Simulation optimization approach for dynamic and stochastic closed loop supply chain network

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Abstract. In this paper, four simulation optimization (SO) models are developed by combining simulation and genetic algorithm. In proposed models, optimal values of inventory control parameters and the number of facilities to be opened are determined simultaneously for periodic review and continuous review systems, respectively. Furthermore, single product and multi-components of closed-loop supply chain (CLSC) network are created considering two different objective functions of review systems to gain a sustainable competitive advantage for companies. We seek to offer valuable insights for creating robust and user-friendly CLSC network where the forward network includes suppliers, plants, retailers, and customers, and reverse network includes collection centers, disassembly centers, refurbishing centers, and disposal center. The results of this study demonstrated that four SO models have a significant potential to satisfy the customer's needs since average service level of the models is at least 81.8%. The total supply chain cost can be decreased at least 3% and at most 22% on average with proposed continuous review model whose objective is the minimization of differences between the total overordering cost and the total underordering cost (C-D). Furthermore, the total lost sales cost can be improved at least 15% and at most 89% on average with C-D model.

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1. Introduction

Over the past years, companies are facing the ongoing challenge to evaluate and organize their strategies due to the waste and pollution management, government policy and environmental protection, organizational and customer pressures. Many companies need to take a renewed interest about the concept of reverse logistics in supply chain management to remain competitive and manage their business effectively. Reverse logistics include all the activities related to the conversion and the flows of goods and services with their information from original sources to final consumers [1]. Review of the related literature shows that reverse logistics can be divided into recovery network and closed-loop network. First case fully concentrates on recovery activities [2]. Recovery network includes the collection of used products from the customer back to the supply chain, reprocessing and redistribution of products. Typical examples of recovery networks include customers, collection centers, disassembly centers, refurbishing centers, and remanufacturing. In second case, forward and reverse networks are integrated to avoid the sub-optimality resulting from separated design [3]. Typical examples of closed-loop network include suppliers, manufacturing, distribution centers, retailers, customers, collection centers, disassembly centers, refurbishing centers, and remanufacturing. The present study is to propose a closed-loop supply chain (CLSC) network and to provide recommendations on the management of a closed-loop network. CLSC can be defined as “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” [4]. The sample structure of CLSC is presented in Figure 1 for wood industry.

Insert Figure 1.

Companies are seriously exploring the correct strategy to manage complex, multifaceted, and nuanced issues in CLSC. Although each supply chain has its own characteristics, proposed methods should provide satisfying information to solve the problem of each supply chain. Adaptable methods which are reasonably detailed and accurate in representing the complexity and uncertainty are the core of complex CLSC problems. There is a need to use them in order to overcome the challenges of satisfying the rapidly changing needs. In this context, companies force researchers to create adaptable supply chain. Note that adaptability can be defined as an ability of a supply chain system to vary the behavior of supply chain system to preserve, improve, or obtain the new characteristics for satisfying the supply chain goal in the conditions of environment changing in time, the priori information about which is incomplete [5].

Due to the environmental concerns, economic benefits, and regulation, CLSC became an important topic for researchers and managers. In literature, many analytical methods are available to solve the CLSC. However, stochastic environment should be taken into account to provide a much more realistic solution methodology. At this point, simulation optimization (SO) undoubtedly plays a remarkable role because of its capability and its adaptability to supply chains. Unlike other SO methodologies for CLSC studies, we created a new adaptable SO to cope with the difficulties of CLSC problems under stochastic environment and lost sales option with periodic/continuous review system and compared the proposed methodology considering two different objective functions. SO is an umbrella term for methods used to handle all the dynamically changing CLSC variables [6]. A comprehensive review of SO methods is available in [6]. Although various research papers are available related to SO methods in forward network, reverse network and CLSC network, the analysis results showed that the number of papers published in CLSC should be increased to provide a basis and guidelines for researchers and practitioners to link SO with real-world applications. Aware of the importance of developing an SO method to improve the performance of the companies, we created CLSC network including four supply chain members in forward network and four supply chain members in reverse direction using SO. SO consists of two phases: an optimization phase that searches to determine candidate optimal solutions and a simulation phase that evaluates the performance of candidate solutions. There is no clear methodology available about proposed SO method whose objective is to determine how many and which plants/retailers should be opened, and how the optimal parameters of periodic/continuous review system are determined in literature. To manage, set, and meet expectation about today's CLSC problem, proposed SO model can be easily used as a complementary tool.

2. Literature

Product recoveries at the end of their life cycles are crucial to achieve sustainable business practices. Successful product recovery processes can also be useful to save landfill space by decreasing the amount of total waste. In addition, they reduce the risks of hazardous wastes and conserve energy with component reuse [7]. In this context, the traditional supply chains need to be expanded by CLSC. In literature, many guidelines are available to develop a CLSC and also there are a growing number of interests in providing a general framework for CLSC. A brief review of CLSC models is given in Table 1.

Insert Table 1

Modeling supply chains is hard, especially when the modeling has to take uncertainty into account. In general, two forms of uncertainties are available in supply chain. The uncertainty of linkage is the first one. It is principally related to the interaction or cooperation among supply chain members. The second form of uncertainty is related to the inner operations in supply chain [25]. To restrain the impacts of uncertain environment on CLSC system, Huang et al. [25] presented a class of dynamic models to analyze different system structure of CLSC and considered the three uncertainties related to the time-delay, system cost parameters, and demand disturbances. Shi et al. [26] optimized the profit of the network by integrating three aspects which are inventory control, production, and product acquisition management. Ramezani et al. [1] created a stochastic multi-echelon problem that included single sourcing of customers in CLSC network with multi-level capacities. The study maximized the total profit and customer service level while minimizing the total number of defects. Ramezani et al. [27] integrated strategic decisions with tactical decisions to extend the existing CLSC models where finite scenarios were used to define uncertain demand and return rate. Saeedi et al. [28] proposed a De Novo programming with queuing systems to cope with the uncertainty of the parameters for CLSC.

Fathollahi-Fard et al. [29] presented the multi-period and scenario-based CLSC and employed the multi-objective version of improved social engineering optimizer. Life cycle assessment based methodology was also applied to estimate the sustainability aspects. Samuel et al. [30] investigated the implications of the quality of returns on the CLSC network under the different carbon policies using a deterministic mathematical model and its robust version. Bhatia et al. [31] described and analyzed critical factors for the implementation of CLSC in the Indian automotive sector. The cause and effect group of factors, as well as the cause-effect relationships between them were investigated. In the CLSC, Govindan et al. [32] firstly evaluated and selected the circular suppliers and then allocated optimal orders. In addition, demand uncertainty was taken into account in the CLSC using heterogeneous vehicles. Uncertainties have significantly increased the challenge of model optimization and the complexity of CLSC management. Peng et al. [33] reviewed previous research on the uncertainties that are inherent in a CLSC. New versions of CLSC models exploit more factors addressing the real situation [34] such as sustainable CLSC [35], resilient and sustainable CLSC [36], and green CLSC with profit sharing contract [37].

From the literature it is clear that many works addressed the CLSC network problem. Exact methods have proved to be one of the most widely used methods in supply chain. On the other hand, complex real world problems are generally not solvable with exact methods in a reasonable amount of time. At this point, heuristics/metaheuristics methods can be used to determine good solutions with less computational effort in a reasonable amount of time. Furthermore, simulation is an important tool to model and evaluate the CLSC. Hybrid methods can also be used since it combines the advantages of used methods. Therefore, we employed the SO to cope with highly complex and nonlinear CLSC problem. The reality of CLSC is generally much more complex than corresponding forward network problems [38] since reverse network provides ill-known parameters influencing the forward network and therefore making the entire supply chain environment uncertain [21]. Hence, simulation is coupled with optimization model that orchestrate the simulation of a sequence of system configurations to provide an optimal or near optimal solution [39].

In the area of forward/reverse/CLSCs SO models are still being investigated by relatively few researchers. For example, Zhou and Xue [40] proposed a SO model that integrates the simulation model and the Genetic Algorithm (GA) to evaluate reverse logistics problem in the context of emergency. Shokohyar and Mansour [41] developed a sustainable recovery network where social, environmental, and economical objectives are considered simultaneously to manage total waste from electrical and electronic equipment in Iran. Zolfagharinia et al. [42] developed a hybrid solution method that integrated discrete event simulation and meta-heuristic algorithm to determine optimal solution for inventory control problem.

Due to its ability of capturing the high complexity of CLSC issues, SO can be efficiently used to cope with the stringent pressures from today’s companies. The main contribution of this paper is to ensure a remarkable solution for CLSC problem and to promptly cope with any changes in forward and reverse supply chain network. Basically, this paper also serves the following purposes:

(1) create adaptable SO method to provide a general guideline on creating forward and reverse supply chain network under fully uncertain and dynamic environment and lost sales option,

(2) employ SO method to address a new CLSC problem where optimal values of inventory control parameters and the number of facilities (e.g. plants and retailers) to be opened are determined simultaneously while using both periodic/continuous review options separately,

(3) make a decision about the objective of the CLSC network where the minimization of total CLSC cost and the minimization of the differences between the total overordering cost and the total underordering cost are taken into account.

(4) make possible for practitioners and theoretical researchers to analyze CLSC and to be helpful for further insight into CLSC.

(5) present whether a difference among supply chain members are available when forward and reverse supply chain network are taken into account.

3. Problem Definition

The suppliers are responsible for supplying the components to the plants. Plants produce end-products based on returned components (i.e., purchased from refurbishing centers) and new components (i.e., purchased from suppliers). Also, collection centers send a percentage of products directly to plants. Note that the plants in the CLSC network produce homogeneous end-products; the output of one plant cannot be distinguished from the others. Thus, there is no perceived quality depreciation of end-products made from returned and new components as well. Then, end-products are sent from plants to retailers on demand. In the next part of the network, they are carried to customers. The proposed system is given in Figure 2 where v denotes the ratio of products that are transferred to plants and $1-v$ denotes the ratio of products that are transferred from collection centers to disassembly center. *y* represents the ratio of products that are transferred from disassembly centers to disposal. *1-y* represents the ratio of products that are transferred from disassembly centers to refurbishing centers.

Insert Figure 2.

SO models are used to determine which plant/retailer should be opened based on the defined objective function. Furthermore, proposed models are utilized to determine the inventory control parameters of plants and retailers. The inventory level in each plant and each retailer is controlled using periodic and continuous (s, S) policy where s denotes reorder point and S represents the order-up-to level. In periodic (s, S) policy, inventory levels of all plants and all retailers are all inspected at every R time units where R is a fixed constant and assumed to be 5 days. In continuous (s, S) policy, a replenishment order is placed to increase the product's inventory level to the order-up-to level (S) when this inventory level reaches or drops below the reorder point (s). Unsatisfied demands are lost. The same principle is applied to plants. Retailer's replenishment order is met according to the inventory level of plants and unsatisfied demands are considered as lost sales.

In this paper, components are sequentially pushed into plants, synchronizing with occurrence of reverse. Therefore, returned products and remanufactured products would be kept as inventory in plants. Inventory is not considered for reverse network. The distribution of the customer order quantity at retailers has a Poisson distribution with a rate parameter of 50. Also, we assumed that customer arrival at retailers is 1 per day. The other parameter values related to retailers and plants are all given in Table 2. In addition, transportation cost is proportional to the unit transportation cost, the transportation time, and the order quantity at each shipment (see, Appendix D) for each supply chain member. Unit transportation cost is assumed to be $ Uniform (0.75, 3.00). To model the supply chain members, the cost components' values are obtained from the knowledge and experience of researchers.

Insert Table 2

The general optimization problem is briefly described as follows.

$$min\ F = f\left(X\right) \tag{1}$$

$$X \in \Omega \tag{2}$$

X can be continuous or discrete variables. It is a vector with n unknown decision variables. X indicated as $[x_1, x_2, ..., x_n]^T$. Ω denotes a problem space and F is a real value in a real area. $f\left(X\right)$ is the objective function and is a map from solution space to a real area. The optimization aim is to explore a solution that minimizes the objective function given in Equation 1-2.

Equality and inequality constraints can also be added as follows in Equation 3-5.

$$h\left(X\right) = 0, \tag{3}$$

$$g\left(X\right) \leq 0 \tag{4}$$

$$X_{min} \leq X \leq X_{max}, \tag{5}$$

X_{min} and X_{max} are minimum and maximum bound of X, respectively.

$h\left(X\right)$ and $g\left(X\right)$ are vector functions, given as in Equation 6-7.

$$h\left(X\right) = \left[h_1\left(X\right), h_2\left(X\right), \ldots, h_{m_1}\left(X\right)\right]^T \tag{6}$$

$$g\left(X\right) = \left[g_1\left(X\right), g_2\left(X\right), \ldots, g_{m_2}\left(X\right)\right]^T \tag{7}$$

$h_i\left(X\right)$ and $g_i\left(X\right) \forall i$ are first order continuous differentiable functions. m_1 and m_2 represent the numbers of equality and inequality constraints. Details about the optimization problem can be found in [43]. In the study, the inventory conservation at the supply chain members is taken as equality constraints. Basic inequality constraints can be summarized as follows: inventories are not allowed to be negative; the inventory at the supply chain members cannot exceed maximum capacity; the reorder point of supply chain members should be smaller than order-up-to level of supply chain members; the demand of customers can be totally met, partially met or lost.

In the proposed CLSC network, two different objective functions are employed to create four SO models. First objective function, called Obj1, minimizes the total CLSC cost. Second objective function, called Obj2, minimizes the difference between the total overordering cost and the total underordering cost. The first SO model represents a periodic review model whose objective is Obj1 and is called (P-T). The second SO model represents a periodic review model whose objective is Obj2 and called (P-D). The third SO model represents a continuous review model whose objective is Obj1 and called (C-T). The fourth SO model represents a continuous review model whose objective is Obj2 and called (C-D). The proposed methods for the CLSC network are given in Table 3.

Insert Table 3 and Table 4

The objective functions are defined using equation (8) or equation (9). Definition of the average holding cost, the lost sales cost, the order cost per use, the order processing cost, and the processing cost are summarized in Göçken et al. [44]. Note that order processing cost for reverse network includes only the order processing cost rate. Parameters and notations used in the CLSC network are summarized in Table 4.

P-D model and C-D model: The minimization of difference between the total overordering cost and the total underordering cost (THL) means that proposed model minimizes the differences between the total average holding cost and the total lost sales cost (Equation 8).

$$THL = \sum_{n=1}^{12}(\mathrm{THL_n}) = \sum_{n=1}^{12}(\sum_{\mathrm{i}=1}^{4}\left(\mathrm{h_i}\,{}^{+}X_i^n - \mathrm{I}\left\{X_i^n \le s_i\right\}\left(\mathrm{k_i}\,{}^{-}X_i^n\right)\right) + \sum_{\mathrm{j}=1}^{4}\left(\mathrm{h_j}\,{}^{+}X_j^n - \mathrm{I}\left\{X_j^n \le s_j\right\}\left(\mathrm{k_j}\,{}^{-}X_j^n\right)\right) \tag{8}$$

P-T model and C-T model: Total CLSC cost (TCC) include the total average holding cost, the total order cost per use, the total lost sales cost, the total order processing cost, the total processing cost, the total transportation cost, the total purchasing cost from collection centers, the total purchasing cost from refurbishing centers, the total purchasing cost from suppliers, the total fixed cost for retailers, and the total fixed cost for plants (Equation 9).

$$TCC = \sum_{n=1}^{12}(\mathrm{TCC_n}) = \sum_{n=1}^{12}(\sum_{\mathrm{i}=1}^{4}(\mathrm{h_i}\,{}^{+}X_i^n + \mathrm{I}\left\{X_i^n \le s_i\right\}\left(\mathrm{k_i}\,{}^{-}X_i^n + p_iP_i + c_i + O_i + T_i + PC_i + PR_i + PS_i + F_i\right)) + \sum_{\mathrm{j}=1}^{4}\left(\mathrm{h_j}\,{}^{+}X_j^n + \mathrm{I}\left\{X_j^n \le s_j\right\}\left(\mathrm{k_j}\right.\right. \tag{9}$$

Collection centers collect the returned products from customers. Products have a triangular recovery ratio to collection centers with endpoints (0.25, 0.35) and mode at 0.30 (Table 2). After testing and inspecting in collection centers, some of them are sent to plants and all others are shipped to disassembly centers where the components are grouped into reusable and unusable components. Products have a triangular transfer ratio from collection centers to disassembly centers with endpoints (0.65, 0.75) and mode at 0.70. At this point, remaining products (triangular distribution with endpoints (0.25, 0.35) and mode at 0.30) are transported from collection centers to plants. Products have a triangular transfer ratio from disassembly centers to refurbishing centers with endpoints (0.75, 0.85) and mode at 0.80. Also, remaining products (triangular distribution with endpoints (0.25, 0.15) and mode at 0.20) are transported from disassembly centers to a disposal center outside of the CLSC. Reusable components are transported to refurbishing facilities to be inspected and refurbished. Finally, they are transferred to plants.

4. Simulation Optimization

The possibilities of integrating simulation and optimization are very diverse in form and the suitable design highly depends on the characteristics of the problem. However, the design of a good interaction is still a problem regarding the study of specific application fields, even for today's standards [45]. General SO problems have three distinctive features. Noisy is the first one. Second important characteristic is computationally expensive. In SO, evaluation of each objective function needs simulation replications, and may be very time consuming and computationally expensive when a complex and large scale simulation model is involved. Finally, there is generally little or no mathematical expression to exploit due to the complex model logic [46]. To overcome these challenges, it is crucial to have a comprehensive overview of the simulation and optimization models. An extensive overview of the full spectrum of simulation and optimization models is given in [45].

System design and implementation of CLSC under uncertainty can be extremely difficult to promote many issues in the network. However, SO models can capture all the details in CLSC and incorporate every aspect of uncertainty in the network without any limitations and assumptions. At this point, determining high-quality solutions in the context of SO has a critical importance and GA can be successfully used to optimize multimodal, discontinuous, and non-differentiable functions for that purpose [47]. GA is a family of randomized search procedures [48]. The main characteristic of GA is the simultaneous evaluation of many solutions [49]. In this study, a simulation model is coupled with GA to optimize designs and operations of forward and reverse networks in the supply chain. GA has been widely adopted in various problems due to its proven effectiveness (see [50-53] for detail). Azadivar and Tompkins [48] presented that GA does not require operating in a geometrically identified solution space unlike other SO methods.

In GA, chromosome structure is firstly defined to present a set of parameters. First part of the chromosome denotes facilities (plants and retailers) to be opened. Thus, we determine which retailer is used to meet customer's orders and which plant is used to satisfy retailer's replenishment order. The second part of the chromosome denotes the determination of the initial inventory, reorder point, and order up-to level of each plant and each retailer. Also, inventory level of components is defined in the second part to determine the replenishment point for plants (Figure 3).

Insert Figure 3.

In GA, selection, crossover, and mutation operators are repeatedly employed to create new chromosomes. After preliminary runs the values of population size, number of iterations, crossover rate, and mutation rate is set to be 20, 200, 0.8, and 0.05, respectively. Tournament is used as the selection operator. It is better than other selection operators because it does not use fitness function directly. The working principle of tournament selection and a clear description of its advantages can be found in [54].

In SO model, GA alters decision variables to explore the solution space and the simulation model evaluates each solution performance. The proposed model is initialized by running GA to determine the optimal parameters in CLSC network. GA generates a new set of solutions and feeds these back to the simulation model. This process of generating and evaluating solutions continues until predetermined termination criteria are satisfied. The proposed SO model is given in Figure 4.

Insert Figure 4.

In this study, simulation models are developed by using Simio (Version: 7.121.12363), GA is coded by using C# (Visual Studio Community 2015). Simio centers around intelligent objects and provides a new object-based paradigm that radically changes the way objects are built and used [55]. Briefly, the characteristics of our simulation model are summarized as follows:

Insert Figure 5.

- Single product flows through the chain. Product consists of three components that have different utilization rates (Figure 5).
- The model considers multi-period.
- Proposed model is used to determine how many and which plants/retailers should be opened. However, the locations of supply chain members are known and fixed.
- The amounts of returned products through the reverse network in each time period are stochastic.
- The remanufactured products and the new products are indistinguishable to the customer. There is no perceived quality depreciation of end-products made from returned and new components as well.
- Periodic or continuous (s, S) policy is used to control inventory level of plants and retailers. According to periodic review (s, S) policy, inventory level of plants and retailers are fulfilled until the order up to level (S) whenever it lowers to a value less than or equal to the reorder level (s) at the beginning of each review period. According to continuous (s, S) policy whenever the inventory level falls below the reorder level (s), an order is made to increase the inventory level until the order-up-to level (S) is reached.
- Inventory is not allowed at the reverse network.
- Transfer times are assumed to be stochastic.

5. Results and Discussion

In this paper, we presented that designing and modeling of CLSC problem can be efficiently made using SO models since a large number of properties are easily incorporated into models to cope with uncertainty in decision making environment. Proposed GA based SO models determine appropriate plant/retailer to achieve more profits and higher customer service level together. Note that the convergence characteristics of GA for proposed methods are given in Figure 6. In addition, the inventory control parameters of plants and retailers are identified to reduce lost sales in forward network. Note that inventory of reverse network is not taken into account due to the push-type strategy. The scale of this study is as follows: four plants, four retailers, two collection centers, two disassembly centers, two refurbishing centers. Selected plants and retailers for each model and theirs determined inventory control variables are given in Table 5. Note that the order-up-to levels of most of the supply chain members are significantly less for the C-D model. Suppliers have the responsibility to manage the inventories of the plants, given that the information about inventory level of components is accessible. Suppliers decide about the plant's replenishment quantity and replenishment point. Plant's replenishment time is determined according to the inventory level of component 1.

Insert Figure 6

Insert Table 5

A replenishment order is placed to increase the inventory level of components including component 1, component 2, and component 3 when inventory level of component 1 reaches or drops below the point that is determined by proposed models as given in Table 5. Note that either component 1 or component 2 or component 3 can be considered for this purpose since there is no matter in which component is selected. After replenishment order is placed, replenishment quantity for component 1, component 2, and component 3 is determined using uniformly distributed number between 0 and 500. To remain competitive in today's condition, companies force themselves to meet customer needs better than their competitors. At this point, average service level that can be easily used to evaluate companies is frequently incorporated into the decision making process. Average service level (Equation 10) is defined as the ratio of current inventory level in retailer/plant to the number of units ordered by the customers/retailer over total number of incoming orders (see Table 5). Simulation is run over a one-year period and consists of 20 replications. Average of 20 replications' results is used to evaluate the performance of plants and retailers over periods.

$$Average\,service\,level = \sum_{a=0}^{Per\ Arrival} \min\left(1,\ \frac{Current\ Inventory\ Level}{Incoming\ Order\ Quantity}\right) / \,Total\ Number\ of\ Incoming\ Orders \qquad (10)$$

Insert Table 6

To help shape the future policy for companies, controlling cost components affecting CLSC network is important. The values and shares of cost components are given in Table 6. P-T model and P-D model have higher TCC than C-T model and C-D model. C-D model has the lowest TCC while P-T model has the highest TCC. The largest share for P-T model is the lost sales cost. The largest share for P-D model, C-T model, and C-D model is the purchasing cost from suppliers. Pie chart analysis of cost share for proposed methods is also given in Figure 7. Each number in Figure 7 represents one cost component that is given in Table 6.

Insert Figure 7

5.1. Forward network analysis

The complexities and uncertainties in companies have motivated researchers to search for competitive advantages considering SO. Especially, SO model based inventory control and supplier selection is of vital importance for companies' success since supply chain members should be replenished without hurting the level of product availability. For a more detailed performance analysis of SO models, quantity-based analysis (totally met order quantity

(TMOQ), totally lost order quantity (TLOQ), and partially lost order quantity (PLOQ)), probability based analysis (order met probability (P1) (Equation 11) and overall order met probability (P2) (Equation 12)), order-based analysis (number of totally met orders (NTMO), number of totally lost orders (NTLO), and number of partially lost orders (NPLO)) are analyzed over twelve periods (Table 7).

$$P1 = \int_{n-1}^{n} \min\left(1, \frac{Current\,Inventory\,Level}{Incoming\,Order\,Quantity}\right) dt \qquad (11)$$

$$P2 = \int_{0}^{n} \min\left(1, \frac{Current\,Inventory\,Level}{Incoming\,Order\,Quantity}\right) dt \qquad (12)$$

Cost analysis of Plant 1 showed that the largest share is the lost sales cost for P-T Model, P-D Model, and C-T Model. On the other hand, the largest share of Plant 1 with C-D Model is the average holding cost. Although the values of TLOQ and NTLO are zero for all models at Plant 1, the total value of PLOQ can be improved with C-D model.

Insert Table 7

Cost analysis of Plant 2 showed that the largest share is the average holding cost for P-D Model and C-D Model. On the other hand, the largest share of Plant 2 with C-T Model is the processing cost. Although the values of TLOQ and NTLO are zero for all models in Plant 2, the total value of PLOQ can be decreased with C-D model.

Cost analysis of Plant 3 showed that the largest share is the average holding cost for P-T Model while the largest share is the lost sales cost for C-D Model. Although the values of TLOQ and NTLO are zero for C-D model and P-T model in Plant 3, the total values of PLOQ and NPLO can be improved with P-T model.

For Plant 4, the largest share is the lost sales cost for P-T Model and P-D Model. Although the values of TLOQ and NTLO are zero for P-T model and P-D model in Plant 4, the total value of PLOQ can be improved with P-D model.

For Retailer 1, the largest share is the lost sales cost for P-T model and P-D model. However, P-D model can be selected to decrease the total lost sales cost of Retailer 1. Furthermore, P-D model decreases the total value of TLOQ, PLOQ, NPLO, and NTLO of Retailer 1 when compared with P-T Model.

The analysis of Retailer 2 showed that the largest share is the order processing cost for P-T model, C-T Model, and C-D Model. On the other hand, the largest share of Retailer 2 with P-D Model is the lost sales cost. C-D model seems to be a better option for Retailer 2 to improve responsiveness since C-D model reduces the total value of TLOQ, PLOQ, and NPLO at Retailer 2.

For Retailer 3, the largest share is the order processing cost for C-T Model and C-D Model. On the other hand, the largest share of Retailer 3 with P-D Model is the average holding cost. C-D model seems to be a better option for Retailer 3 to meet all incoming orders.

For Retailer 4, the largest share is the order processing cost for C-D Model. On the other hand, the largest share of Retailer 4 with P-T Model is the lost sales cost. C-D model reduces the total value of TLOQ, PLOQ, NPLO, and NTLO of Retailer 4 when compared with P-T Model.

5.2. Reverse network analysis

The growing need for product recovery due to the increasing economic gains while protecting the environment requires companies to consider reverse networks in their supply chains. In our proposed supply chain, a reverse network begins with a collection center that is used to collect the returned products from customers. Since customer demands are stochastic, the occurrence of returned products is also stochastic.

The analysis of collection center 1 (C1) and collection center 2 (C2) including number of incoming orders per period and quantity of incoming products per period are given in

Appendix A1. The number and quantity of incoming products over twelve periods vary with respect to model types and collection centers.

The analysis of disassembly center 1 (D2) and disassembly center 2 (D2) including number of incoming orders per period, quantity of incoming products per period, and quantity of disposed products per period are given in Appendix A2.

Incoming products are disassembled in D1 and D2 according to the BOM structure that is given in Figure 5, and then reusable components are sent to refurbishing center 1 (R1) and refurbishing center 2 (R2) where components are tested and refurbished. Analysis of refurbishing centers is given in Appendix A3 where the number of incoming components per period and the quantity of incoming components per period are given.

5.3. Lead time based analysis

To provide more useful information, the lead time related statistics are evaluated. Taking into account the stochastic lead times further increase the importance of these statistics. Note that, at some periods there will be no replenishment orders for both plants and retailers, denoted as "-" in following sections.

5.3.1. Analysis of average holding unit

Table 8-9 summarizes the average holding unit that is hold at both plants and retailers during the lead time periods. Considering all Plants with all types of models the average holding unit varies between 10 units and 348 units. However, the average holding units of Retailers vary between no unit and 217 units.

Insert Table 8 And Table 9

5.3.2. Analysis of lead time over period

The minimum length of lead time period for Plants is observed at Plant 3 with P-T Model (i.e., 0.43 hours of related review period) and the maximum length of lead time is observed at Plant 2 with C-T Model (i.e., 205.56 hours of related review period) (see Appendix B1). Also, the minimum length of lead time period for Retailers is observed at Retailer 2 with C-D Model (i.e., 37.69 hours of related review period) and the maximum length of lead time period is observed at Retailer 2 with P-T Model (i.e., 71.62 hours of related review period) (see Appendix B2).

The total length of lead time over 12 periods for Plants varies between 474.3 hours (P-D Model for Plant 2) and 2167.14 hours (C-T Model for Plant 2). For Retailers, the total length of lead time over 12 periods varies between 484.27 hours (Retailer 2 with C-D Model) and 833.96 hours (Retailer 2 with P-T Model). Such a large gap between minimum and maximum values shows the importance of taking stochastic behavior of the system into account.

5.3.3. Analysis of order met probability

Order met probability per lead time period (OMPL) is computed by using the following Equation 13.

$$\int_{n}^{end\ of\ lead\ time} \min\left(1, \frac{Current\ Inventory\ Level}{Incoming\ Order\ Quantity}\right) dt \tag{13}$$

The OMPL is generally high for almost all Plants (see Appendix C1). The OMPL for Plants is at most 1 which means that 100% of incoming orders met during the lead time period. The minimum OMPL for Plants is observed at Plant 4 with P-T Model as 0.673 which means that 32.7% of incoming orders were lost during that lead time period. The OMPL for Retailers is at least 0.032 (P-D Model for Retailer 2) and at most 1 (see Appendix C2).

It can be said that OMPL should be improved for some Retailers to increase the customer satisfaction. High OMPL can be achieved by using continuous review policy (especially the C-D Model) for Retailers.

Controlling inventory during the lead time period is important to achieve both strategic and tactical success in inventory management. On the other hand, modeling of inventory control systems in a stochastic environment needs too much computational effort to solve and sometimes they are not solvable in reasonable time. Therefore, we used SO model to provide a significant opportunity to respond effectively in dynamic and stochastic problems.

6. Conclusion

To integrate the forward network and reverse network, we designed SO models that capture many issues concerning complex real-world problems simultaneously. Due to its ability to mitigate difficulties, SO has become a remarkable option to establish a reliable network of CLSC under today's stringent pressures. In this study, controlling inventory level and determining appropriate CLSC members to be opened is considered to improve the performance of the CLSC network. We used four suppliers, four plants, four retailers, two collection centers, two disassembly centers, and two refurbishing centers to give a detailed analysis of CLSC network.

Numerical results showed that the SO model has a significant potential to handle data uncertainty and provides an important guide to researchers and managers throughout the decision making process. According to the cost analysis, the TCC of P-T model can be improved approximately 11%, 20%, and 22% with P-D model, C-T model, and C-D model, respectively. In addition, the TCC of P-D model can be improved approximately 10% and 12% with C-T model and C-D model, respectively. The TCC of C-T model can be improved approximately 3% with C-D model.

According to the quantity-based analysis, the total value of PLOQ with P-T model can be improved approximately 40%, 68%, and 76% with P-D model, C-D model, and C-T model, respectively. In addition, the total value of PLOQ with P-D model can be improved approximately 47% and 59% with C-D model and C-T model, respectively. The total value of PLOQ with C-D model can be improved approximately 23% with C-T model.

According to the quantity-based analysis, the total value of TLOQ with P-T model can be improved approximately 48%, 95%, and 99.98% with P-D model, C-T model, and C-D model, respectively. In addition, the total value of TLOQ with P-D model can be improved approximately 90% and 99.96% with C-T model and C-D model, respectively. The total value of TLOQ with C-T model can be improved approximately 99.57% with C-D model.

According to the order-based analysis, the total value of NPLO with P-T model can be improved approximately 23%, 62%, and 66% with P-D model, C-T model, and C-D model, respectively. In addition, the total value of NPLO with P-D model can be improved approximately 50% and 57% with C-T model and C-D model, respectively. The total value of NPLO with C-T model can be improved approximately 12% with C-D model.

According to the order-based analysis, the total value of NTLO with P-T model can be improved approximately 47%, 95%, and 99.57% with P-D model, C-T model, and C-D model, respectively. In addition, the total value of NTLO with P-D model can be improved approximately 90% and 99% with C-T model and C-D model, respectively. The total value of NTLO with C-T model can be improved approximately 92% with C-D model.

In conclusion, this study can convince the majority of researchers and managers to make use of SO model due to the high service level. In addition, proposed SO model can easily be adapted to various problems. Employing sequential SO, alternate SO, and iterative SO to solve the CLSC problems can be considered as a future work. The other good direction for future work can be to take other metaheuristics into account to compare the performances of the SO models.

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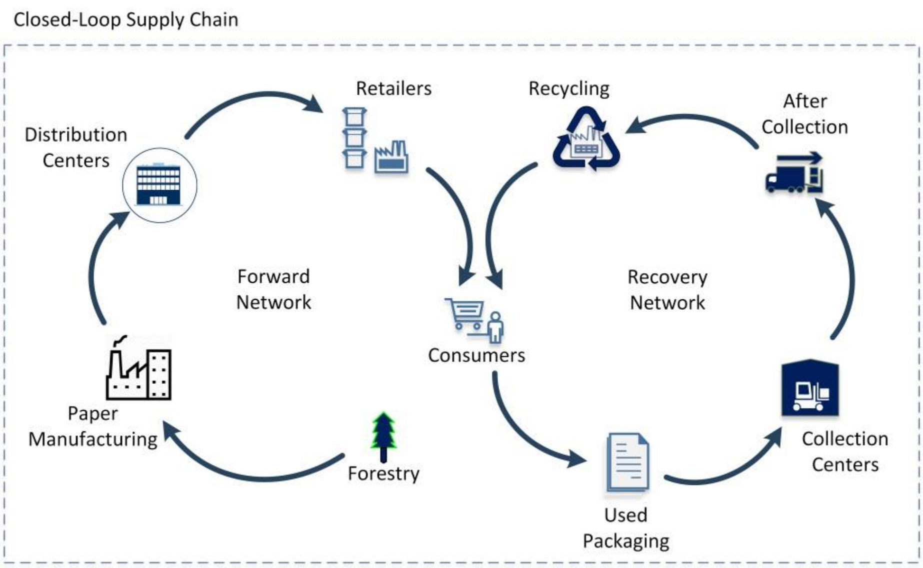


Figure 1. The sample structure of CLSC for wood industry.

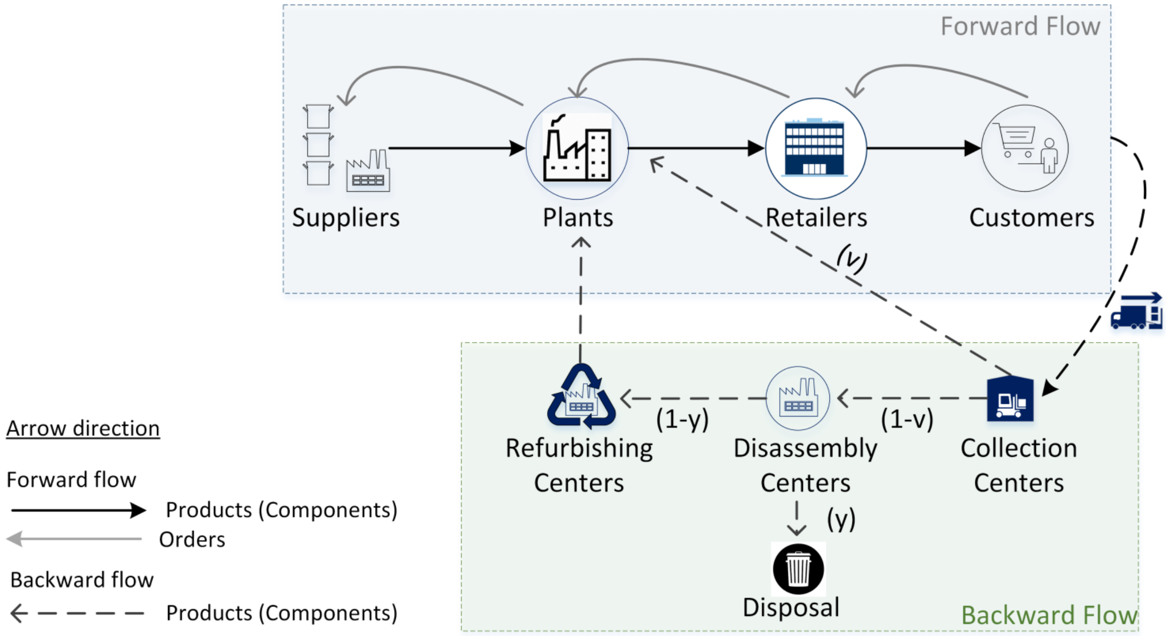


Figure 2. The proposed CLSC network.

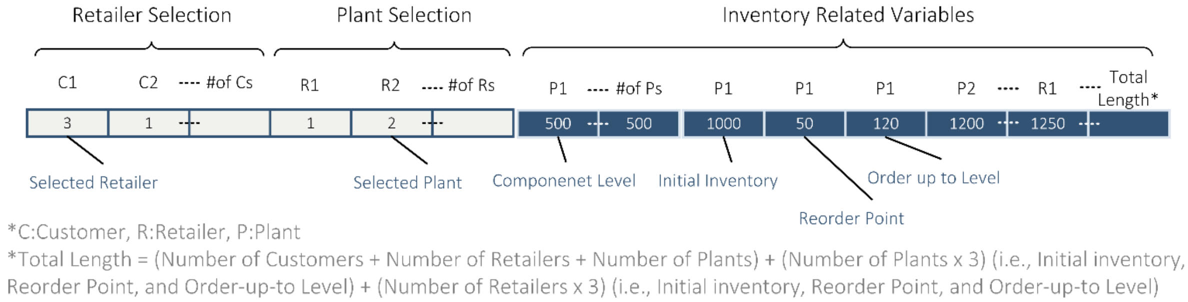


Figure 3. The chromosome structure of the proposed models.

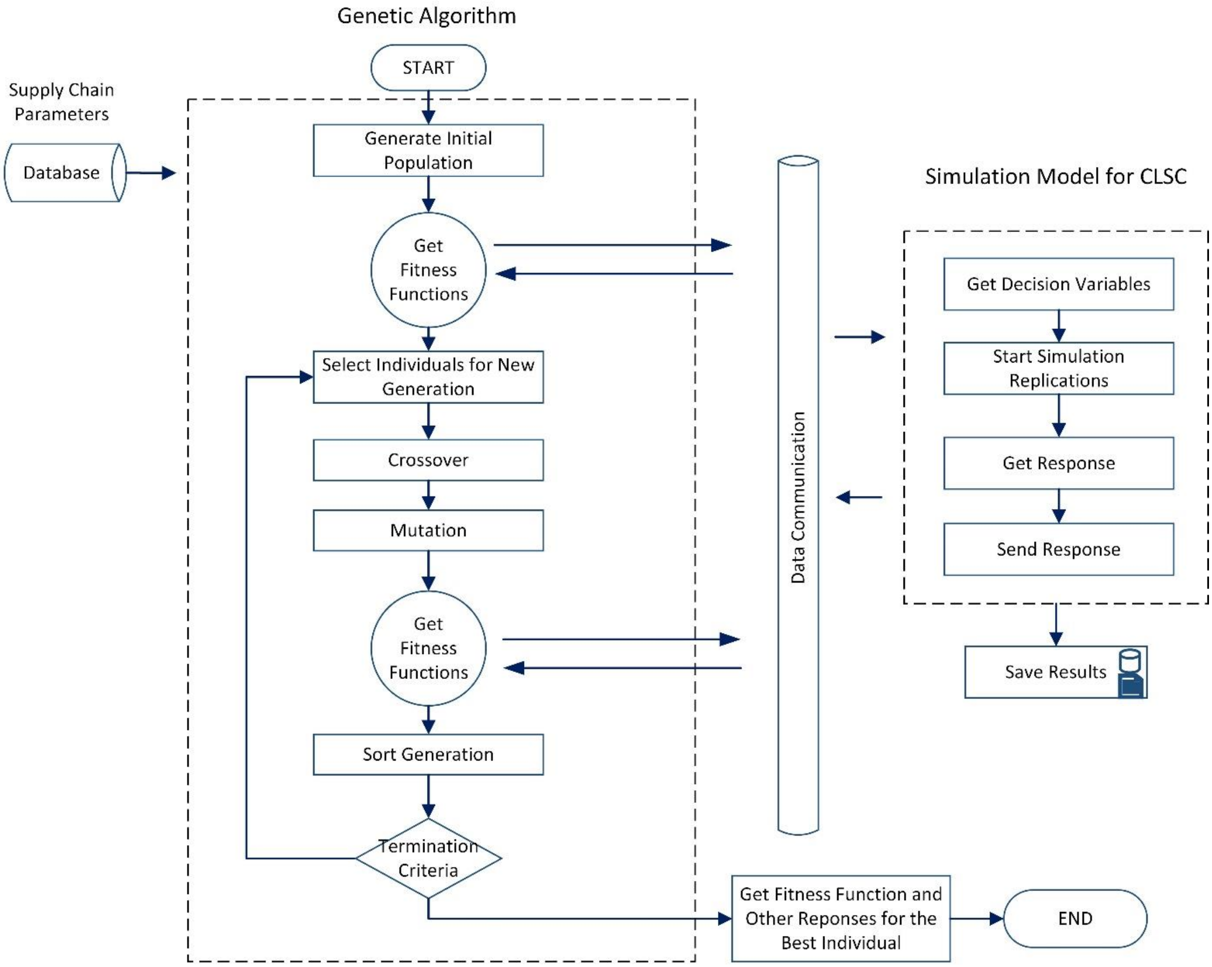


Figure 4. General structure of the proposed model.

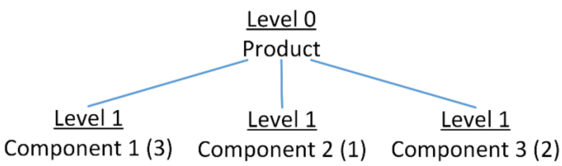
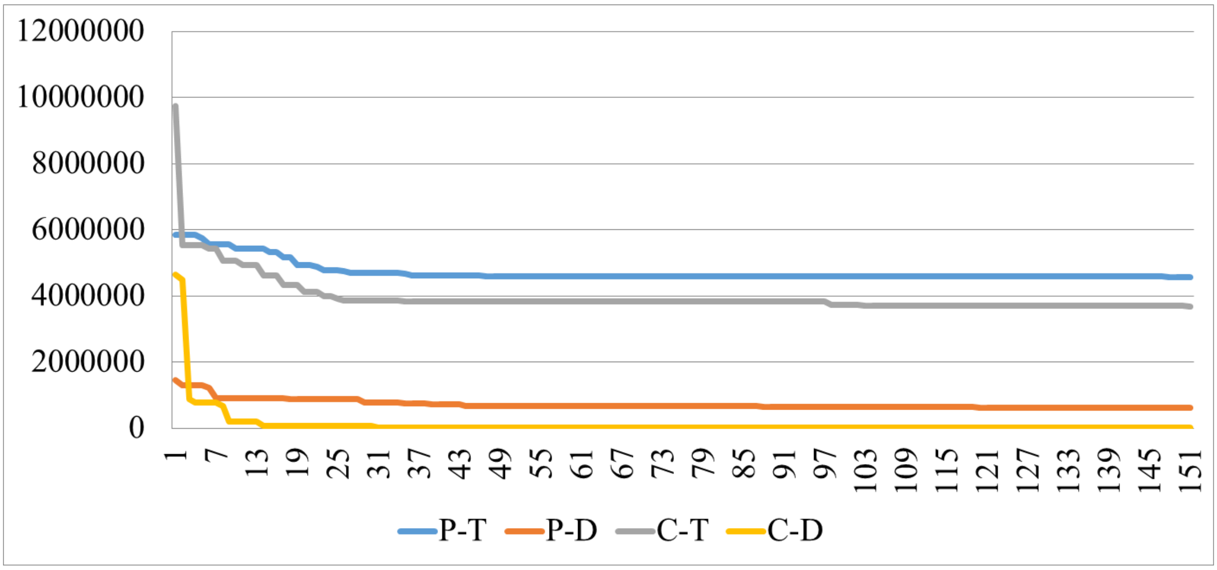


Figure 5. Bill of materials (BOM) of a product.



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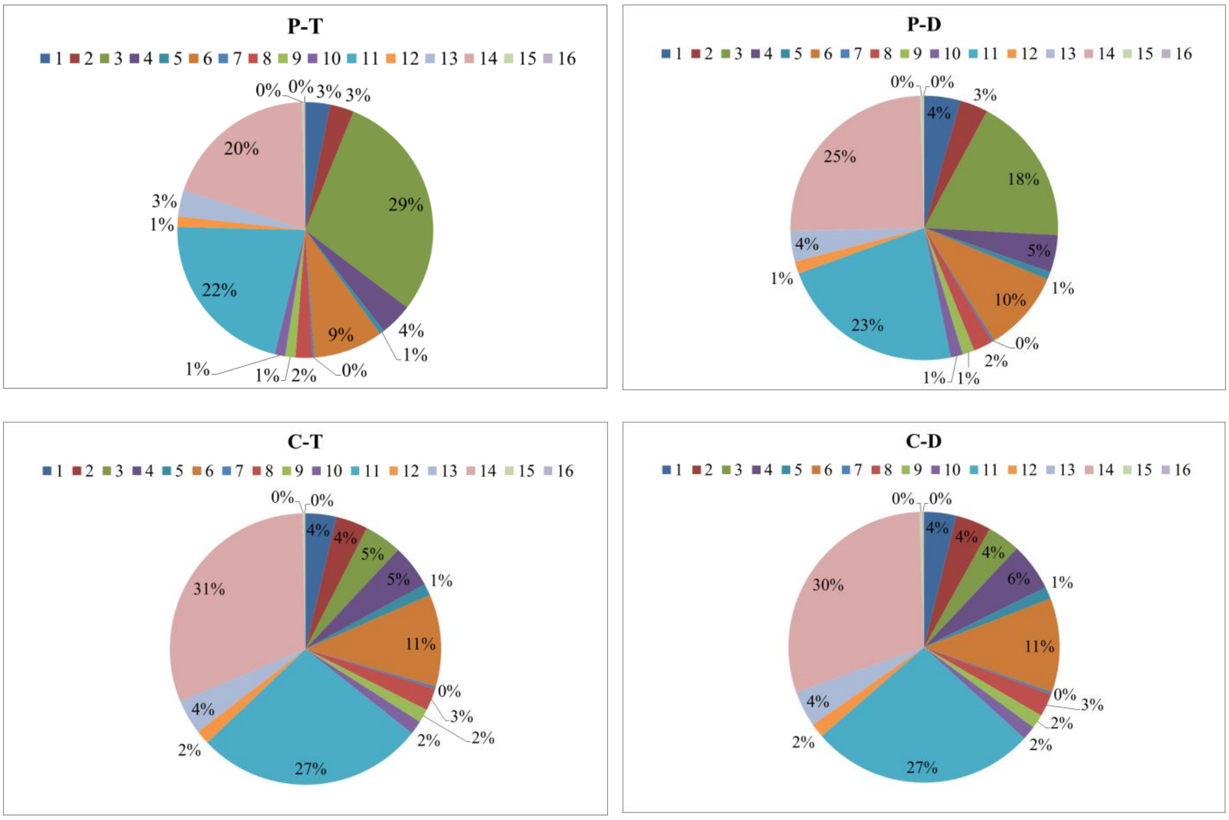

Figure 7. Pie chart analysis of cost share for proposed methods.

Tables

Table 1. A review of CLSC models.

Author (s)	Forward Supply Chain Member	Reverse Supply Chain Member	Solution Method	a*	b*	c*	d*	e*	f*	g*
Zeballos et al. [8]	Factories, Warehouses, Customers	Sorting Centers	Mixed Integer Linear Programming		√		√		√	
Özceylan and Paksoy [9]	Raw Material Suppliers, Plants, Retailers, Customers	Collection Centers, Disassembly Centers, Refurbishing Centers	Mixed Integer Programming		√		√	√		
Amin and Zhang [10]	Plants, Demand Markets	Collection Centers, Disposal Center	Mixed Integer Linear Programming	√			√		√	√
Kalaitzidou et al. [11]	Generalized Production/ Distribution/Recovery/Re-Distribution	Traditional Collection, Redistribution Centers	Mixed Integer Linear Programming		√		√	√		
Govindan et al. [12]	Hybrid Manufacturing Facility, Warehouse, Distribution Center	Collection Center, Hybrid Recovery Facility	Mixed Integer Linear Programming		√		√	√		√
Özceylan et al. [13]	Subassembly Suppliers, Assemblers, Retailers, Customers	Collection Centers, Refurbishing Centers, Disassemblers, Disposal Location	Mixed Integer Nonlinear Programming		√	√		√		
Hasani et al. [14]	Suppliers, Manufacturers, Warehouses/Distributors, Wholesalers	Collection/Recovery Facilities, Wholesalers	Mixed Integer Nonlinear Programming Model, Memetic Algorithm		√		√		√	
Zhalechian et al. [15]	Suppliers, Distribution Centers, Retailers	Distribution Centers, Retailers, Potential Remanufacturing Centers	Mixed-Integer Nonlinear Programming, Self-Adaptive Genetic Algorithm and Variable Neighborhood Search Algorithm		√		√		√	√
Zohal and Soleimani [16]	Suppliers, Manufacturing Facilities (Factories), Distribution Centers	Collection Centers, Recycling Centers, Disposal Centers	Integer Linear Programming Model, Ant Colony Optimization	√		√		√		√
Keyvanshokooh et al. [17]	Manufacturing/Remanufacturing Centers, Distribution Centers, Retailers	Collection Centers, Disposal Centers	Hybrid Robust Stochastic Programming		√	√			√	
Jeihoonian et al. [18]	Suppliers, Manufacturing Facilities, Distribution	Collection Centers, Disassembly Centers, Bulk Recycling	Accelerating Benders Decomposition	√		√			√	

	Centers, End-Users	Centers, Disposal Centers, Material Recycling Centers, Remanufacturing Centers								
Özkır and Başlıgil [19]	Suppliers, Plants, Distribution Centers, Customers	Collection Points, Reverse Centers, Recovery Facilities	Fuzzy Multiple Objective Optimization		√		√		√	√
Vahdani et al. [20]	Raw Material Suppliers, Iron and Steel Facilities, Metal Manufacturing Facilities, Distribution Centers, Customer Zones	Collection Centers, Steel Scrap Processing Facilities	Interval Fuzzy Possibilistic Chance-Constrained Model				√		√	√
Jindal and Sangwan [21]	Raw Material Suppliers, Plants, Distributors, Retailers, Customers	Collection/Repair Centers, Disassembly Centers, Refurbishing Centers, Recycling Centers, Disposal Centers	Fuzzy Mixed Integer Linear Programming	√			√		√	
Amin and Baki [22]	Suppliers, Plants, Distribution Centers, Markets	Collection Centers, Disposal Center	Corley Model, Fuzzy Programming		√		√		√	√
Moghaddam [23]	Suppliers, Manufacturing/Refurbishing	Manufacturing/Refurbishing, Disassembly, Disposal Facilities	Hybrid Monte Carlo Simulation Integrated with Goal Programming				√	√		√
Dai and Zheng [24]	Raw Material Suppliers, Manufactures, Distributor Centers, Customer Zones	Collection Centers, Decomposition Centers	Monte Carlo Simulation with Hybrid Genetic Algorithm, Fuzzy Programming and Chance-Constrained Programming		√		√		√	
Proposed method	Suppliers, Plants, Retailers, Customers	Collection Centers, Disassembly Centers, Refurbishing Centers, Disposal Center	SO method		√		√		√	

***a-Single Period, b-Multiple Period, c-Single Product, d-Multiple Product (components), e-Deterministic Parameters, f-Uncertain (Random) Parameter, g-Multi-Objective**

Table 2. The parameter values of supply chain members.

Plants	Retailers
Fixed Cost: \$ Uniform(3000, 5000) Order Cost Per Use: \$ Uniform(50,100) Unit Lost Sales Cost: \$ Uniform(80, 100) Order Holding Cost Rate: \$ Uniform(5,10) Cost per Use: \$ Uniform(10,20) Processing Cost Rate: \$ Uniform(5,10) Average Holding Cost: \$ Uniform(2,5) Purchasing Cost (From Suppliers): \$ Uniform(40,50) Purchasing Cost (From Refurbishing): \$ Uniform(8,10) Purchasing Cost (From Collection): \$ Uniform(5,8) Processing Time: Triangular(3,5,7) minutes Order Processing Time: Uniform(2,5) hours	Fixed Cost: \$ Uniform(2000, 3000) Order Cost Per Use: \$ Uniform(50,100) Unit Lost Sales Cost: \$ Uniform(80, 100) Order Holding Cost Rate: \$ Uniform(5,10) Cost per Use: \$ Uniform(10,20) Processing Cost Rate: \$ Uniform(5,10) Average Holding Cost: \$ Uniform(2,5) Processing Time: Triangular(1,2,3) minutes Order Processing Time: Uniform(2,5) hours
Collection Centers, Disassembly Centers & Refurbishing Centers	
Processing Time: Triangular(1,2,3) minutes Collection/Disassembly/Refurbishing Cost: Uniform(2,5) Processing Cost Rate: Uniform(5,10) Ratio from Customers to Collection Centers: Triangular (0.25,0.3,0.35) Ratio from Collection Centers to Disassembly Centers: Triangular (0.65,0.7,0.75) Ratio from Collection Centers to Plants: Triangular (0.25,0.3,0.35) Ratio from Disassembly Centers to Refurbishing Centers: Triangular (0.75,0.8,0.85) Ratio from Disassembly Centers to Disposal Center: Triangular (0.15,0.2,0.25)	

Table 3. The proposed methods for CLSC network.

Model Type	Inventory control system	Objective function
P-T	Periodic Review	Obj1
P-D	Periodic Review	Obj2
C-T	Continuous Review	Obj1
C-D	Continuous Review	Obj2

Table 4. Parameters and notations used in CLSC network.

Parameters	
I	Plants ($i = 1,2,\ldots,I$)
J	Retailers ($j = 1,2,\ldots,J$)
C	Collection Centers ($c = 1,2,\ldots,C$)
D	Disassembly Centers ($d = 1,2,\ldots,D$)
R	Refurbishing Centers ($r = 1,2,\ldots,R$)
N	Set of periods ($n = 1,2,\ldots,N$)
s_i	Reorder point for plant i
s_j	Reorder point for retailer j
X_i^n	Inventory level of plant i at the end of period n
X_j^n	Inventory level of retailer j at the end of period n
${}^{-}X_i^n$	Unmet customer order quantity of plant i at the end of period n
${}^{-}X_j^n$	Unmet customer order quantity of retailer j at the end of period n
${}^{+}X_i^n$	Time-weighted average inventory level of plant i over period n
${}^{+}X_j^n$	Time-weighted average inventory level of retailer j over period n
$\mathrm{h_i}$	Inventory holding cost of plant i for each unit of inventory
$\mathrm{h_j}$	Inventory holding cost of retailer j for each unit of inventory
$\mathrm{k_i}$	Lost sales cost of plant i for each unit of stockout
$\mathrm{k_j}$	Lost sales cost of retailer j for each unit of stockout
p_i	Processing cost of plant i

p_j	Processing cost of retailer j
p_c	Processing cost of collection center i
p_d	Processing cost of disassembly center d
p_r	Processing cost of refurbishing center r
P_i	Processing time of plant i
P_c	Processing time of collection center c
P_d	Processing time of disassembly center d
P_r	Processing time of refurbishing center r
P_j	Processing time of retailer j
c_i	Order cost per use of plant i
c_j	Order cost per use of retailer j
O_i	Order processing cost of plant i
O_j	Order processing cost of retailer j
O_c	Order processing cost of collection center c
O_d	Order processing cost of disassembly center d
O_r	Order processing cost of refurbishing center r
$\mathrm{I}\{.\}$	Indicator function of the set
T_i	Total transportation cost of plant i
T_j	Total transportation cost of retailer j
T_c	Total transportation cost of collection center c
T_d	Total transportation cost of disassembly center d
T_r	Total transportation cost of refurbishing center r
PC_i	Purchasing cost from collection center i
PR_i	Purchasing cost from refurbishing center i
PS_i	Purchasing cost from supplier i
F_i	Total fixed opening cost of plant i
F_j	Total fixed opening cost of retailer j

Table 5. Average service levels and inventory control parameters for SO models.

Supply chain member	Inventory control policy	Inventory Level of Component 1	Initial Inventory	Reorder Point	Order-up-to Level	Average service level
Plant 1	**P-T**	1032	963	277	2267	0.968
	P-D	1108	1549	393	2059	0.985
	C-T	539	1008	209	1518	0.986
	C-D	568	904	208	1133	0.995
Plant 2	**P-D**	1308	1485	227	1566	0.978
	C-T	679	1547	244	1518	0.996
	C-D	742	1901	386	800	0.998
Plant 3	**P-T**	1007	1761	303	2433	0.971
	C-D	548	1961	179	680	0.929
Plant 4	**P-T**	1309	1384	325	1300	0.963
	P-D	1549	1297	104	1248	0.951
Retailer 1	**P-T**	-	1839	188	1300	0.818
	P-D	-	1504	227	1629	0.971
Retailer 2	**P-T**	-	1384	319	1175	0.992
	P-D	-	1485	271	2085	0.883
	C-T	-	1464	319	1814	0.986
	C-D	-	1559	334	560	1.000
Retailer 3	**P-D**	-	1504	271	2003	0.992
	C-T	-	1662	231	1815	0.991
	C-D	-	1930	228	647	1.000
Retailer 4	**P-T**	-	1988	325	1329	0.829

C-D	-	1559	303	1437	1.000

Table 6. The values and shares of cost components for CLSC.

	Cost Components	**P-T**		**P-D**		**C-T**		**C-D**	
		Cost ($)	**Share (%)**	**Cost ($)**	**Share (%)**	**Cost ($)**	**Share (%)**	**Cost ($)**	**Share (%)**
1	**Total Average Holding Cost**	142566	3,13	178849	4,39	135073	3,68	136970	3,84
2	**Total Order Cost Per Use**	138344	3,03	137708	3,38	139047	3,79	150619	4,22
3	**Lost Sales Cost**	1331522	29,20	736991	18,10	164918	4,50	140731	3,94
4	**Total Order Processing Cost**	186767	4,10	185716	4,56	187973	5,13	203447	5,70
5	**Total Processing Cost**	27289	0,60	38140	0,94	51044	1,39	51690	1,45
6	**Total Order Processing Cost for Reverse Network**	401406	8,80	401634	9,86	401523	10,95	400982	11,23
7	**Total Processing Cost for Reverse Network**	10826	0,24	10823	0,27	10822	0,30	10826	0,30
8	**Total Collection Cost**	97343	2,13	97428	2,39	97540	2,66	97329	2,73
9	**Total Disassembly Cost**	59840	1,31	59849	1,47	59796	1,63	59835	1,68
10	**Total Refurbishing Cost**	59363	1,30	59393	1,46	59323	1,62	59430	1,66
11	**Total Transportation Cost**	981861	21,53	919228	22,58	998855	27,24	959846	26,88
12	**Total Purchasing Cost From Collection Centers**	60170	1,32	60137	1,48	60225	1,64	60064	1,68
13	**Total Purchasing Cost From Refurbishing Centers**	153333	3,36	153369	3,77	153196	4,18	153419	4,30
14	**Total Purchasing Cost From Suppliers**	889991	19,52	1013020	24,88	1134400	30,94	1066680	29,87
15	**Total Fixed Cost for Plants**	11998	0,26	12047	0,30	8156	0,22	12092	0,34
16	**Total Fixed Cost for Retailers**	7306	0,16	7519	0,18	4835	0,13	7319	0,20

Table 7. The analysis of supply chain members.

Supply chain member	Inventory control policy	Total PLOQ	Total TLOQ	Total TMOQ	Total NPLO	Total NTLO	Total NTMO	Average P1	Average P2
Plant 1	**P-T**	972	0	18602	9	0	15	0.977	0.963
	P-D	787	0	45505	2	0	23	0.988	0.963
	C-T	483	0	33825	1	0	21	0.991	0.971
	C-D	195	0	34247	1	0	30	0.996	0.986
Plant 2	**P-D**	413	0	8850	5	0	5	0.979	0.974
	C-T	214	0	52856	1	0	35	0.999	0.998
	C-D	89	0	34662	1	0	138	0.998	0.998
Plant 3	**P-T**	465	0	12952	5	0	13	0.980	0.990
	C-D	1271	0	9992	18	0	22	0.944	0.964
Plant 4	**P-T**	2211	0	28196	2	0	22	0.976	0.991
	P-D	899	0	3360	9	0	2	0.962	0.967
Retailer 1	**P-T**	570	6087	28844	23	121	576	0.802	0.800
	P-D	191	317	17266	8	6	345	0.972	0.973
Retailer 2	**P-T**	86	43	17679	5	1	355	0.993	0.993
	P-D	594	5738	47084	23	115	941	0.864	0.842
	C-T	298	465	52878	13	9	1058	0.955	0.956
	C-D	2	3	35958	1	1	720	1.000	1.000
Retailer 3	**P-D**	61	83	17773	3	2	356	0.992	0.993
	C-T	206	146	35289	10	3	707	0.984	0.985
	C-D	0	0	18028	0	0	360	1.000	1.000
Retailer 4	**P-T**	599	5612	29300	23	112	585	0.814	0.836
	C-D	4	0	35943	1	0	720	1.000	1.000

Table 8. The Average holding unit of plants.

Period	Plant 1				Plant 2			Plant 3		Plant 4	
	P-T	**P-D**	**C-T**	**C-D**	**P-D**	**C-T**	**C-D**	**P-T**	**C-D**	**P-T**	**P-D**
1	-	95	50	50	-	143	348	-	-	-	-
2	90	227	127	88	100	173	326	180	-	237	84
3	112	225	168	93	100	178	334	96	10	191	86
4	110	228	166	91	113	172	330	92	12	210	87
5	116	235	161	99	129	180	333	-	12	207	80
6	107	229	154	97	142	193	336	93	11	218	73
7	124	228	151	89	109	185	326	52	13	198	79
8	106	233	160	93	126	178	336	104	12	197	82
9	111	224	168	101	139	179	333	-	11	210	78
10	115	232	159	101	131	174	326	96	12	188	78
11	110	240	153	93	121	179	326	78	12	197	79
12	120	232	162	96	128	179	338	99	10	219	74

Table 9. The Average holding unit of retailers.

Period	Retailer 1		Retailer 2				Retailer 3			Retailer 4	
	P-T	**P-D**	**P-T**	**P-D**	**C-T**	**C-D**	**P-D**	**C-T**	**C-D**	**P-T**	**C-D**
1	0	129	61	0	160	212	170	124	-	0	211
2	4	12	101	13	171	210	3	143	156	13	205
3	6	67	99	9	167	213	85	128	156	9	209
4	4	44	107	9	162	205	96	125	155	11	204
5	4	42	102	8	183	214	128	133	161	7	217
6	7	53	86	7	160	210	95	126	157	4	208
7	3	60	102	7	177	207	150	132	153	4	200
8	5	50	127	6	171	217	121	131	153	3	202
9	5	52	96	7	170	214	123	118	153	2	208
10	3	37	123	8	167	205	115	119	156	4	212
11	6	40	95	10	155	210	107	133	155	7	206
12	6	47	113	7	164	208	137	127	153	2	211