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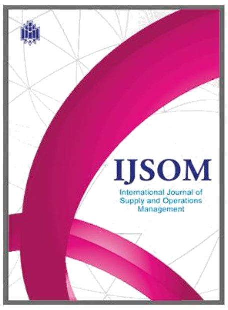

Modeling a Multi-period Multi-product Closed-loop Supply Chain Network Design Problem Considering Reused Cost and Capacity Constraints

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Abstract
The importance of remanufacturing used products into new ones has been widely recognized in the literature and in practice. This is due to both of economic opportunities and environmental aspects. This paper aims to design a new integrated multi-period & multi-product closed-loop supply chain network considering reused cost and capacity constraints for all stages. In this problem the stages of supplier, assembler, retailer, customer, collection center, refurbishing center, and disassembler is regarded consequently. The considered objective function is total cost factors that consists of 7 components: costs of associated with locating the plants and retailers, purchasing, transportation, collection of used products from customers, disposal for subassemblies, refurbishing, and finally refund to customers. First, parameters and decision variables of this problem are defined, then a mixed integer linear programming mathematical model is presented. The proposed mathematical model is run applying the GAMS software. Two real examples (shed light, and power-outlet) are considered to solve using the proposed mathematical model. These two examples were obtained based on data in two new references. Since this problem is known as NP-Hard, the model is run just for small-sized problem consists of four suppliers, two disassemblers, two retailers, and two periods. The results are analysed and some sensitivity analysis have been done for the effective factors. These result show that, the demand has a less effect on total cost. But Purchasing/refurbishing cost ratio has a high effect on the objective function. Finally, the capacity of collection and refurbishing centers has a high effect in primary changes and this effect gradually reduced. So having the proper capacity for collection and refurbishing centers and also creating balance between different stages can reduce overall cost.

Keywords: Capacity constraints; Closed-loop supply chains; Reused costs.

1. Introduction

The classic supply chain approach, which is nowadays called the forward supply chain, is not concerned with end-of-life (EOL) products. Then, the reverse supply chain, or reverse logistics (RL), aims to account for EOL products in the most environmentally friendly manner possible. The evolution of supply chains leads to an integrated approach of considering both forward and reverse supply chains simultaneously known as the closed-loop supply chain (CLSC) (Chopra and Meindl, 2010, Georgiadis and Besiou, 2010, Maliki et al., 2016, Govindan and Soleimani, 2017). The growing interest in the collection of disused products for recovering resources is reasonable considering environmental issues and is also more profitable (Lee et al. 2009, Quariguasi Frota Neto, Walther, Bloemhof, Van Nunen, and Spengler, 2010). For example, batteries, cellular phones, computers, shoes, automobiles, refrigerators, bottles etc. should be brought back to reuse or disposal according to environmental considerations. So, the reversal logistic has recently attracted wide attention according to sustainability and environmental themes all over the world (Bjørn and Hauschild, 2013, Elbounjimi et al. 2014, Das et al. 2015, MacArthur Foundation, 2014, Kaya et al. 2016).

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Correspondingly, all activities and solutions like the logistics management of the overall lifecycle of parts and products should be integrated into a top level of supply-chain procedure (Yang et al. 2009, Amini et al. 2016). The closed-loop supply-chain (CLSC) network structure is a good method for managing the overall lifecycle of parts and products. Therefore, the new and business-perspective type of CLSC definition can be found in Guide and Van Wassenhove (2009)

as follows: “the design, control, and operation of a system to maximize value creation over the entire life cycle of a product with dynamic recovery of value from different types and volumes of returns over time.” In this approach to supply chain, EOL products play a vital role. So, some of the many activities that should be done during a CLSC are as follows:

- Recycling, to have more raw materials or parts
- Remanufacturing, to resale products to secondary markets or if possible to primary markets
- Repairing, to sell products in the secondary markets

In a CLSC network, some new materials or parts are also needed from suppliers to replace which are not recoverable through the system (Jayaraman et al., 1999, Gaura, et al. 2017). In this kind of network system, the objective is to optimize some performance measures, for instance to minimize collection, transportation, purchasing, recovery, and disposal costs as well as the fixed costs of potential collection places and retailers.

In this study, a multi-period multi-product closed-loop supply-chain network model, which consists of forward and reverse logistics, is introduced, and a new mixed integer linear programming model is developed to minimize total cost factors.

The rest of this paper is organized as follows: In section 2, a brief review of the literature is provided. In Section 3, the problem is defined and a new mixed integer linear programming model is presented. Results of computational experiments are given in Section 4, and finally the conclusions and future studies are offered in Section 5.

2. Review of the literature

Supply chain management (SCM) is usually defined as the efficient planning, execution, and control of all the operations between suppliers, manufacturers, warehouses, retailers, and customers (Cardenas-Barron and Sana, 2014). Sustainable SCM involves making decisions about supply chain operations that meet the existing needs while maintaining the usefulness of products for the future. The sustainable approach not only considers the economic benefits while making a decision, but also takes social and environmental impacts into account. To enhance value creation over the product lifecycle, to improve the sustainability of supply chains, and to give more attention to environmental aspects, evolution of the supply chains leads to an integrated approach called the closed-loop supply chain (CLSC) (Zavvar Sabegh, et al. 2016, Govindan and Soleimani, 2017).

Stindt and Sahamie (2014) classified the quantitative studies of closed-loop supply chain in four groups of network design, production planning, product returns management, and forecasting. In closed loop supply chain there are different options for recovery such as reuse, repair, remanufacturing, refurbishing, retrieval and recycling; in which remanufacturing that transforms the defective products into an as-good-as new condition is attractive in terms of environmental concerns, legislation and economics (Torkaman, Fatemi Ghomi, and Karimi, 2017).

The first attempt at remanufacturing was made by Schrady (1967) who developed an economic order quantity model for products that can be repaired. He did not consider disposal costs and assumed that manufacturing and repair are instantaneous and infinite. Later, Richter (1996) developed a hybrid system that considers both production and repair for Schrady's model. Robert Lund (1996) also did a study about the remanufacturing industry of domestic U.S. steel in 1996 and suggested that the remanufacturing industry should be larger in terms of employment and gross sales. In the same vein, some researchers including Guide (1996), Guide and Srivastava (1998), Fleischmann et al. (1997), Jayaraman et al. (1999), Fleischmann et al. (2001), and Krikke et al. (2003) worked on improving central collection and remanufacturing shop control.

Also, several researchers have often focused on mathematical modelling in different cases. For instance, Teunter (2004) developed a new mathematical model for finite and infinite production and recovery rates with the assumption that recovered products are as good as new and satisfy the same demand. Similarly, Min et al. (2006) investigated the CLSC network design problem involving both spatial and temporal consolidation of returned products, and proposed a new mixed integer nonlinear programming model. This problem was also studied by Yang et al. (2009) who introduced a new model including suppliers, manufacturers, retailers, customers, and recovery centers in which each section has its own aims in conflict with each other.

In another study, El-Saadany and Jaber (2010) developed an optimization model that accounts for waste disposal cost while considering price and quality dependent return rate. The CLSC network problem focusing on the operations of Reduce, Recovery, and Reuse (as 3R) was studied by Wang and Hsu (2010). They developed an integer linear programming formulation and a genetic algorithm based on spanning tree to determine locations of various facilities. Kannan et al. (2010) proposed a new CLSC network model in the multi-echelon multi-period condition for product returns. They looked for the optimum usage of secondary lead recovered from the spent lead–acid batteries for producing new batteries, and considered material procurement, production, distribution, recycling, and disposal. Pishvaee et al. (2011) also proposed a new robust optimization model for handling the inherent uncertainty of input data and factors in the CLSC network problem. The proposed model which is a deterministic mixed integer programming model was presented by using the recent extensions in the robust optimization theory. In another work, a mixed integer linear programming model was constructed based on the lifecycle of a network consisting of manufacturing facilities, collection, repair, disassembly, recycling, and disposal by Amin and Zhang (2012). They considered three types of return contains in their model: commercial returns, end-of-life products, and end-of-use products.

Qiang et al. (2013) studied a CLSC network design problem in which collection centers recycle product directly from the demand market. They formulated this problem as a finite-dimensional variation inequality problem. Capturing the uncertainty in demand, which is associated with penalties, namely inventory and shortage costs, is the major innovation and contribution that differentiates their study from other works. Considering an integrated CLSC problem with the aim of optimizing the strategic goals and tactical decisions simultaneously, Ozceylan et al. (2014) introduced a model which could be used as a part of an integrated tool to support decision making within supply chain management. They intended to minimize costs of transportation, purchasing, refurbishing, and operating the disassembly workstations, so a nonlinear mixed integer programming formulation was developed. Then to evaluate the performance of the proposed model, some numerical examples were used, and sensitivity of the solutions with respect to parameters like purchasing/refurbishing cost ratio was examined. For more information on the closed-loop supply chain and reverse logistics, readers could study the paper of Govindan et al. (2015) which illustrates this subject by reviewing 382 papers published between 2007 and 2013. More recently, Elbounjimi et al. (2015) studied the problem of designing a multi-echelon and capacitated closed-loop supply chain network that provides different products. They defined the total profit of chain as the objective function, and developed a mixed-integer linear programming formulation for the problem. Guo and Ya (2015) derived a stochastic model with quality dependent collection rate, buy-back price, and remanufacturing cost. Jeihoonian et al. (2015) proposed a stochastic mixed-integer programing model for a CLSC network design problem in which the reverse network involves several types of recovery options. Dutta et al. (2016) built a multi-period recovery framework to examine the optimal buy-back price. They discussed the return rate improvement of used products by considering uncertain demand and capacity. Optimization of the closed-loop supply chain of multi-items with returned subassemblies was studied by Tahirov et al. (2016). They developed a new mathematical model for this kind of supply chain where a product (new or remanufactured) and its spare parts are returned and disassembled for recovery. Recently, Moshtagh et al. (2017) studied a stochastic CLSC model with shortages and rework. They considered quality based returns with different demands of manufactured and remanufactured products. Furthermore, Masoudipour et al. (2017) studied the possibility of closing the chain in a textile company and the effects of such a decision on the profits of the chain. So, they proposed a bi-objective model to formulate the CLSC problem which includes the manufacturers, distributors and, customers in the forward chain as well as remanufacturing, repairing, and recycling centers in the backward chain. This model is applicable to industries with zero-waste strategy and similar recovery facilities. Chen et al. (2017) says that due to environmental issues, product refurbishment is becoming more and more important nowadays and optimization of products refurbishing process in closed loop supply chain needs to be studied. In this regard, they established a multi-period model for this problem to deal with the uncertainties.

Based on the research reviewed here, it is clear that there is a research potential for making use of a closed-loop supply-chain network. Besides, to the researchers' knowledge, there has been no study on the multi-period multi-product condition of the closed-loop supply chain network considering reused cost and capacity constraints for all stages. The purpose of this research is, therefore, to study and design a new integrated closed-loop supply chain network considering the multi-period multi-product condition and capacity constraints for all stages. The considered objective function is total cost factors. This idea is got from a study by Ozceylan and Paksoy (2013) although collection costs and reused costs considering the bill of materials besides disposal costs for the network are added to study as the contributions of this paper to the relevant literature. Moreover, this study is developed based on two real examples of shed light and power-outlet.

3. Problem definition and modeling

The problem considered in this study can be defined as designing an integrated problem of closed-loop supply chain network considering the bill of material and reused costs. The objective is to minimize total cost factors. To understand it better, assume a product with two parts as an example of a CLSC which contains the forward chain and the reverse chain. The former is used to purchase and assemble parts to form end products and deliver them to end users whereas the latter is used for collecting, refurbishing, disassembling, and disposal of the subassemblies or products.

Two ways can be used for supplying the system with subassemblies: one involves using suppliers and the other involves disassembling returned products. The network discussed here can be conceptualized in a framework as shown in Figure 1.

The network includes a number of suppliers that provide different parts/components as raw materials with a certain utilization number to plants in which they are transformed into the same number of products. Purchased items are processed and then assembled in an assembly section or line, and final products are transported to retailers. After that, the products are delivered to distributers or customers as a forward flow logistic. The reverse flow logistic starts with collecting the used products from end users or repair centers. The used products are sent to the chain for several reasons like insufficiency or lack of satisfactory quality specifications or defectiveness. Each customer zone has a known demand that must be satisfied, and it is assumed that a percentage of the demand is provided by a certain amount of used products. Finally, all used products must be collected from customer zones. They can be transported to disassembly centers, or they can be directly shipped to refurbishing centers if do not require any substantial processing. The products returned to the disassembly centers are revised, classified, and organized by the disposal and remanufacturing strategy. Returned products that are of good quality for remanufacturing can be disassembled, recovered, reprocessed, cleaned, and tested until they become new parts. Disassembly lines are usually essential to transform the discarded products to parts/components, just like assembly lines which are used to assemble components into a final product with a high volume (Demirel and Gokcen 2008). After refurbishing, the new products are transported to retailers in order to be delivered to customers. There are several types of costs in this system such as transportation, purchasing, refurbishing, collection, refund to customers, disposal, and fixed costs of potential plants and retailers.

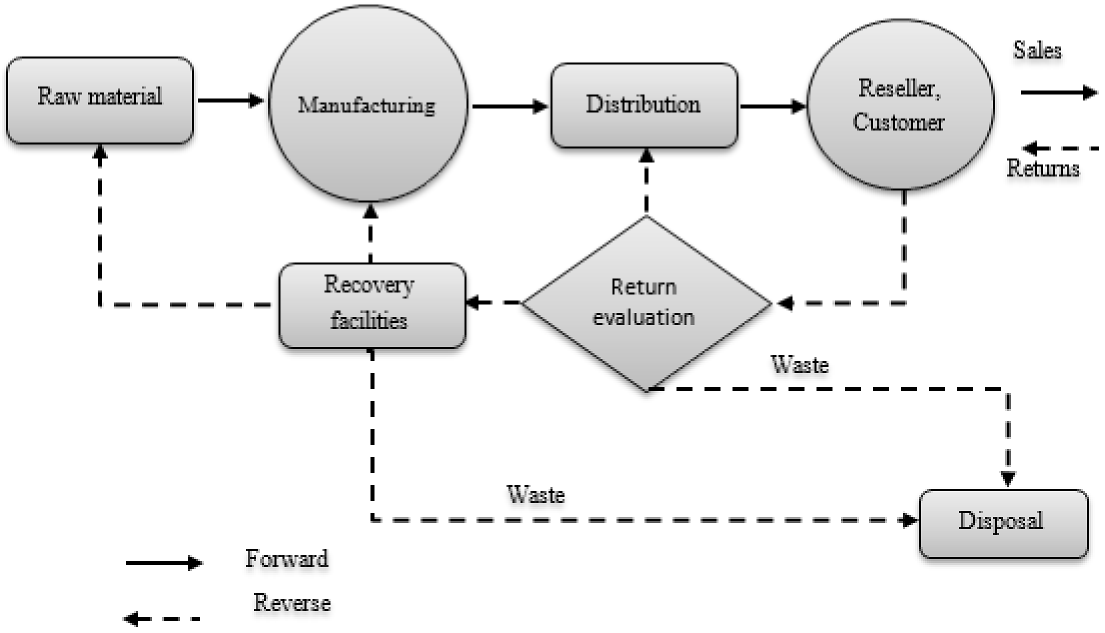

Figure 1. A generic form of forward/reverse logistics (Tonanont et al., 2008).

The basic assumptions of the proposed model are as follows:

- The demand for each product is specified and fixed.
- Total demands of each product must be fully met for each end user.
- The capacities of all facilities, both forward and reverse, are limited and fixed.
- All cost ratios are deterministic and known a priori.
- The rates of collection, disposal, and disassembly are known.
- All workstations can process any task with the same costs.

These assumptions which are the standard assumptions for the closed-loop supply-chain design are also considered in other studies (e.g. Sheu et al. 2005, Neto et al. 2008, Wang and Hsu 2010). Besides, Wang and Hsu (2010) state that a common assumption is that it is better to consider the recovery amount as a function of customer demand in the recovery systems.

In the following the mixed integer mathematical model and its formulation which provides all of the above mentioned decision parameters and assumptions are presented. First, the index sets, decision making variables, and parameters are defined. Then, the mixed integer mathematical model is developed and illustrated.

Index sets:

$I = \{1, 2, \ldots\}, i \in I$	Index set of suppliers
$J = \{1, 2, \ldots\}, j \in J$	Index set of assemblers
$K = \{1, 2, \ldots\}, k \in K$	Index set of retailers
$L = \{1, 2, \ldots\}, l \in L$	Index set of customers
$M = \{1, 2, \ldots\}, m \in M$	Index set of collection centers
$R = \{1, 2, \ldots\}, r \in R$	Index set of refurbishing centers
$D = \{1, 2, \ldots\}, d \in D$	Index set of disassemblers
$C = \{1, 2, \ldots\}, c \in C$	Index set of subassemblies
$G = \{1, 2, \ldots\}, g \in G$	Index set of products
$P = \{1, 2, \ldots\}, p \in P$	Index set of period

Variables:

X_{gcijp}	amount of subassembly *c* of product *g* shipped from supplier *i* to assembler *j* in period *p*
Y_{gjkp}	amount of product *g* shipped from plant *j* to retailer *k* in period *p*
W_{gklp}	amount of product *g* shipped from retailer *k* to customer *l* in period *p*
A_{glmp}	amount of product *g* collected from customer *l* to collection center *m* in period *p*
B_{gmrp}	amount of product *g* shipped from collection center *m* to refurbishing center *r* in period *p*
S_{gmdp}	amount of product *g* shipped from collection center *m* to disassembler *d* in period *p*
E_{grkp}	amount of product *g* shipped from refurbishing center *r* to retailer *k* in period *p*
$Z_{\mathrm{gcd}\,jp}$	amount of subassembly *c* of product *g* shipped from disassembler *d* to assembler *j* in period *p*
$F_{\mathrm{gcd}\,p}$	amount of subassembly *c* of product *g* disposed from disassembler *d* to disposal in period *p*
H_{jp}	If plant *j* is open in period *p*, 1; otherwise, 0.
V_{kp}	If retailer *k* is open in period *p*, 1; otherwise, 0.

Parameters:

d_{ij}	distance between supplier *i* and assembler *j*
d_{jk}	distance between assembler *j* and retailer *k*
d_{kl}	distance between retailer *k* and customer *l*
d_{lm}	distance between customer *l* and collection center *m*
d_{mr}	distance between collection center *m* and refurbishing center *r*
d_{md}	distance between collection center *m* and disassembler *d*
d_{rk}	distance between refurbishing center *r* and retailer *k*
d_{dj}	distance between disassembler *d* and assembler *j*
d_{d}	distance between disassembler *d* and the disposal unit
a_{gcip}	capacity of subassembly *c* of supplier *i* in period *p*
b_{gjp}	capacity of assembler *j* for product *g* in period *p*
c_{gkp}	capacity of retailer *k* for product g in period *p*
u_{glp}	demand of customer *l* for product g in period *p*

e_{gmp}	capacity of collection center *m* for product g in period *p*
f_{grp}	capacity of refurbishing center *r* for product g in period *p*
$g_{\mathrm{gcd}\,p}$	capacity of disassembler *d* for subassembly *c* of product *g* in period *p*
t	shipping cost
s_{gci}	purchasing cost of subassembly *c* of product *g* of supplier *i*
w_{gr}	refurbishing cost of product *g* of refurbishing center *r*
$(cc)_{glm}$	collection cost of product *g*
$(rf)_{glm}$	refund to customers costs of product *g*
$(wdc)_{gc}$	disposal cost of subassembly *c* of product *g*
α_{jp}	the fixed opening cost of plant j in period p
β_{kp}	the fixed opening cost of retailer k in period p
q_{gc}	number of subassembly *c* in product *g*
H_p	maximum available number of plants in period *p*
V_p	maximum available number of retailer in period *p*
$\theta_{\max}$	maximum percentage of collected products from customers
$\theta_{\min}$	minimum percentage of collected products from customers
λ	percentage of product which is sent to refurbishing centers from collection centers
μ	percentage of subassembly which is sent to assemblers from disassemblers

Mathematical formulation:

$$\begin{aligned}
MinimizeZ = \Bigg(& \sum_{g\in G}\sum_{c\in C}\sum_{i\in I}\sum_{j\in J}\sum_{p\in P} X_{gcijp} * d_{ij} + \sum_{g\in G}\sum_{j\in J}\sum_{k\in K}\sum_{p\in P} Y_{gjkp} * d_{jk} + \sum_{g\in G}\sum_{k\in K}\sum_{l\in L}\sum_{p\in P} W_{gklp} * d_{kl} \\
& + \sum_{g\in G}\sum_{l\in L}\sum_{m\in M}\sum_{p\in P} A_{glmp} * d_{lm} + \sum_{g\in G}\sum_{m\in M}\sum_{r\in R}\sum_{p\in P} B_{mrp} * d_{mr} + \sum_{g\in G}\sum_{m\in M}\sum_{d\in D}\sum_{p\in P} S_{gmdp} * d_{md} \\
& + \sum_{g\in G}\sum_{r\in R}\sum_{k\in K}\sum_{p\in P} E_{grkp} * d_{rk} + \sum_{g\in G}\sum_{c\in C}\sum_{d\in D}\sum_{j\in J}\sum_{p\in P} Z_{\mathrm{gcd}\,jp} * d_{dj} + \sum_{g\in G}\sum_{c\in C}\sum_{d\in D}\sum_{p\in P} F_{\mathrm{gcd}\,p} * d_{dc} \Bigg)
\end{aligned} \tag{1}$$

$$+\left(\sum_{g\in G}\sum_{c\in C}\sum_{i\in I}\sum_{j\in J}\sum_{p\in P} X_{gcijp} * s_{gci} \right) \tag{2}$$

$$+\left(\sum_{g\in G}\sum_{m\in M}\sum_{r\in R}\sum_{p\in P} B_{gmrp} * w_{gr} \right) \tag{3}$$

$$+\left(\sum_{g\in G}\sum_{l\in L}\sum_{m\in M}\sum_{p\in P} A_{glmp} * (rf)_{glm} \right) \tag{4}$$

$$+\left(\sum_{g\in G}\sum_{l\in L}\sum_{m\in M}\sum_{p\in P} A_{glmp} * (cc)_{glm} \right) \tag{5}$$

$$+\left(\sum_{g\in G}\sum_{c\in C}\sum_{d\in D}\sum_{p\in P} F_{\mathrm{gcd}\,p} * (wdc)_{gc} \right) \tag{6}$$

$$+\left(\sum_{j}\sum_{p} H_{jp} * \alpha_{jp} + \sum_{k}\sum_{p} V_{kp} * \beta_{kp} \right) \tag{7}$$

$$\sum_{j\in J} X_{gcijp} \le a_{gcip} \qquad \forall g\in G, c\in C, i\in I, p\in P \qquad (8)$$

$$\sum_{k\in K} Y_{gjkp} \le b_{gjp} * H_{jp} \qquad \forall g\in G, j\in J, p\in P \qquad (9)$$

$$\sum_{l\in L} W_{gklp} \le c_{gkp} * V_{kp} \qquad \forall g\in G, k\in K, p\in P \qquad (10)$$

$$\sum_{k\in K} W_{gklp} \ge u_{glp} \qquad \forall g\in G, l\in L, p\in P \qquad (11)$$

$$\sum_{r\in R} B_{gmrp} + \sum_{d\in D} S_{gmdp} \le e_{gmp} \qquad \forall g\in G, m\in M, p\in P \qquad (12)$$

$$\sum_{k\in K} E_{grkp} \le f_{grp} \qquad \forall g\in G, r\in R, p\in P \qquad (13)$$

$$F_{\mathrm{gcd}\,p} + \sum_{j\in J} Z_{\mathrm{gcd}\,jp} \le g_{\mathrm{gcd}\,p} \qquad \forall g\in G, c\in C, d\in D, p\in P \qquad (14)$$

$$\sum_{j} H_{jp} \le H_{p} \qquad \forall p\in P \qquad (15)$$

$$\sum_{k} V_{kp} \le V_{p} \qquad \forall p\in P \qquad (16)$$

$$\sum_{j\in J} Y_{gjkp} + \sum_{r\in R} E_{grk\,(p-1)} - \sum_{l\in L} W_{gklp} = 0 \qquad \forall g\in G, c\in C, j\in J, p\in P \qquad (17)$$

$$\sum_{i\in I} X_{gcijp} + \sum_{d\in D} Z_{\mathrm{gcd}\,j\,(p-1)} - \sum_{k\in K} Y_{gjkp} * q_{gc} = 0 \qquad \forall g\in G, k\in K, p\in P \qquad (18)$$

$$\theta_{\min} \sum_{k\in K} W_{gklp} \le \sum_{m\in M} A_{gklp} \le \theta_{\max} \sum_{k\in K} W_{gklp} \qquad \forall g\in G, l\in L, p\in P \qquad (19)$$

$$\lambda \sum_{l\in L} A_{glmp} - \sum_{r\in R} B_{gmrp} = 0 \qquad \forall g\in G, m\in M, p\in P \qquad (20)$$

$$\sum_{m\in M} B_{gmrp} - \sum_{k\in K} E_{grkp} = 0 \qquad \forall g\in G, r\in R, p\in P \qquad (21)$$

$$(1-\lambda) \sum_{l\in L} A_{glmp} - \sum_{d\in D} S_{gmdp} = 0 \qquad \forall g\in G, m\in M, p\in P \qquad (22)$$

$$(1-\mu) \sum_{m\in M} S_{gmdp} * q_{gc} - F_{\mathrm{gcd}\,p} = 0 \qquad \forall g\in G, c\in C, d\in D, p\in P \qquad (23)$$

$$\mu \sum S_{gmdp} * q_{gc} - \sum_{j\in J} Z_{\mathrm{gcd}\,jp} = 0 \qquad \forall g\in G, c\in C, d\in D, p\in P \qquad (24)$$

$$\begin{aligned} &X_{gcijp}, Y_{gjkp}, W_{gklp}, A_{glmp}, B_{gmrp}, S_{gmdp}, && \forall g\in G, c\in C, i\in I, j\in J, k\in K, l\in L \\ &E_{grkp}, Z_{\mathrm{gcd}\,jp}, F_{\mathrm{gcd}\,p} \ge 0 && , m\in M, r\in R, d\in D, p\in P \end{aligned} \qquad (25)$$

$$H_{jp}, V_{kp} \in \{0,1\} \qquad \forall j\in J, k\in K, p\in P \qquad (26)$$

The objective function has seven components. The cost of transportation in the forward and reverse chains is represented in (1). The second component denotes the cost of purchasing the subassembly parts as equation (2). The cost of refurbishing is shown in (3). The forth component, shown in (4), indicates the cost of refund to customers for product. The fifth component represents the cost of collecting used products from customers as equation (5). The sixth component shows the cost of disposal for subassemblies as (6). The final component represents the fixed costs of locating the plants and retailers (7). Constraints (8)–(14) state the needs to regard the capacity of suppliers, plants, retailers, collection centers, refurbishing centers, and disassembly centers, respectively. The number of plants and retailers that can be opened are limited by constraints (15) and (16). Equations (17)–(24) are used to balance the forward and reverse part facilities: the quantities that enter a facility should be equal to the amount of products/parts that leave it. Non-negativity restriction on the decision variables is guaranteed by constraint (25). Finally, constraint (26) defines the binary variables.

4. Computational experiments

In order to run the proposed mathematical model and evaluate the results, some test problems are applied in various conditions. The test problems are obtained from the data in Ozceylan et al. (2014) by considering new parameters of the current study. For this purpose, a randomly generated numerical example is used to illustrate the basic ideas and to derive insights. It is run for two recyclable hand-lights and power-outlet. The complete illustration is presented below.

4.1. Description of the data

The network for the numerical example, shown in Figure 2, consists of four subassembly suppliers, two assemblers, two retailers, and four customers in the forward chain.

The suppliers provide required sources to produce the products, namely a hand-light, shown in Figure 3 with its seven different subassemblies (Tang et al., 2002), and a power-outlet, shown in Figure 4 as the second sample. The reverse logistics network in the sample problem contains two of each collection, disassembly, and refurbishing center. The collection centers are responsible for collecting the used products from repair centers and customers. In the first period, the subassemblies are assembled in assembler's centers and sent to retailers or customers. The reverse flow starts with the collection of used hand-lights from customers, where the collected amount is in an interval uniform ($\theta_{\min}$ to $\theta_{\max}$) and where ($1-\lambda$) % of the collected amount is directed to disassemblers; the rest that do not require any substantial processing are directly shipped to the refurbishing centers. After doing refurbishes activities, the used hand-lights are transported to the retailers to be delivered to customers during the subsequent period. Following this process, the subassemblies are classified based on their condition: usable subassemblies are sent to the assemblers to be reused in the next period while the rest are disposed of. We go through the same process involving collection and refurbishing activities for the second example (power-outlet) in the next section so that power-outlets could be delivered to customers as new products.

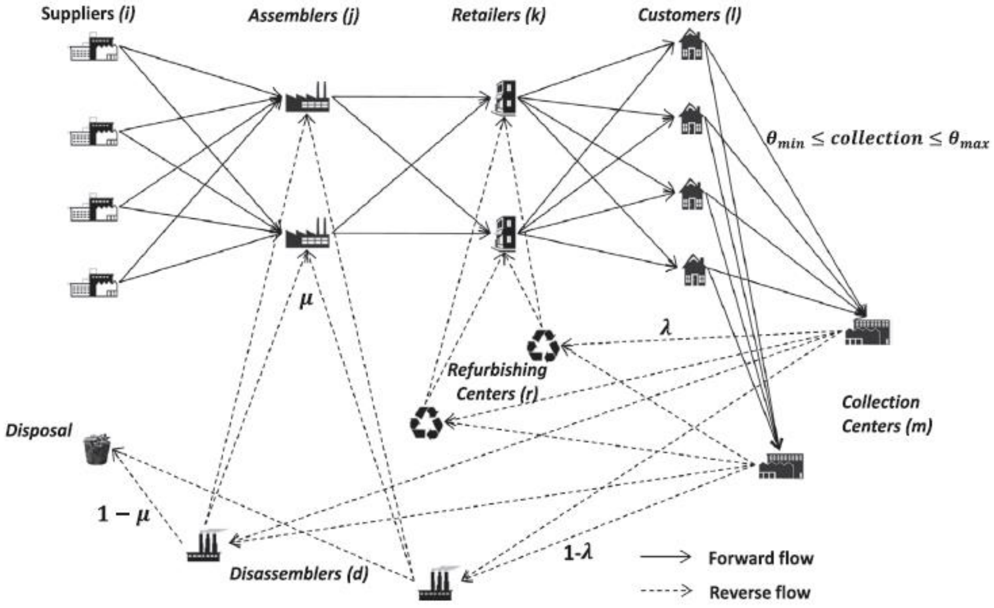

Figure 2. The CLSC network for the numerical example

For the numerical example, the unit transportation cost (t) is considered as 5.23 cents per ton-km.
One period is considered 4 months (16 weeks), with six working days in a week, each of 9 hour long. The problem is modeled using two periods. Several experiments were handled in order to tune the needed parameters, and the final amount was determined as follows:

$(cc)_{glm}$: \$5/product

$(rf)_{glm}$: \$10/product

$(wdc)_{gc}$: \$5/subassembly

The remaining parameters were taken from the study of Ozceylan and Paksoy (2014) as follows: H_p =2, V_p =2, $\theta_{\min}$ = 20%, $\theta_{\max}$ = 80%, λ =30%, μ =70%, s_{gci} =\$25/subassembly, w_{gr} =\$10/product, the fixed costs are found to be \$5000 (α_{jp}) and \$3000 (β_{kp}) for each plant and retailer in all periods, respectively.

Tables 1–4 depicts the distances, capacities, and demands of the numerical example.

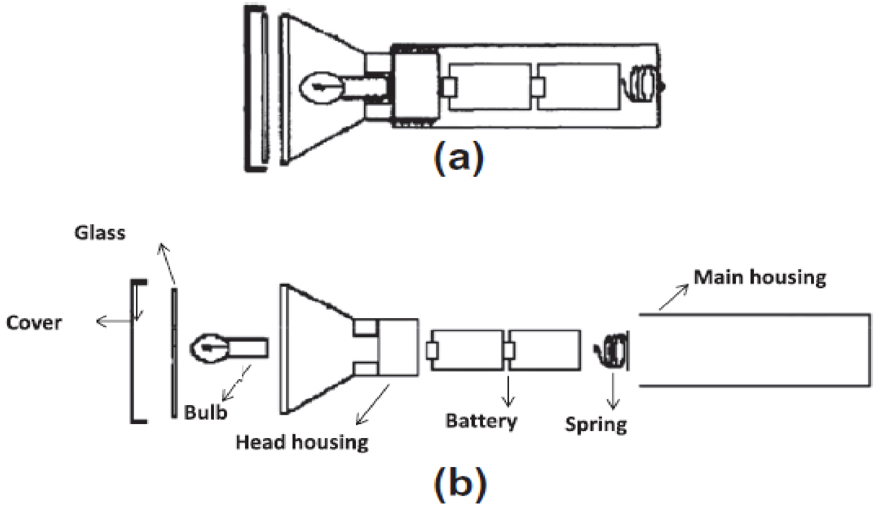

Figure 3. (a) A hand-light and (b) its subassemblies (Ozceylan and Paksoy. 2014).

Table 1. Distance values between facilities (km)

	Assembler 1	Assembler 2	Collection center 1	Collection center 2	Disposal
Supplier 1	100	130	-	-	-
Supplier 2	110	150	-	-	-
Supplier 3	140	80	-	-	-
Supplier 4	190	185	-	-	-
Retailer 1	160	120	-	-	-
Retailer 2	80	100	-	-	-
Disassembler 1	120	150	130	110	50
Disassembler 2	290	270	160	120	60

Table 2. Distance values between facilities (km)

	Customer 1	Customer 2	Customer 3	Customer 4	Refurbishing center 1	Refurbishing center 2
Retailer 1	220	260	150	170	220	260
Retailer 2	320	290	210	330	180	150
Collection center 1	50	80	100	90	90	100
Collection center 2	110	95	65	87	80	95

Table 4. End product capacities of facilities and demands of customers (tons)

Periods	Assemblers		Retailers		Customers				Collection centers		Refurbishing centers	
	1	2	1	2	1	2	3	4	1	2	1	2
1	670	590	520	580	160	160	180	190	200	230	240	210
2	550	470	530	330	170	180	170	180	230	220	210	260

4.2. The solution of the numerical problem

According the mixed integer linear programming formulation that was presented as (1)–(26) of the sample CLSC network, there are 580 variables and 530 constraints for the considered conditions. All computational experiments are conducted on a PC with an Intel Core i7 processor with 8 GB of RAM, and the computation time required to solve the model to optimality using the GAMS CPLEX solver is 4 CPU seconds. When the proposed model is solved for the given example, the total cost, which includes transportation, purchasing, refurbishing, collection, refund to customers, disposal, and fixed costs, is found to be 319524.97 for two periods. Table 5 presents all of the costs.

Table 3. Subassembly capacities of suppliers and disassemblers (tons)

	Subassembly						
	1	**2**	**3**	**4**	**5**	**6**	**7**
Supplier1							
Period1	585	451	424	523	567	559	480
Period2	435	557	539	579	485	489	509
Supplier2							
Period1	401	480	447	437	460	422	416
Period2	503	408	592	480	527	588	415
Supplier3							
Period1	577	465	512	537	578	457	509
Period2	498	591	465	499	544	425	408
Supplier4							
Period1	507	475	453	485	434	496	449
Period2	431	496	508	425	559	451	480
Disassembler1							
Period1	280	219	295	279	292	289	224
Period2	232	254	203	228	221	279	283
Disassembler2							
Period1	471	426	426	449	420	452	487
Period2	471	482	444	415	436	471	437

Table 5. Performance results of the problem

	Performance criteria	Value ($)	Percentage of total cost
Obj.	Total objective function value	319524.97	100
Obj. 1	Total transportation costs	94334.97	29.52
Obj. 2	Total purchasing costs	210160.00	65.77
Obj. 3	Total refurbishing costs	1810.00	0.57
Obj. 4	Total collection cost	960.00	0.30
Obj. 5	Total refund to customer cost	4400.00	1.38
Obj. 6	Total disposal cost	760.00	0.24
Obj. 7	Total fixed costs	7100.00	2.22

As it is evident in the table, the purchasing cost is the highest with 65.77%, followed by the transportation costs which account for 29.52% of the overall cost while the minimum share (i.e. 0.24%) belongs to the disposal costs. The experimental optimal results for the problem in both periods are shown in Table 6.

Table 6. Optimal distribution flow of the problem

	Amount of purchased parts	Amount of assembled products	Amount of collected products	Amount of refurbished products	Amount of disassembled products	Amount of disposed parts
Period 1	5520	690	430	129	301	722
Period 2	2880	571	140	42	98	232

The first column in Table 6 shows the purchased components that should be assembled in plants during the first and second periods. According to Table 6, in total 5520 tons of components are purchased from suppliers, and a total of 690 tons of end products are transported to customers through retailers after assembly in period 1. Two of the potential plants and retailers are opened in the optimal solution during any period. A total of 430 tons of end products are gathered and transported to the collection centers to be inspected. Also, 129 tons of used products in good condition will be shipped to refurbishing centers. The remainder of the collected used products is transported to the disassemblers. A similar analysis can be performed for the optimal distributions in the second period. With the use of recycled subassemblies from the first period, the capacity utilization rates of suppliers are decreased as expected.

Now, another practical example is illustrated and solved using the proposed mathematical model. This new example is about power-outlet. Suppose that suppliers provide three different kinds of parts to produce a power-outlet as shown in Figure 4.

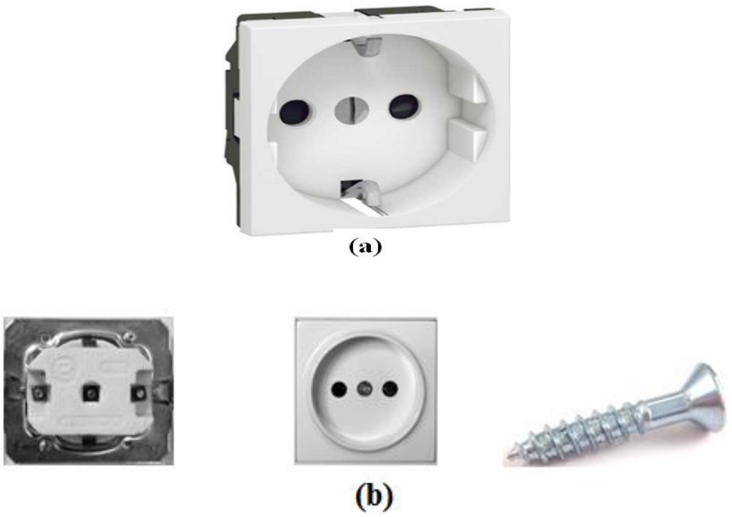

Figure 4 (a). A power-outlet and (b) its components

Tables 7–8 present similar data (capacities and demands) of the second numerical example (power-outlet). It is assumed that there are 3 subassemblies, 4 suppliers, and 2 disassemblers.

Table 7. Subassembly capacities of suppliers and disassemblers (tons)

	Subassembly		
	1	**2**	**3**
Supplier1			
Period1	920	720	620
Period2	810	710	610
Supplier2			
Period1	920	750	620
Period2	910	740	610
Supplier3			
Period1	929	720	620
Period2	910	710	610
Supplier4			
Period1	1080	970	720
Period2	1050	930	710
Disassembler1			
Period1	840	850	980
Period2	760	830	740
Disassembler2			
Period1	980	820	950
Period2	780	740	730

The results of solving the second numerical example including the amounts of cost elements are presented in Table 9. Like in the first example, the purchasing cost is the highest with 64.86%, followed by the total transportation costs which account for 30.34% of the overall cost, and the minimum share is due to disposal costs with 0.27%.

Table 8. End product capacities of facilities and demands of customers (tons)

Periods	**Assemblers**		**retailers**		**Customers**				**Collection centers**		**Refurbishing centers**	
	1	**2**	**1**	**2**	**1**	**2**	**3**	**4**	**1**	**2**	**1**	**2**
1	670	490	520	480	230	160	240	260	250	270	170	180
2	450	470	430	330	220	180	230	250	280	260	180	190

For simplicity, the other need parameters are considered as the first example.

Table 9. Performance results for the problem of the second product

	Performance criteria	Value ($)	Percentage of total cost
Obj.	Total objective function value	694238.6	100
Obj. 1	Total transportation costs	210688.03	30.34
Obj. 2	Total purchasing costs	450320.10	64.86
Obj. 3	Total refurbishing costs	3820.15	0.55
Obj. 4	Total collection cost	2200.06	0.32
Obj. 5	Total refund to customer cost	10400.00	1.48
Obj. 6	Total disposal cost	1900.26	0.27
Obj. 7	Total fixed costs	15000.00	2.18

4.3. Scenario analyses

It is well-known that all parameters of optimization problems are estimated or determined based on the previous information. So, it is quite possible that these parameters change over time. Therefore, it is important to study and analyze different scenarios for parameter changing. In this section the results of additional computational experiments based on changing the amounts of parameters are presented to gain a better understanding of the potential of the model and to see how changes in the parameters of the problem influence the solution value.

4.3.1. Effects of changing demands (Scenario 1)

Figure (5) and (6) present effects of changes in the customers' demands on the amount of objective function in examples 1 and 2, respectively. In this analysis, the amount of customers' demands is changed between -20% and +20%. As the results reveal, the largest increase is seen in the costs of purchasing and transportation.

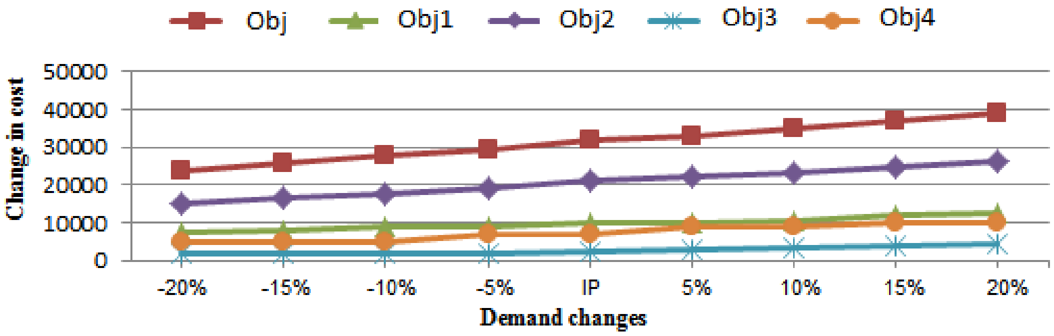

Figure 5. Effects of demand changes on each objective function for the hand-light example.

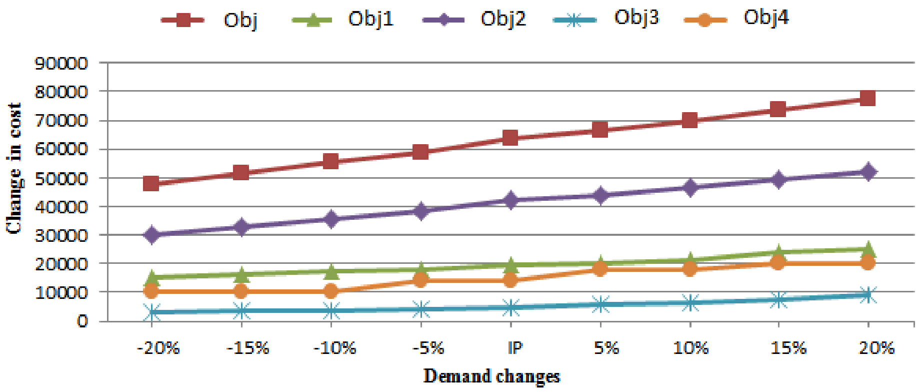

Figure 6. Effects of demand changes on each objective function for the power-outlet example.

4.3.2. Sensitivity to changes in the purchasing/refurbishing cost ratio (Scenario 2)

Another important parameter in the considered problem is the rate of purchasing cost to refurbishing cost of products. The results of the effect of this parameter on the total objective function and its elements are shown in Figures (7) and

(8) for both examples. The results indicate that increasing the purchasing/refurbishing cost ratio causes rises in both the purchasing and total cost. Besides. Other changes decrease the transportation and refurbishing cost.

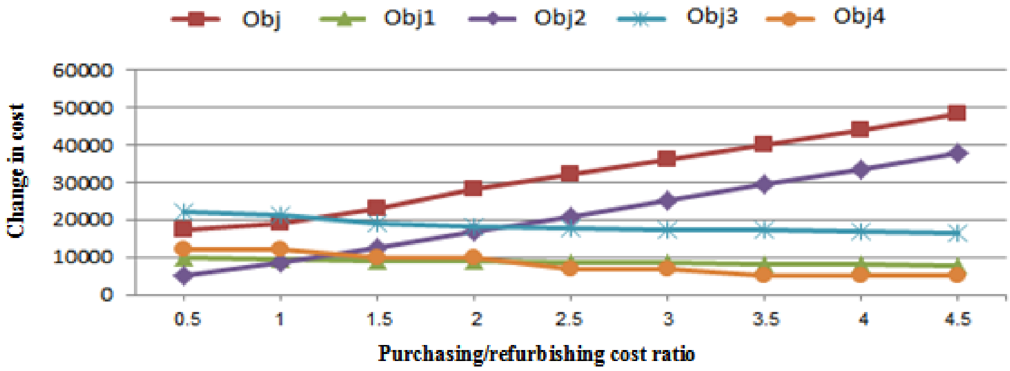

Figure 7. Effects of different ratios on each objective function for the hand-light example.

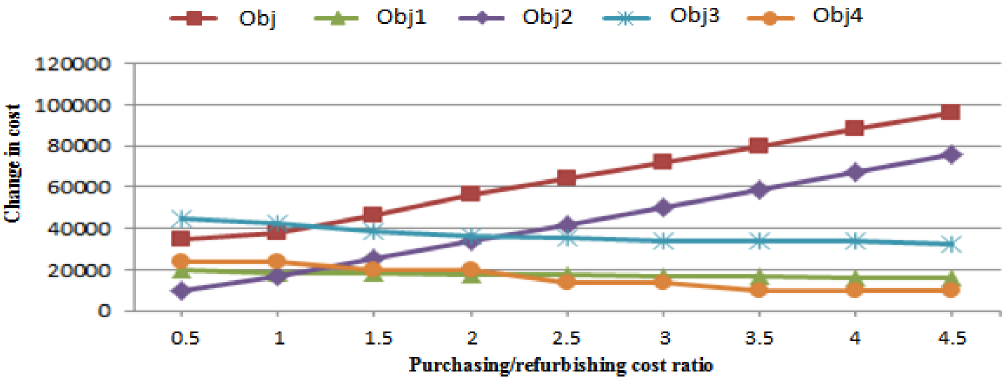

Figure 8. Effects of different ratios on each objective function for the power-outlet example.

4.3.3. Sensitivity to the capacities of collection and refurbishing centers (Scenario 3)

The objective function follows the capacities of collection and refurbishing centers. Thus, in order to analyze the effect of this parameter on the objective function, we have changed the capacity between -20% and +20%. The results are shown in Figures (9) and (10) for the example 1 and 2, respectively. According to the figures, increases in the capacities of collection and refurbishing centers lead to rises in both the transportation and refurbishing costs and decreases in the purchasing cost. The other costs elements are not affected.

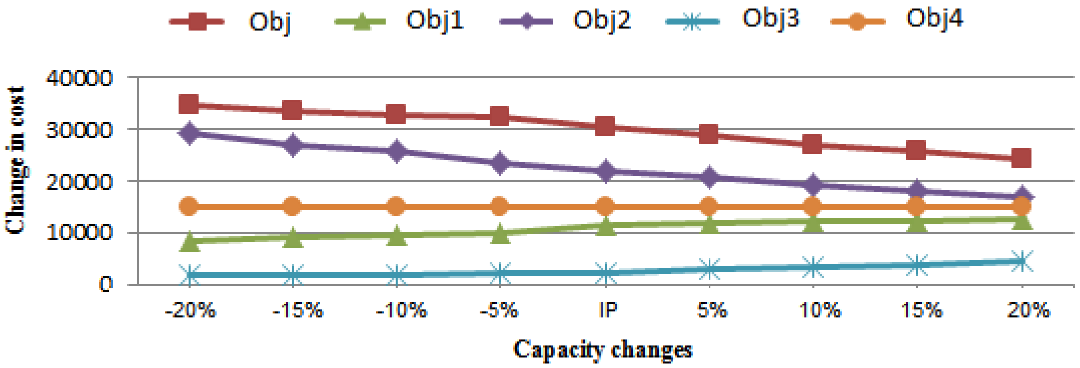

Figure 9. Effects of capacity changes on each objective function for the hand-light example.

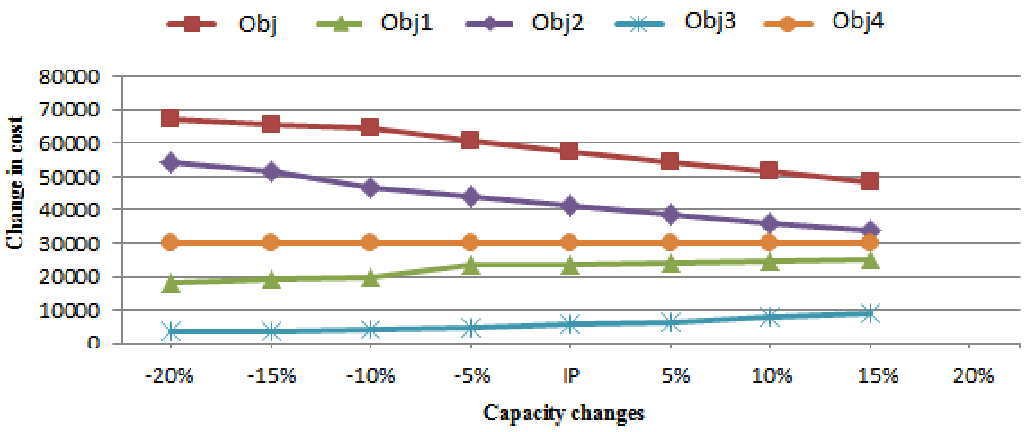

Figure 10. Effects of capacity changes on each objective function for the power-outlet example.

5. Summary and Conclusion

Due to environmental issues, product refurbishment and remanufacturing the used product is becoming more and more important nowadays. Therefore, optimization of products refurbishing process in closed-loop supply chain needs to be studied. Moreover pay attention to the cost of this process is another important problem. There are several situations in real-world such as reused cost and capacity limits for stages that few academic research focus on these situations carefully.

In this paper, a closed-loop supply-chain network in multi-period & multi-product condition and considering reused cost was studied. The objective function contains all elements of costs. At first problem was described and a mixed integer linear programming mathematical model was developed. Two realistic network instances as base cases was used to apply the proposed mathematical model. These two problems were obtained based on data in two new references. Since this problem is known as NP-Hard, so it was solved just in small sized-scale consists of four suppliers, two disassemblers, two retailers and two periods. The results were analysed in some indexes. Also some sensitivity analysis were done for the effective factors such as demand of customers, capacity of collection and refurbishing centers, and Purchasing/refurbishing cost ratio. These result show that, the demand has a less effect on total cost. But Purchasing/refurbishing cost ratio has a high effect on the objective function. More detail result shows that cost of purchasing the subassembly parts has the most sensitivity against the changes and so managers should more attention to this cost element. Finally, the capacity of collection and refurbishing centers has a high effect in primary changes and this effect gradually reduced. Therefore determination the proper capacity for collection and refurbishing centers and also creating balance between different stages can reduce overall cost.

To continue future work, we recommend investigating this problem with considering unexpected disturbances in parameters of the supply chain. Considering aspects of energy consumption as a new objective can be another attractive study field. Also, according to this problem is NP-Hard, some metaheuristic such as Particle Swarm Optimization (PSO), Imperialist Competitive Algorithm (ICA) algorithms can be developed for large-sized problems.

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