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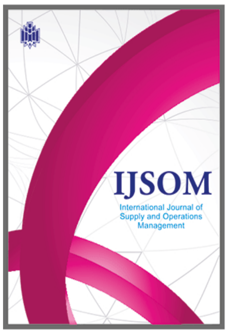

A collocation-based approach to designing remanufacturing closed–loop supply chain network

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Abstract

Closed-loop supply chain network design is a critical issue due to its impact on both economic and environmental performances of the supply chain. In this paper, we address the problem of designing a multi-echelon, multi-product and capacitated closed-loop supply chain network. First, the problem is modeled with a mixed-integer, non-linear programming model that aims to maximize the total closed-loop supply chain profit. To reduce the complexity of the model, it was first linearized and solved by LINGO. Computational results and sensitivity analysis are conducted to demonstrate the performance of the proposed model. The main contribution of the proposed model is to address two economic viability issues of a closed-loop supply chain. The first issue is the collection of a sufficient quantity of end-of-life products that are assured by retailers against an acquisition price. The second issue lies in exploiting the benefits of the collocation of forward facilities and reverse facilities.

Keywords: Closed-loop supply chain; Collocation decision; Network design; Remanufacturing.

1. Introduction

Traditionally, supply chains have been treated as linear systems, in which efficient approaches are often used to reduce the costs and the time of the network activities, starting from raw material suppliers to manufacturers and through distributors and retailers to end customers, but without considering the management of end-of-life products in the corporate strategy and in the product design.

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Under various drivers, such as economic opportunities, environmental legislation and growing concerns among customers, closed-loop supply chains have proactively been initiated by some leading companies (General Motors, Kodak and Xerox, etc.), and have attracted more researchers to this field. The logistics network design that integrates reverse logistics is a crucial issue because of its impact on economic and environmental performance. In addition to traditional decisions regarding location/allocation, more decisions must be made to ensure the economic viability of the logistics network. The first question relates to the coordination and the sharing of existing resources between activities in and out (Wang and Hsu, 2010). For example, hybrid treatment plants show cost savings and pollution reduction as a result of the sharing of means of transport and infrastructure. The second problem concerns the decisions regarding the anticipated acquisition which allows better control of the quantity, time and quality of end-of-life products (Guide et al. 2003). Another element consists in choosing the best collection channel (Savaskan et al. 2004). This paper addresses these issues by using a mixed integer programming model. The remaining of the paper is organized as follows: Section 2 presents the related literature review, Section 3 presents a description of the problem, Section 4 introduces the mathematical model, Section 5 reveals the results, and Section 6 is dedicated to the conclusion.

2. Related literature review

During the last decade, many models were developed for reverse logistics and closed-loop supply chain network design. Most of these models have been developed based on the facility location theory. For extensive reviews, see Elbounjimi et al. (2014). The existing models are ranging from single product, single period deterministic mixed-integer linear programming models (Fleischmann et al. 2001) to multiple products, multiple period stochastic mixed-integer non-linear programming models (Lee, and Dong, 2009). Fleischmann et al. (2001) were among the first to model an integrated forward/reverse supply chain network design. They studied the economic impact of integrating reverse flows in the forward supply chain, and concluded that depending on the context of the problem, an integrated design of forward and reverse supply chain can provide significant cost benefit against a sequential design. Beamon and Fernandes (2004) presentd a multi-period and capacitated MILP model aiming to determine a closed-loop supply chain (CLSC) with hybrid manufacturing/remanufacturing. Salema et al. (2007) extended the model of Fleischmann et al. (2001) to include multi-product, capacity limitation and uncertainty aspects. Moreover, Ko and Evans (2007) developed a mixed integer non-linear programming model to design an integrated forward/reverse logistics network driving by a third-party logistics provider and they present a MINLP model for the simultaneous design of the forward and return network. Demirel and Gökçen (2008) developed a multi-product MILP model to design a network composed of manufacturing, distribution, collection and disassembly sites. They concluded that companies should provide appropriate incentives for customers and retailers in order to increase the number of returns. Wang and Hsu, 2010 presented a MILP model aiming to design a CLSC network for a single product. Amin and Zhang (2012) proposed a MILP model based on the lifecycle of a network consisting of manufacturing facilities, collection, repair, disassembly, recycling and disposal. The model considers three types of returns (commercial returns, end-of-life products, and end-of-use products). Pishvaee et al. (2010) developed a MILP model to configure a CLSC in which the sites have limited capacity and the selection of hybrid sites for distribution/collection is a decision variable. Due to a high level of uncertainty on the reverse logistics supply side, establishing efficient acquisition strategies with the end-user leads to minimizing uncertainty in quantity, timing, and relatively in the quality of used-products, and therefore helps in ensuring a good planning of the capacities and operations (Guide and al. 2003). Acquisition strategies can be divided in two groups: financial incentives given to the end-user to return its products before the end of its life, and organizational incentives, referring to leasing or renting of a product for a certain period. Another aspect related to the collection issue is to determine who collects the used products from their end-users.

Table 1.Characteristics of the Reviewed Articles

Article	Problem definition					Modelling		Objectives			Decision variables			
	Multi-product	Multi-period	Limited Capacity	Multi- stages	Proactive Acquisition	MILP	MINLP	Costs	Profit	Others	Location/Allocation	Hybrid facilities	Transportation amount	Capacity selection
Fleischmann, et al.(2001)				•		•		•			•		•	
Beamon and Fernandes (2004)		•		•		•		•			•		•	
Salema et al. (2007)	•		•	•		•		•			•		•	
Ko and Evans (2007)	•	•	•	•			•	•			•	•	•	
Lee and Dong (2009)				•		•		•			•		•	
Demirel and Gökçen (2008)	•		•	•		•		•			•		•	
Wang and Hsu (2010)			•	•				•			•		•	
Pishvaee et al. (2010)			•	•	•			•		•	•	•	•	•
Amin and Zhang (2012)	•		•	•					•		•		•	
Keyvanshoko-oh et al. (2013)	•	•	•	•	•	•		•			•		•	
Our article	•		•	•	•	•			•		•	•	•	

Savaskan et al. (2004) found that the retailer is better positioned to collect returns than the OEM or the third party. The cost-saving from integrating forward and reverse facilities is studied in numerous papers. For instance, Pishvaee et al. (2010) developed a bi-objective MINLP-based approach to minimize the total costs, and also maximize the responsiveness of an integrated forward/reverse logistics network. Lee and Dong (2009) developed a MILP model for an integrated logistics network design for end-of-lease computer products. They considered a simple network with a single production centre, and a given number of hybrid distribution/collection facilities to be opened. Keyvanshokooh et al. (2013) developed a multi-period, multi-product MILP for the design of a CLSC network. Their model determines, among other things, decisions related to hybrid distribution/collection centre locations. In order to structure a relevant literature review of this work and also to show the main contributions of this paper, we have classified the most previous papers according to four general characteristics: definition of the problem, modelling, objectives, decision variables (see Table 1). The characteristics of our paper have been presented in the last row of this table. In summary, the majority of existing models have focused on segregated location of forward and reverse facilities, and also considered the reverse logistics as a waste-driven system in which there is no control on the return supply. Thus, the proposed model aims to design a multi-product, multi-hybrid facilities CLSC network. In addition, unlike the common practice in the literature, we address the collocation of all facilities (manufacturing/remanufacturing and distribution/collection), as well as the collection that is carried out by retailers who have direct and frequent contact with consumers.

3. Definition of the problem

The closed-loop supply chain discussed in this paper is a multi-product and multi-stage closed-loop supply chain. The general structure of the proposed closed-loop supply chain is illustrated in Figure 1. In the forward flow, the products are delivered to a number of retailers from manufacturing and remanufacturing plants via distribution centres to meet the given demand of each retailer. It should be noted that remanufactured products are considered as new ones and they are sold at the same price.

After being collected and inspected, the returned products are sorted into two groups: products to be remanufactured and not-recoverable products. The first group will be sent to remanufacturing plants while the second group will be sent to disposal centres. It should be noted that after the recovery process, the recovered products are incorporated to the forward flow as new ones. In this problem, instead of locating forward facilities and reverse facilities separately, the model takes the hybrid facilities into account wherein both forward and reverse facilities are established at the same locations.

If hybrid processing facilities can be used or not depends on the trade-off of fixed opening costs and variable costs. That is, in this problem, hybrid facility location is a decision variable.

The following assumptions are considered in the formulation of the model:

1. The model is multi-echelon and multi-product;
2. To ensure enough quantity of returns, a financial incentive is paid to the retailer for every used product collected;

3. All retailers' demands are deterministic and should be satisfied;
4. The quantity of return from each retailer is a fraction of its previous demand;
5. The return refers to a percentage of used products acquired by the retailer;
6. Excepting suppliers and disposal centres, all other facilities are capacitated;
7. Potential locations, capacities of all facilities, and all cost parameters are predetermined.

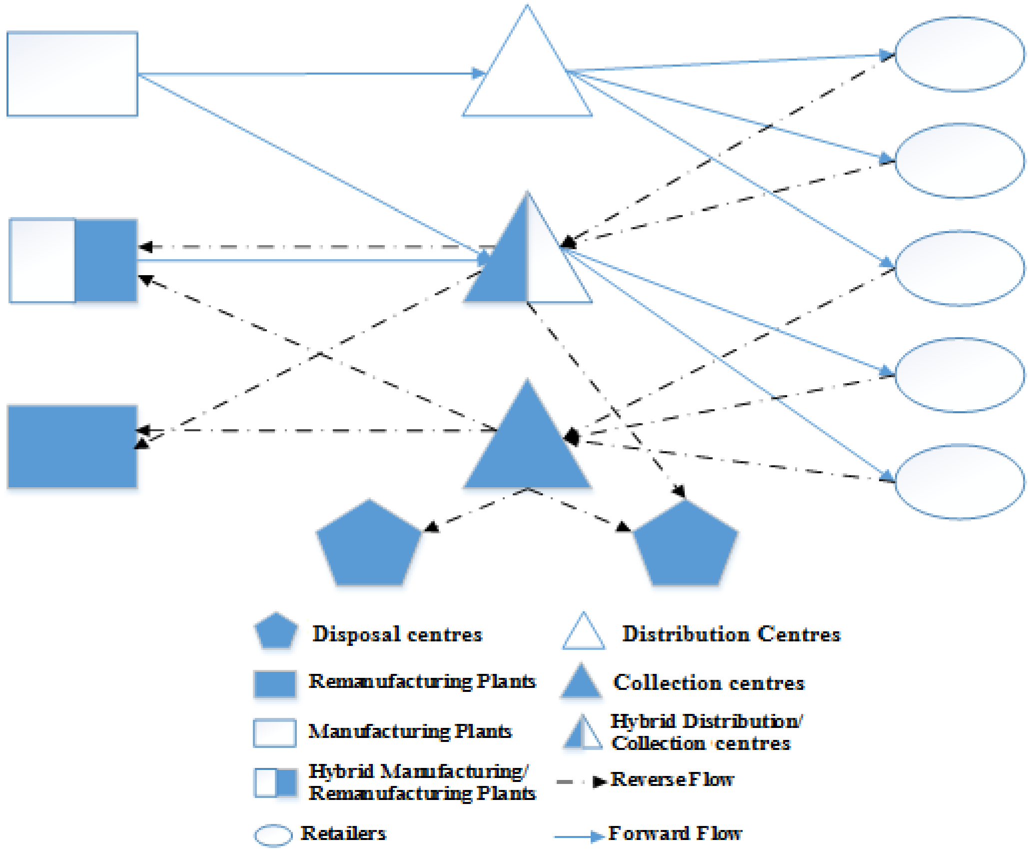

Figure 1. The Closed-loop Remanufacturing Supply Chain Network

4. Formulation of the model

Before presenting the mathematical model, we first provide a verbal description of the model as follows:

Objective Function = Minimization of Fixed opening costs + Transportation costs - Savings from collocation of facilities + Production costs + Remanufacturing costs + Acquisition costs of used products + Inspection costs + Disposal costs.

Subject to:

- Satisfying all forward and reverse demands;
- Flows are balancing between network nodes;
- Capacity constraints;
- Logical constraints related to facilities location;
- Non-negativity and binary constraints.

The following notations are used in the formulation of the model:

Notations

Sets and Index

I: Set of potential locations for manufacturing plants, $i \in I$;

L: Set of potential locations for remanufacturing plants, $l \in L$;

E: Set of potential collocations for manufacturing plants and remanufacturing plants

$e \in E, E \subset I, E \subset L$;

J: Set of potential locations for distribution centres, $j \in J$;

K: Set of potential locations for collection centres, $k \in K$;

F: Set of potential locations for hybrid distribution/collection centres, $f \in F, F \subset J, F \subset K$;

N: Set of fixed locations of retailers, $n \in N$;

M: Set of fixed locations of final disposal centres, $m \in M$;

P: Set of products, $p \in P$;

Parameters

D_{np}: Demand from retailer n for product p;

α_p: Return rate for product p;

β_p : Return rate for product p from retailer n;

FmP_i: Fixed costs for opening a manufacturing plant at location i;

FrP_l : Fixed costs for opening a remanufacturing plant at location l;

FD_j: Fixed costs for opening a distribution centre at location j;

FC_k: Fixed costs for opening a collection centre at location k;

GP_e: Fixed saving costs associated with the opening of a hybrid manufacturing/remanufacturing plant at location e;

GD_f: Fixed saving costs associated with the opening of a hybrid distribution/collection centre at location f;

$CAPM_{ip}$: Capacity of manufacturing plant i for product p;

$CAPR_{lp}$: Capacity of remanufacturing plant l for product p;

$CAPD_{jp}$: Capacity of distribution centre j for product p;

$CAPC_{kp}$: Capacity of collection centre k for product p;

CAq_{pn}: Unit acquisition price for product p from retailer n;

CP_p: Unit manufacturing costs of product p;

$CRem_p$: Unit remanufacturing costs of product p;

TIJ_{pij}: Unit transportation costs for product p shipped from manufacturing plant i to distribution centre j;

TLJ_{plj}: Unit transportation costs for product p shipped from remanufacturing plant l to distribution centre j;

TJN_{pjn}: Unit transportation costs for product p shipped from distribution centre j to retailer n;

TNK_{pnk}: Unit transportation costs for product p shipped from retailer n to collection centre k;

TKL_{pkl} : Unit transportation costs for product p shipped from collection centre k to remanufacturing plant l;

TKM_{pkl}: Unit transportation costs for product p shipped from collection centre k to disposal centre m;

Decision variables

A_i : Binary variable equals to 1 if a manufacturing plant is opened at location i, 0 otherwise;

B_l : Binary variable equals to 1 if a remanufacturing plant is opened at location l, 0 otherwise;

C_j : Binary variable equals to 1 if a distribution centre is opened at location j, 0 otherwise;

D_k: Binary variable equals to 1 if a collection/inspection centre is opened at location k, 0 otherwise;

$Y_e = A_e * B_e$: Collocation binary variable equals to 1 if a manufacturing plant and a remanufacturing plant are both opened at location $e \in E$ $(E \subset I, E \subset L)$, 0 otherwise;

$Z_f = C_f * D_f$: Collocation binary variable equals to 1 if a distribution centre and a collection/inspection centre are both opened at location $f \in F$ $(F \subset J, F \subset K)$, 0 otherwise;

XIJ_{pij}: Quantity of product p shipped from manufacturing plant i to distribution centre j;

XLJ_{plj}: Quantity of product p shipped from remanufacturing plant l to distribution centre j;

XJN_{pjn}: Quantity of product p shipped from distribution centre j to retailer n;

XNK_{pnk}: Quantity of product p shipped from retailer n to collection centre k;

XKL_{pkl}: Quantity of product p shipped from collection centre k to remanufacturing plant l;

XKM_{pkm}: Quantity of product p shipped from collection centre k to disposal centre m.

According to the above assumptions, indices, parameters and decision variables, the problem can be formulated as a mixed integer non-linear programming (MINLP) model:

$$
\begin{aligned}
\text{Min Total costs} = {} & \sum_i FmP_i\, A_i + \sum_l FrP_l\, B_l + \sum_j FD_j\, C_j + \sum_k FC_k\, D_k - \sum_e GP_e A_e\, B_e \\
& - \sum_f GD_j C_f\, D_f + \sum_p \sum_i \sum_j CM_{pi}\, XIJ_{pij} + \sum_p \sum_l \sum_j CR_{pl}\, XLJ_{plj} + \sum_p \sum_i \sum_j TCIJ_{pij}\, XIJ_{pij} + \\
& \sum_p \sum_l \sum_j TLJ_{plj}\, XLJ_{plj} + \sum_p \sum_j \sum_n TJN_{pjn}\, XJN_{pjn} + \sum_p \sum_n \sum_k TNK_{pnk}\, XNK_{pnk} + \\
& \sum_p \sum_k \sum_l TKL_{pkl}\, XKL_{pkl} + \sum_p \sum_k \sum_l TKM_{pkm}\, XKM_{pkm} + \sum_p \sum_n \sum_k CA_{pn}\, XNK_{pnk} + \\
& \sum_p \sum_n \sum_k CIns_{pn}\, XNK_{pnk}
\end{aligned} \quad (1)
$$

Subject to:

$$\sum_j XJN_{pjn} \leq D_{np} \qquad \forall n, p \qquad (2)$$

$$\sum_k XNK_{pnk} \leq \alpha_p\, D_{np} \qquad \forall n, p \qquad (3)$$

$$\sum_i XIJ_{pij} + \sum_l XLJ_{plj} = \sum_n XJN_{pjn} \qquad \forall j, p \qquad (4)$$

$$\sum_l XKL_{pkl} + \sum_m XKM_{pkm} = \sum_n XNK_{pnk} \qquad \forall k, p \qquad (5)$$

$$\sum_m XKM_{pkm} \leq \beta_p \sum_n XNK_{pnk} \qquad \forall k, p \qquad (6)$$

$$\sum_i XIJ_{pij} \leq A_i \; CAPM_{ip} \qquad \forall i, p \qquad (7)$$

$$\sum_l XLJ_{plj} \leq B_l \; CAPR_{lp} \qquad \forall l, p \qquad (8)$$

$$\sum_l XKL_{pkl} \leq B_l \; CAPR_{lp} \qquad \forall l, p \qquad (9)$$

$$\sum_i XIJ_{pij} + \sum_l XLJ_{plj} \leq D_j \; CAPDis_{ip} \qquad \forall j, p \qquad (10)$$

$$\sum_n XNK_{pnk} \leq C_k \; CAPCol_{ip} \qquad \forall k, p \qquad (11)$$

$$\sum_m XKM_{pkm} + \sum_l XKL_{pkl} \leq C_k \; CAPCol_{ip} \qquad \forall j, p \qquad (12)$$

$$A_i, B_l, C_j, D_k \in \{0, 1\} \qquad \forall i, j, l, k, p \qquad (13)$$

$$XIJ_{pij}, XLJ_{plj}, XJK_{pjk}, XNK_{pnk}, XKL_{pkl}, XKM_{pkm} \geq 0 \qquad i, j, l, k, n, p \qquad (14)$$

The objective function (1) minimizes the total costs including fixed opening costs, cost savings associated with integrating facilities at the same locations, manufacturing costs, remanufacturing costs, transportation costs, acquisition costs of used products from retailers, inspection costs, and disposal costs. Constraint (2) ensures that the demand of each customer is satisfied. Constraint (3) states that returned products from each retailer is equal or smaller than a prefixed fraction of the retailer demand. Constraints (4) and (5) assure the balance of the flows at the distribution centre and at the collection/inspection center. Constraint (6) ensures that the number of products sent to the disposal center is equal or smaller to the prefixed ratio of the number of returns. Constraint (7) ensures that the manufacturing plant capacity is respected. Constraints (8) and (9) ensure that the remanufacturing plant capacity is respected. Constraint (10) indicates if the distribution centre capacity is respected. Constraints (11) and (12) indicate if the collection/inspection centre capacity is respected. Constraints (13) and (14) enforce the binary and non-negativity requirements of the decision variables.

Linearization of the MINLP model:

The multiplication of two binary variables in the objective function involves two non-linear terms: $\sum_e GP_e A_e B_e$ and $\sum_f GD_j C_f D_f$. To overcome this complexity, the model is linearized by replacing the multiplication of two binary variables by one binary variable. Thus, the reformulation of the objective function is as follows:

$$Y_e = A_e B_e, \quad Y_e \in \{0, 1\} \ , \forall e \in E$$

$$Z_f = C_f D_f, \quad Z_f \in \{0, 1\} \ , \forall f \in F$$

$$\text{MIN} = \sum_i CP_i A_i + \sum_l FrP_l B_l + \sum_j FD_j C_j + \sum_k FC_k D_k - \sum_e GP_e Y_e - \sum_f GD_j Z_f$$

$$+ \sum_p \sum_i \sum_j CM_{pi} XIJ_{pij} + \sum_p \sum_l \sum_j CR_{pl} XLJ_{plj} + \sum_p \sum_i \sum_j TCIJ_{pij} XIJ_{pij} + \sum_p \sum_l \sum_j TLJ_{plj} XLJ_{plj}$$

$$+ \sum_p \sum_j \sum_n TJN_{pjn} XJN_{pjn} + \sum_p \sum_n \sum_k TNK_{pnk} XNK_{pnk} + \sum_p \sum_k \sum_l TKL_{pkl} XKL_{pkl}$$

$$+ \sum_p \sum_k \sum_l TKM_{pkm} XKM_{pkm} + \sum_p \sum_n \sum_k CA_{pn} XNK_{pnk} + \sum_p \sum_n \sum_k CIns_{pn} XNK_{pnk}$$

When a manufacturing plant and a remanufacturing plant are collocated at the same place ($Y_e = A_e B_e = 1$), this involves that both manufacturing plant and remanufacturing plant should be opened at this location ($A_e = 1$ and $B_e = 1$). Also when a distribution centre and a collection/inspection centre are collocated at the same place ($Z_f = C_f D_f = 1$), this involves that both centers should be opened at this location ($C_f = 1$ and $D_f = 1$). To assure these conditions the following logical constraints should be added to the model:

$$A_e + B_e \geq 2Y_e \qquad \forall e \in E \qquad (15)$$

$$C_f + D_f \geq 2Z_f \qquad \forall f \in F \qquad (16)$$

Constraint (15) verifies if a hybrid facility is opened at location e, then both manufacturing and remanufacturing plants should be opened in this location concurrently. The same applies for distribution and collection centers in constraint (16).

5. Computational results

In order to illustrate the usefulness of the proposed model, a small-sized problem is considered which comprises 3 potential manufacturing plants, 2 potential remanufacturing plants, 3 distribution centres, 3 collection centres, and 4 retailers. Other parameters are generated randomly using the uniform distributions specified in Table 2.

Table 2. Values of the Parameters Used in the Test Problem

Parameters	Range
D_{ip}	Uniform distribution (500,2500)
α_p	Uniform distribution (0.3,0.6)
β_p	Uniform distribution (0.3,0.9)
FmP_i	Uniform distribution (70000,90000)
FrP_l	Uniform distribution (50000,70000)
FD_j	Uniform distribution (15000,30000)
FC_k	Uniform distribution (15000,30000)
GP_e	Uniform distribution (60000,90000)
GD_j	Uniform distribution (12000,18000)
$CAPM_{ip}$	Uniform distribution (2000,4000)
$CAPR_{lp}$	Uniform distribution (1000,2000)
$CAPD_{jp}$	Uniform distribution (2000,5000)
$CAPC_{kp}$	Uniform distribution (2000,5000)
CAq_{pn}	Uniform distribution (10,30)
CP_p	Uniform distribution (60,100)
$CRem_p$	Uniform distribution (40,70)
TIJ_{pij} ,TLJ_{pij} , TJN_{pij} ,TNK_{pij} ,TKL_{pij} ,TKM_{pij}	Uniform distribution (1,4)

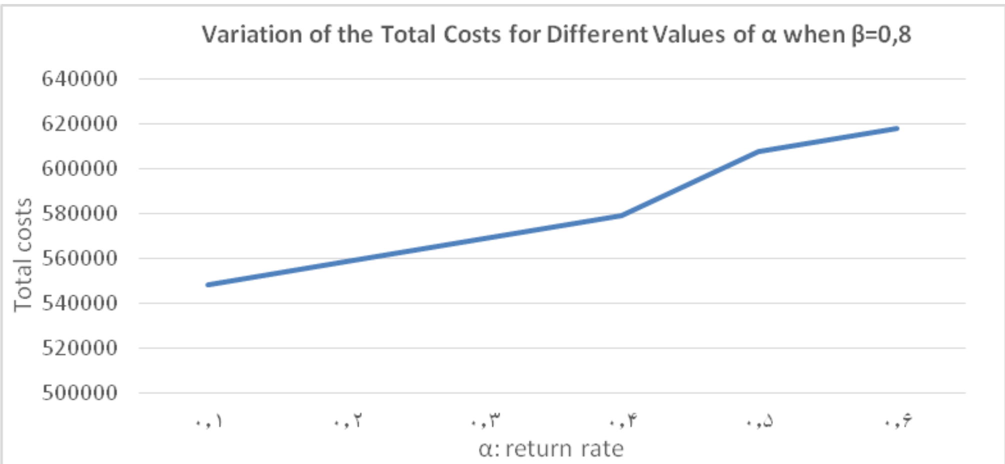

Figure 2. Impact of the Return Rate Variation on the Total Costs

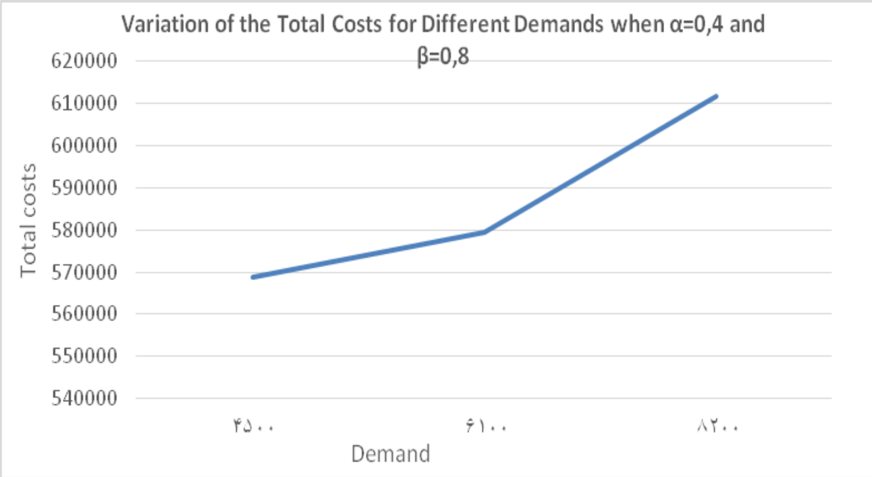

Figure 3. Impact of the Demand Variation on the Total Costs

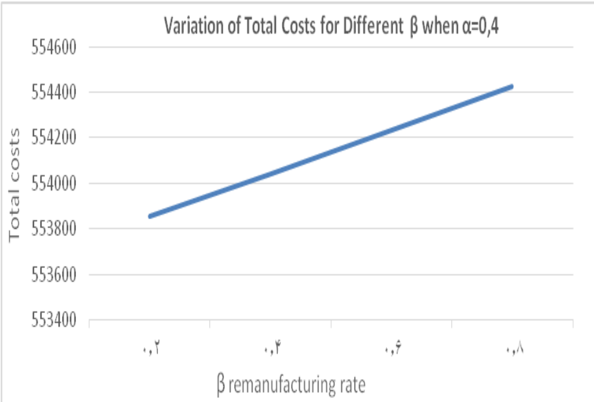

Figure 4. Impact of the Remanufacturing Rate Variation on the Total Costs

The problem is solved by LINGO 11.0, on a computer with 3.2 GHZ and 8 GB RAM. In the optimal CLSC network design, there is one hybrid manufacturing/remanufacturing plant located at location 2, one manufacturing plant located at location 3, one distribution centre at location 1 and another one at location2, one collection centre at location1, and one hybrid distribution/collection centre at location 2. The optimal solution provides a cost saving of $48.000 from the collocation of facilities.

As illustrated in Figure 2 and Figure 3, it is noticeable that the increase in demand and return ratio increases the total costs of the network. In addition, the total costs are more sensitive to the demand compared to the return ratio. Moreover, for a fixed return rate, the total costs increase with the increase of the remanufacturing rate (Figure 4). This result can be explained by the quality of the returned products. The results point out that hybrid facilities generate cost savings. Moreover, increasing the quantity of returns is an essential strategy to increase the benefits of the closed-loop supply chain.

6. Conclusion

In this paper, the problem of collocation of a remanufacturing closed-loop supply chain is modeled with a mixed non-integer programming approach and then linearized and solved by Lingo software. Computational results show that this MILP model can provide an efficient opportunity for managers to make proper decisions for designing remanufacturing closed-loop supply chain network among various facilities at various locations. The results of this work confirm the findings of Ko and Evans (2007) and Pishvaee et al. (2010) regarding the collocation of distribution/collection facilities.

The value added of this work is twofold: the consideration of collocation decisions at two levels of the logistics network (manufacturing/remanufacturing as well as distribution/collection facilities) and the modelling of the retailer as a collector of end-of life products in order to reduce costs and ensure the acquisition of a sufficient quantity of returns, which is a condition of the remanufacturing economic viability. The collocation decision depends largely on the capacity of the installation, as well as on the volume of returned products.

For future research, the model can be expanded to include other value recovery alternatives involved in the reverse logistics network design problem. In addition, development of multi-objective optimization approach which explicitly analyzes the trade-offs among the cost and environmental impacts could be an interesting extension of this work

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