorporated both strategic and tactical decisions. The presented CLSC network included five echelons (i.e. suppliers, producers, warehouses, distributors, and customer zones) in the forward direction and seven echelons (i.e. collection & inspection centers, disposal centers, recycling centers, remanufacturing centers, recovering centers, redistributors, and second customers) in the reverse direction. A detailed sensitivity analysis was done to investigate the effects of change in demands, capacity, and reverse rates on network total cost. Moreover, the created optimum network for this industrial case was compared with current operating conditions, showing the benefits of an optimized network.

As shown in Table 3 the obtained results of this study determine how many facilities (supplier, producers, etc.) should be utilized, which facilities should be opened, how many products should be transferred between facilities for each period. In this study, the changing capacity of disposal, recycling, and recovering centers had no effect on total costs. While increasing the capacity of suppliers decreased the total costs. These conclusions show that the recycling ratio has more effect on total cost in comparison with disposal and recovering ratios. The introduced approach has some limitations. A single-objective approach, minimizing costs, was applied for designing CLSC network, while other important objectives such as minimizing the environmental effects maximizing the social impacts can be considered. Accordingly, it is suggested that the deterministic approach of the study be improved by taking non-deterministic parameters into account. In order to solve the MILP model and reach the optimal solutions in a reasonable time, using meta-heuristics, such as genetic algorithms or particle swarm optimization algorithms are recommended. Other characteristics of product returns such as return type, volume, timing, quality, early and late returns should be considered to design CLSC network for future studies.

Disclosure statement

No potential conflict of interest was reported by the authors.

Funding

This work was supported by the Natural Sciences and Engineering Research Council of Canada (NSERC) [No: 155147-2013].

ORCID

Ehsan Pourjavad http://orcid.org/0000-0002-9223-751X
Rene V. Mayorga http://orcid.org/0000-0001-8365-6571

References

Alshamsi, A., & Diabat, A. (2015). A reverse logistics network design. *Journal of Manufacturing Systems*, *37*(3), 589–598.

Alumur, S. A., Nickel, S., Saldanha-da Gama, F., & Verter, V. (2012). Multi-period reverse logistics network design. *European Journal of Operational Research*, *220*(1), 67–78.

Aras, N., Aksen, D., & Gonul Tanugˇur, A. (2008). Locating collection centers for incentive dependent returns under a pick-up policy with capacitated vehicles. *European Journal of Operational Research*, *191*, 1223–1240.

Balaman, S. Y., & Selim, H. (2014). A network design model for biomass to energy supply chains with anaerobic digestion systems. *Applied Energy*, *130*, 289–304.

Bowersox, D. J., Closs, D. J., & Cooper, M. B. (2002). *Supply chain logistics management*. New York, NY: McGraw-Hill, International Edition.

Ch., A., Ch., V., Aidonis, D., Moussiopoulos, N., Iakovou, E., & Banias, G. (2010). Optimising reverse logistics network to support policy-making in the case of electrical and electronic equipment. *Waste Management*, *30*(12), 2592–2600.

Chiou, C. Y., Chen, H. C., Yu, C. T., & Yeh, C. Y. (2012). Consideration factors of reverse logistics implementation -A case study of Taiwan's electronics industry. *Procedia-Social and Behavioral Sciences*, *40*, 375–381.

Chopra, S., & Meindl, P. (2007). *Supply chain management: Strategy, planning and operation* (3rd ed.) book. New Jersey, NJ: Pearson Prentice Hall Inc.

Fleischmann, M., Beullens, P., Bloemh of Ruwaard, J. M., & Wassenhove, L. N. (2001). The impact of product recovery on logistics network design. *Production and Operations Management*, *10*(2), 156–173.

Gaur, J., Amini, M., & Rao, A. K. (2017). Closed-loop supply chain configuration for new and reconditioned products: An integrated optimization model. *Omega*, *66*(B), 212–223.

Jayaraman, V. (2006). Production planning for closed-loop supply chains with product recovery and reuse: An analytical approach. *International Journal of Production Research*, *44*(5), 981–998.

Kim, K. B., Song, I. S., & Jeong, B. J. (2006). Supply planning model for remanufacturing system in reverse logistics environment. *Computers & Industrial Engineering*, *51*(2), 279–287.

Kumar, S., & Yamaoka, T. (2007). System dynamics study of the Japanese automotive industry closed loop supply chain. *Journal of Manufacturing Technology Management*, *18*(2), 115–138.

Kusumastuti, R. D., Piplani, R., & Lim, G. H. (2008). Redesigning closed-loop service network at a computer manufacturer: A case study. *International Journal of Production Economics*, *111*(2), 244–260.

Lee, D. H., & Dong, M. (2008). A heuristic approach to logistics network design for end-of-lease computer products recovery. *Transportation Research Part E: Logistics and Transportation Review*, *44*(3), 455–474.

Ozceylan, E., & Paksoy, T. (2013). A mixed integer programming model for a closed-loop supply-chain network. *International Journal of Production Research*, *51*(3), 718–734.

Özceylan, E., Paksoy, T., & Bekta, T. (2014). Modeling and optimizing the integrated problem of closed-loop supply chain network design and disassembly line balancing. *Transportation Research Part E: Logistics and Transportation Review*, *61*, 142–164.

Pishvaee, M. S., Kianfar, K., & Karimi, B. (2010). Reverse logistics network design using simulated annealing. *The International Journal of Advanced Manufacturing Technology*, *47*(1–4), 269–281.

Pourjavad, E., & Mayorga, R. V. (2017). A comparative study and measuring performance of manufacturing systems with Mamdani fuzzy inference system. *Journal of Intelligent Manufacturing*. doi:10.1007/s10845-017-1307-5

Ramezani, M., Kimiagari, A. M., & Karimiz, B. (2014). Closed-loop supply chain network design: A financial approach. *Applied Mathematical Modelling*, *38*(15–16), 4099–4119.

Sadjady, H., & Davoudpour, H. (2012). Two-echelon, multi-commodity supply chain network design with mode selection, lead-times and inventory costs. *Computers & Operations Research*, *39*(7), 1345–1354.

Sasikumar, P., Kannan, G., & Haq, A. N. (2010). A multi-echelon reverse logistics network design for product recovery a case of truck tire remanufacturing. *International Journal of Advanced Manufacturing Technology*, *49*(9–12), 1223–1234.

Soleimani, H., & Kannan, G. (2015). A hybrid particle swarm optimization and genetic algorithm for closed-loop supply chain network design in large-scale networks. *Applied Mathematical Modelling*, *39*(14), 3990–4012.

Soleimani, H., Seyyed-Esfahani, M., & Akbarpour Shirazi, M. (2013). A new multi-criteria scenario-based solution approach for stochastic forward/reverse supply chain network design. *Annals of Operations Research*, *242*(2), 399–421.

Thanh, P. N., Bostel, N., & Peton, O. (2008). A dynamic model for facility location in the design of complex supply chains. *International Journal of Production Economics*, *113*, 678–693.

Tsiakis, P., & Papageorgiou, L. G. (2008). Optimal production allocation and distribution supply chain networks. *International Journal of Production Economics*, *111*(2), 468–483.

Uster, H., Easwaran, G., Akcali, E., & Cetinkaya, S. (2007). Benders decomposition with alternative multiple cuts for a multi-product closed-loop supply chain network design model. *Naval Research Logistics*, *54*(8), 890–907.

Xanthopoulos, A., & Iakovou, E. (2009). On the optimal design of the disassembly and recovery processes. *Waste Management*, *29*(5), 1702–1711.

Appendix. Notations, parameters & decision variables

s: Supplier, p: Producer, d: Distributor, w: Warehouse, c: Customer Center, i: Collection & Inspection Center, k: Recovering Center, l: Recycling Center, j: Remanufacturing center, m: Disposal centers, N: Re-distributor center, f: Second customer center, t: Periods.

$ca_{\gamma t}$: Capacity of utilities $\gamma \in \{s, p, w, d, i, m, n, l, k\}$ at time period 't'

fc_{γ}: Fixed cost of opening utilities $\gamma \in \{p, w, i, m, l, j, k, n\}$

tc_{pw}, tc_{pd}, tc_{wc}, tc_{dc}, tc_{ci}, tc_{im}, tc_{il}, tc_{ij}, tc_{ik}, tc_{ls}, tc_{jp}, tc_{ln}, tc_{jn}, tc_{jn}, tc_{nf}: Transportation cost a product between utilities

mc_{pt}: Manufacturing cost at producer 'p' at time period 't'

dc_{mt}: Disposal cost at disposal center 'm' at time period 't'

rc_{lt}: Recycling cost at recycling center 'l' at time period 't'

bc_{kt}: Recovering cost at repairing center 'k' at time period 't'

de_{ct}: Demand of customer center 'c' at time period 't'

ry_t: Recycling ratio at time period 't'

rv_t: Recovering ratio at time period 't'

rd_t: Disposal ratio at time period 't'

rm_t: Remanufacturing ratio at time period 't'

de_{ft}: Demand of second customer center 'f' at time period 't'

X_{spt}, X_{pwt}, X_{pdt}, X_{wct}, X_{dct}, X_{cit}, X_{imt}, X_{ilt}, X_{ijt}, X_{ikt}, X_{lnt}, X_{lst}, X_{jpt}, X_{jnt}, X_{knt}, X_{nft}: Quantity shipped between utilities

$O_{\gamma t}$: 1 if facility $\gamma \in \{s, p, w, d, i, m, l, j, k, n\}$ is to be established at time period 't';0 otherwise