A Multi-Objective Mathematical Model for Closed Loop Supply Chain Design

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Abstract

In this paper, a multi-objective mathematical model is proposed for the design of a closed-loop supply chain (CLSC). A mixed-integer linear programming model is developed with environmental concerns. The proposed multi-objective optimization model captures the trade-off between the total cost, total revenue, and the environment impact. The obtained model helps in assessing the trade-off among different objectives and guides the decision makers to choose the preferred plan among the Pareto optimal solutions. The results show that our multi-objective model can be applied as an effective tool in design of closed supply chain. Meanwhile, a valuable sensitivity analysis is conducted to show the impact of variations of demand, return volume, and disposal rate on the network configuration and model performances.

Keywords
Closed loop supply chain; facility location; mixed integer linear programming; multi-objective optimization model.

1. Introduction

Supply chain (SC) is a network of integrated facilities that interact with each other to add value to the final customer. The SC is classified based on the direction of product flow into forward and reverse supply chains. In the forward supply chain, the raw material passed through several activities before it converted to finished products. The facilities involved along forward supply chain are suppliers, factories, distribution centers, and customers. Activities involved along the reverse supply chain are collection and recovery of product returns due to defects. The facilities involved along reverse supply chain are customers, collection centers, factories, and disposal centers. Integrating both supply chains in a single supply chain leads to a forward/reverse logistic network or closed loop supply chain (CLSC). Several models have been published on the area of strategic planning of CLSC. The strategic decisions are the number and location of plants to be established. In general, facility location of CLSC is the activity of making decisions regarding number of plants or centers to be opened and in which location, allocation to each plant, and products to be processed in each opened facility, while satisfying suitable goals and subjected to limitations.

Majority of the published works in this area have focused on formulating a CLSC network design models considering single objective. However, few authors have developed models for CLSC design in a multi-objective framework. The literature review has shown that total revenue has not been yet considered in the designing of multi-objective CLSC network. Therefore, this work is an attempt to fill the above-mentioned gap by developing a multi-objective model considering total cost, total revenue, and environmental impact. Maximization of revenue will result in different optimal plans than maximization of profit. These plans will lead to increase of market share and enhance cash flow; Ghaithan et al. (2017). In addition, maximizing the revenue is important for any firm to pay its financial commitments and contracts. Furthermore, maximizing the environment technology leads to minimize the supply chain emissions. Because of the growth in awareness regarding climate change, companies are enforced to use environmental friendly materials and clean technologies as the conditions for doing business. The proposed model aims to achieve environmental sustainability.

A valuable sensitivity analysis is conducted to study the impact of three key parameters on the optimal network configuration and the three selected objectives/goals. There parameters are demand, return volume, and disposal rate. The disposal rate of products depends on many factors such as products quality, design and production process, transportation and storage mode, and environmental factors. Large disposal rate influence the structure of the CLSC. Therefore, the companies should seriously consider differentiation policy of an early product or redesign their network. The utility of the proposed model is verified using a real case summarized in (Fleischmann et al. 2001).

The rest of this paper is organized as follows: section 2 reviews previous works. Section 3 states and defines the problem followed by the model formulation in section 4. The case study used to demonstrate the model is presented in section 5. The results and sensitivity analysis are explained and conducted in section 6. The paper is concluded in section 7.

2. Literature Review

Supply chain network planning and design address three types of decisions which differ mainly in time horizon; strategic decisions, tactical decisions, and short-term decisions. The strategic decisions are related to configuration of SC such as the opening facilities number and their locations. The tactical level comprises decisions that take time between 6–24 months such as optimize production quantities, while the operational level involves decisions that are done every week and/ or every day. Recently, many attempts to optimize and develop CLSC design models. In this section, a literature survey of the state-of-the-art papers in designing CLSC network is provided. The literature review considers single and multi-objective optimizations models that are constructed for CLSC. (Ferguson and Souza 2010) proposed a book for the CLSCs. The book summarizes the latest studies on the designing of network of closed loop and provides the directions for future research.

First, single objective models are reviewed. (Gopalakrishnan Easwaran & Halit Üster 2010) developed a closed loop supply chain with hybrid manufacturing or remanufacturing facilities and finite-capacity collection centers. The problem is formulated as a MILP model. The objective is to minimize the total cost of the proposed model.. (Hamed Soleimani et al. 2013) presented a multi-product multi-echelon closed loop supply chain model integrated with planning and designing decisions. The objective of the study is to minimize the total cost of the proposed model. A metaheuristic based on genetic algorithm is used for solving the model.

(Hamed Soleimani and Govindan Kannan 2015) developed a multi-periods, and multi-product model for multi-echelon supply chain. Maximizing the total profit is the objective of this work under supply capacity delivery and on-holding constraints. The authors developed a new elevated hybrid algorithm based on the genetic algorithm and and particle swarm optimization. (Y.T. Chen et al.2015) developed an integrated closed supply chain consisting suppliers, plants, and distribution and customer regions, collecting centers, recycling, and disposal centers. The proposed model is solved using a meta-heuristic algorithm to maximize the total profit.

Yi et al. (2016) explored the design of a retailer oriented CLSC network for the end of life construction machinery remanufacturing. A single objective and mixed integer linear model has been developed and solved using an improved hybrid genetic algorithm.Kaya and Urek (2016) analyzed the CLSC network design problem considering profit as a goal. The authors considered inventory, pricing and incentive issues in the proposed model.Özceylan et al. (2017) proposed a linear programming model for designing a CLSC. The model was validated using a real automotive industry in Turkey.

Several papers have been conducted in the design of CLSC considering multiple objectives. In the following paragraphs, the multi-objective models will be reviewed. (Lee et al. 2007) formulated an integrated MILP model for CLSC design. Minimizing total cost and maximizing customer satisfaction are used as objectives of the model. A genetic algorithm is developed for solving the model. (Pishvaee et al. 2010) considered an integrated MILP model for designing a CLSC problem that minimize the supply chain costs and increase customer satisfaction. The goal is to avoid the approximation solution obtained by designing of a sequential, separate CLSC. (Paksoy et al. 2010) proposed a new multi-objective CLSC model. The considered objectives are minimizing total costs and minimizing total CO_2 emissions.

(Wang et al. 2011) presented a multi-objective green supply chain model for minimizing the environmental impact and total cost . (Khajavi et al. 2011) considered and analyzed a model for CLSC in multi-objective case. Two objectives are considered to maximize the customers responsiveness and minimize the network cost.(Amin & Zhang

2012) formulated a manufacturing CLSC as a MILP model. The proposed work goal is to minimize time of operations in collection centers and defect rates . (Mehrbod et al. 2012) developed a multi-period, and multi-product model for multi-stage CLSC design. Minimizing the costs, the time of delivery, and the collection time of the products are the objectives of the work.

(Ozkır & Başlıgil 2013) proposed a model for CLSC in multi-objective case. The proposed model objectives are to maximize the profit of CLSC, maximize the customer satisfaction and trade satisfaction level. (Vahdani et al. 2013) presented a multi-objective CLSC considering both the networks decisions. Total costs and failure costs are the two objectives that were considered in the proposed model. (Mirakhorli 2014) considered and analyzed a CLSC model in multi-objective case. A heuristic approach based on genetic is employed for solving this model. (Devika et al. 2014) formulated a MILP multi-objective model for CLSC problem. To handle and solve the problem, three different heuristic hybrid methods have been developed. (Eleonora Bottani et al. 2015) investigated the issue of optimizing the asset management process in a real closed-loop supply chain. The proposed closed loop network consists of a pallet provider, a manufacturer and several consumers. A real case study model is developed to optimize both economic and strategic key performance indicators of the system.

Amin and Baki (2017) formulated a multi-objective model for designing a global closed-loop supply chain network considering exchange rates and customs duties. A fuzzy programming is developed for to solve the proposed model. Taleizadeh et al. (2019) developed a mathematical model for designing a CLSC with multi-period considering the social and environmental aspects. To encourage customers to return back the used products, a discount offer is considered.

The literature review indicated that the majority of the published papers have focused on formulating a CLSC network design models considering single objective. The literature review has shown that total revenue has not been yet considered in the designing of multi-objective CLSC network. Accordingly, this work is an attempt to fill the above-mentioned gaps by developing a multi-objective model considering total revenue as an objective function. Total revenue is important in SC because it provides the organization cash flow to fulfill commitments that include salary and payment of loans.

3. Problem Statement

We considered a general CLSC network displayed in Fig. 1. The network contains two entities in the forward network and three entities in reveres network. The nodes in the forward supply chain are plants and demand markets. As the counterpart of forward supply chain, the reverse echelons include collection center, disposal centers, and recovery plants. The goods are manufactured by the manufacturing plants and then are transported to demand markets. Some of these products are returned due to some faults. The returned items are collected and inspected at the collection centers to specify if they need recovery or not. The recoverable return product is sent to the plants and the unrecoverable return products are sent to the disposal centre.

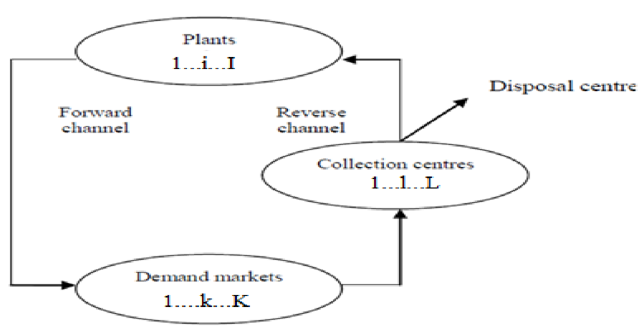

Figure 1: The CLSC network

The aim of this paper is to determine the optimal number of plants and collection centers and their optimal locations. In addition, decide which products should be stored in the facilities, and the flow between the facilities. In this paper, we assume that the demand markets locations are fixed, a single period, the collection centers are responsible to collect all return products from demand markets, and the plants and collection centers locations and capacities are known. In addition, all other parameters are assumed fixed and known. The model minimizes the total cost, maximizes the total revenue, and maximizes the environment technology.

4. Mathematical Model

In this section, the multi-objective model is formulated. Table 1 summarizes the notations used in the model formulation.

Table 1: Sets, parameters, and decision variables.

Sets	
I	Candidate locations of production and reproduction plants (1,2,... ,i . . .,I)
J	Products (1, 2, . . ., j . . .,J)
K	Demand markets (1, 2, . . ., k . . ., K)
L	Candidate locations of collection centres (1,2, . . . ,l . . . ,L)
Parameters	
A_{ij}	Cost of producing product j ∈ J at plant i ∈ I.
B_{ikj}	Cost of shipping product j ∈ J a unit distance between plant i ∈ I and market k ∈K.
C_{klj}	Cost of shipping product j ∈ J a unit distance between market k ∈K and collection center l∈ L.
D_{lij}	Cost of shipping product j ∈ J a unit distance between collection center l∈ L and plant i ∈ I.
O_{lj}	Cost of shipping product j ∈ J a unit distance between collection center l∈ L and disposal centers.
E_i	Cost of construction or opening plant i ∈ I
F_l	Cost of construction or opening collection centre l∈ L
G_j	cost of recovery product j ∈ J
H_j	Cost of disposing product j ∈ J
P_{ij}	Capacity of plant i ∈ I for product j ∈ J
Q_j	Capacity of collection center l∈ L for product j ∈ J
t_{ik}	Distance between plant i ∈ I and market k ∈K.
t_{kl}	Distance between market k ∈K and collection centre l∈ L.
t_{li}	Distance between collection centre l∈ L and plant i ∈ I.
D_{kj}	Demand for product j ∈ J at market k ∈K.
M_{ij}	Value of utilizing friendly environmental materials by plant i ∈ I to produce product j ∈ J.
N_{lj}	Value of utilizing clean technology in collection center l∈ L to produce product j ∈ J.
r_{kj}	Return product j ∈ J from market k ∈K.
α_j	Disposal rate of product j ∈ J.
SP_{jk}	Selling price of product j ∈ J at market k ∈K
Decision variables	
X_{ikj}	Number of units from product j produced by plant i to satisfy demand of market k
Y_{klj}	Number of units from product j returned from market k to collection centre l.
S_{lij}	Number of units from product j returned from collection centre l to plant i
T_{lj}	Number of units from product j returned from collection centre l to disposal centre
Z_i	A binary variable equals to1 if a plant is opened at location i, 0, otherwise
W_l	A binary variable equals to1 if a collection centre is opened at location l, 0, otherwise

The model constructed below considers three objective functions. The first objective (Z_1) is minimization the total cost including setup cost of establishing plants, fixed cost of collection centers, transportation cost of the flow between entities, saving cost of product j, and the disposal cost. The second objective (Z_2) is maximization the technology features to be cleaner and friendly. The materials that can be recyclable is an example of environmental friendly materials. On the other hand, recycling and renewable energy such as solar power are examples of clean technology. M_{ij} and N_{li} are qualitative parameters. Both parameters took values between 0 and 1. The third objective (Z_3) is to maximize the total revenue. It is represented as items prices multiplies number of items sold.

$$\text{Min } Z_1 = \sum_i E_i Z_i + \sum_l F_l W_l + \sum_i \sum_k \sum_j \left(A_{ij} + B_{ikj} t_{ik}\right) X_{ikj} + \sum_k \sum_l \sum_j C_{klj} t_{kl} Y_{klj} + \sum_l \sum_i \sum_j \left(-G_j + D_{lij}\, tli\right) S_{lij} + \sum_l \sum_i \sum_j (H_j + O_{lj}\, t_l)\, T_{lj} \tag{1}$$

$$\text{Max } Z_2 = \sum_i \sum_j M_{ij} \left(\sum_k X_{ikj} + \sum_l S_{lij}\right) + \sum_l \sum_j N_{lj} \left(\sum_k Y_{klj} + \sum_l S_{lij} + T_{lj}\right) \tag{2}$$

$$\text{Max } Z_3 = \sum_i \sum_j \sum_k sp_{jk} X_{ikj} \tag{3}$$

Subjected to:

$\sum_i X_{ikj}$	$\geq$	D_{kj}	$\forall k, j$	(4)
$\sum_l \sum_j S_{lij} + \sum_k \sum_j X_{ikj}$	$\leq$	$Z_i \sum_j P_{ij}$	$\forall i$	(5)
$\sum_l Y_{klj}$	$\leq$	$\sum_i X_{ikj}$	$\forall k, j$	(6)
$\alpha_j \sum_k Y_{klj}$	$\leq$	T_{lj}	$\forall l, j$	(7)
$\sum_k \sum_j Y_{klj}$	$\leq$	$W_l \sum_j Q_j$	$\forall l$	(8)
$\sum_k Y_{klj}$	$=$	$\sum_i S_{lij} + T_{lj}$	$\forall l, j$	(9)
$\sum_l Y_{klj}$	$=$	r_{kj}	$\forall k, j$	(10)
W_l, Z_i	$\in$	$\{0, 1\}$	$\forall i, l$	(11)
$T_{lj}, S_{lij}, Y_{klj}, X_{ikj}$	$\geq$	0	$\forall i, k, l, j$	(12)

Equation (4) represents the demand constraint. Equation (5) represents that the production quantities of each plant must be less than its capacity. Equation (6) implies that the flow in the forward direction of is greater than the flow in the reverse direction. Equation (7) represents disposal rate for each product. Equation (8) represents the capacity of collection constraint. Equation (9) is represents material balance constraint at collection centers. Equation (10) shows the returned products. Equation (11) and (12) represent the binary nature of decision variables and the non-negativity restriction on them respectively.

5. Case Study

In this section, the case study described by (Fleischmann et al. 2001) is considered to illustrate the utility of the proposed model. It is a representative CLSC of copier manufacturing sector. It includes manufactures, demand markets, collection centers, and disposal center. Copy machines are collected at collection centers from customers. The quality of the return copy machines is checked at the collection centers and then either sent to the plants to remanufacture them using the same equipment or sent to disposal center. Some of the return products are used as a source of spare parts especially those that can't be reused as whole. The facilities locations are generated from uniform distribution over a square 100*100. Table 2 shows the data for copy machines case.

Table 2: Data for the case study.

$I = 4$ (number of plants)	$C_j =$ uniform $(0.0045, 0.0055)$	$H_j =$ uniform $(2.25, 2.75)$
$J = 3$ (number of products)	$D_j =$ uniform $(0.0027, 0.0033)$	$P_{ij} =$ uniform $(75{,}600, 92{,}400)$
$K = 5$ (number of demand markets)	$O_j =$ uniform $(0.0014, 0.0017)$	$Q_{lj} =$ uniform $(30{,}600, 37{,}400)$
$L = 4$ (number of collection centers)	$E_i =$ uniform $(4{,}500{,}000, 5{,}500{,}000)$	$D_{kj} = 30{,}000$
$A_j =$ uniform $(13.5, 16.5)$	$F_l =$ uniform $(450{,}000, 550{,}000)$	$r_{kj} = 10{,}000$
$B_j =$ uniform $(0.0131, 0.0160)$	$G_j =$ uniform $(6.3, 7.7)$	$\alpha_j =$ uniform $(0.27, 0.33)$

6. Results and Discussion

The proposed model was coded and solved using GAMS software with commercial solver CPLEX 12.7.1.1. To generate the efficient Pareto-optima points, an Improved Augmented ε-Constraint algorithm proposed by (Mavrotas & Florios 2013) was utilized. The Pareto front of the proposed model are plotted in 3-D to show the relationship between the three objectives as shown in Fig. 2. It is clear that as total revenue increases, total cost increases and environmental impact changes slightly. This relation is due to more sales at demand node which leads to high production and transportation costs.

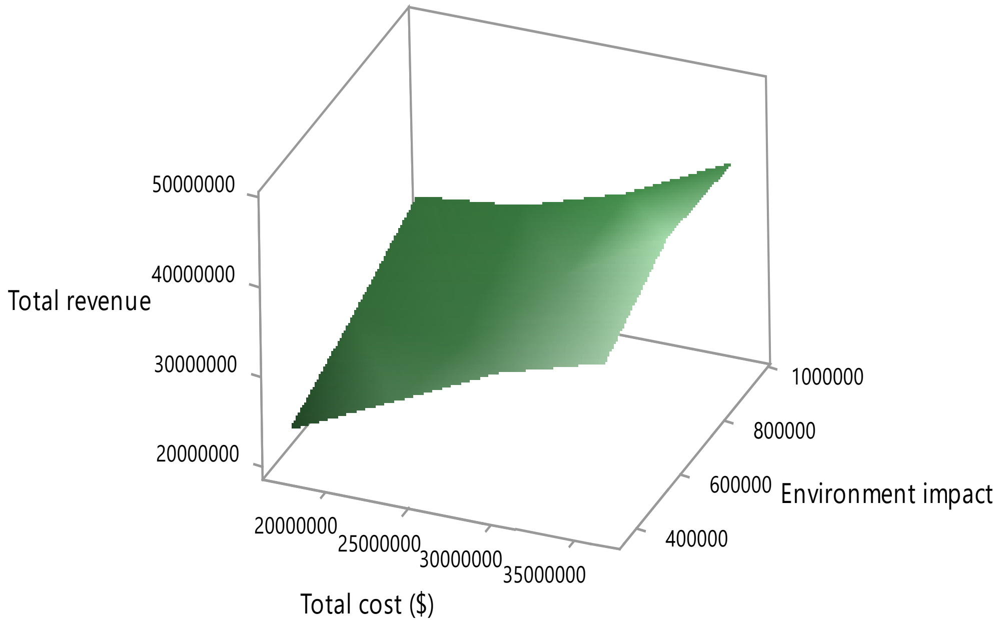

Figure 2: 3D surface plot of the three-objective model

To show the effect of total revenue on the proposed model, different sections are generated at different values of total revenue and is plotted in 2-D graph as shown in Fig. 3. Increasing total revenue leads to dramatic increase in total cost especially for low value of environment impact. On the other hand, total revenue affects environment impact slightly.

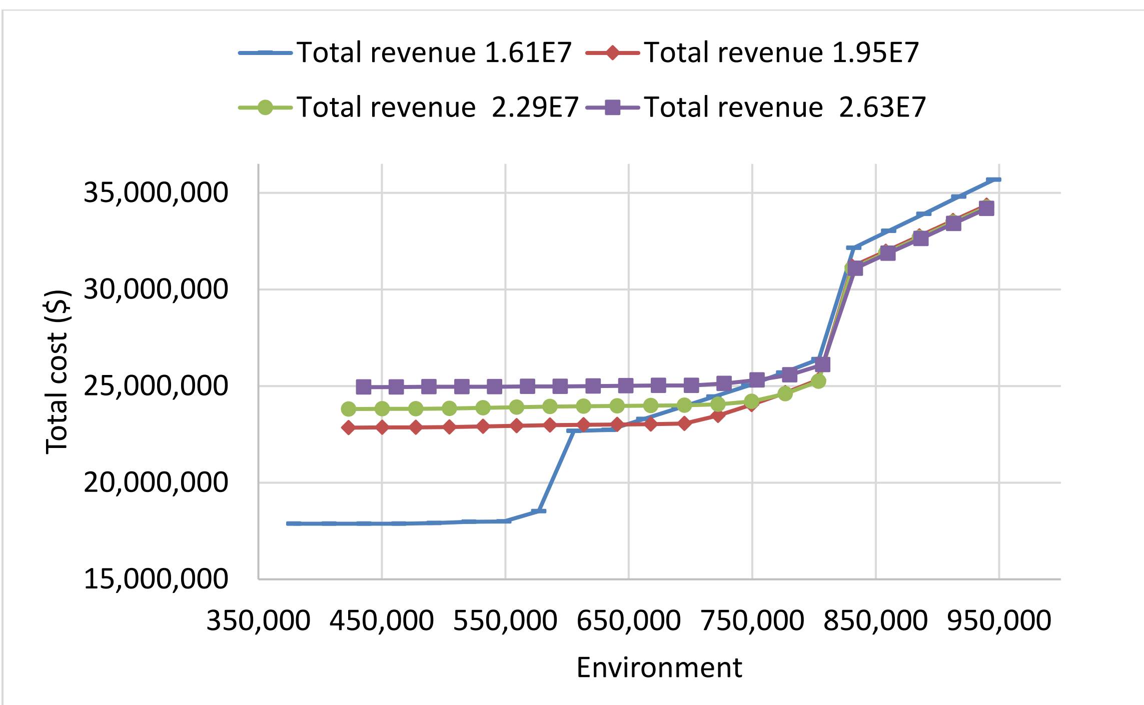

Figure 3: Total cost versus environment at different values of total revenue

Sensitivity analysis is conducted to show the effect of uncontrolled parameters (demand, return, and disposal rate) on performance measures by solving the model for different values of uncontrolled parameters. It is assumed 25% increase (High level 'H') and 25% decrease (Low level 'L') in demand, return, and disposal rate (a combination of 27 scenarios). One plan from each Pareto set is selected using TOPSIS considering high priority for minimization of total cost. The results are summarized in Table 3. A comparison between scenarios are performed based on changes in the objective functions values with respect to the base case (scenario 14) which represents the medium level for all parameters, as illustrated in Table 3.

Table 3: Scenario analysis for the proposed model.

Scenario	**Stochastic parameters levels**			**% change in the objective functions**		
	Demand	**Return**	**Disposal rate**	**Total cost**	**Environment-al impact**	**Total revenue**
1	22500	7500	0.3	-8.87	-11.88	-14.94
2	22500	7500	0.4	-8.03	-12.27	-14.23
3	22500	7500	0.5	-7.19	-12.66	-13.53
4	22500	10000	0.3	-11.36	-3.25	-20.13
5	22500	10000	0.4	-10.24	-3.77	-19.19
6	22500	10000	0.5	-9.12	-4.29	-18.24
7	22500	12500	0.3	-13.09	5.85	-23.01
8	22500	12500	0.4	-14.16	-6.01	-22.71
9	22500	12500	0.5	-10.32	4.55	-20.66
10	30000	7500	0.3	-1.53	-12.96	-1.49
11	30000	7500	0.4	-1.53	-13.37	-1.49
12	30000	7500	0.5	-1.52	-13.79	-1.49
13	30000	10000	0.3	-0.80	-0.29	-1.49
14	30000	10000	0.4	0.00	0.00	0.00
15	30000	10000	0.5	0.79	0.10	1.50
16	30000	12500	0.3	-0.36	6.91	-1.49
17	30000	12500	0.4	-0.32	7.27	-1.49
18	30000	12500	0.5	-0.28	7.64	-1.49
19	37500	7500	0.3	36.18	22.01	31.88
20	37500	7500	0.4	35.08	17.38	26.57
21	37500	7500	0.5	36.33	17.07	28.66
22	37500	10000	0.3	35.64	35.72	32.23
23	37500	10000	0.4	34.89	30.96	27.82
24	37500	10000	0.5	36.62	30.64	30.79
25	37500	12500	0.3	32.53	38.94	24.77
26	37500	12500	0.4	33.57	38.69	24.77
27	37500	12500	0.5	35.57	38.30	28.07

Related to total cost, the results show that the total cost is high sensitive to changes in stochastic parameters. For example, planning for a 25% increase in demand and keeping other two parameters in their base values (scenario 23) would result to a network that has about 35% more cost than the base-case (scenario 14), while assuming 25%

decrease in demand (scenario 5) decrease the cost about 10%. It is noted that, the total cost is less sensitive to changes in return. For instance, planning for a 25% decrease in return (scenario 11) would result to a network that has about 1.53 % less cost than the base-case (scenario 14), while assuming 25% increases in return (scenario 17) decrease the cost about 0.35%. The total cost is less sensitive to the change in disposal rate than return with a variation of almost 0.8% when changing from base to high levels of disposal rate. The effect of disposal rate on total cost is sensitive with high values of demand since high demand means more sales and more disposal units which leads to high total cost. For example, comparing total cost values of scenarios 25 and 27 with scenario 26, total cost changes by about 2%.

Regarding environmental impact, the sensitivity analysis indicates that the environment impact is high sensitive for high values of demand. For example, planning for a 25% increase in demand (scenarios 23) would result in a plan that has about 31 % greater environmental impact than the base-case. Increasing return with 25% (scenario 17) would increase environmental impact by about 7%, while decreasing return 25% less than the base scenario would decrease environmental impact about 13 % less the base case. The disposal rate has less impact on environmental impact.

The results show that the total revenue is high sensitive to changes in demand. For example, planning for a 25% increase in demand (scenario 23) would result to a network that has about 28% more revenue than the base-case, while assuming 25% decrease in demand (scenario 5) reduces the revenue 19%. The return and disposal rate affect total revenue with about 1.5%. It is noted that, the disposal rate has high impact on total revenue for high values of demand. For example, comparing scenario 27 with scenario 26, total revenue changes by about 3.5%.

In general, the effect of demand on all the three performance measures is higher than the other parameters. The effect of return and disposal rate is high when considering high values of demand. Therefore, the sensitivity analysis indicates that the proposed model is robust under variations in the uncontrolled parameters.

Conclusion

In this study, a multi-objective model was developed for a facility location of a closed-loop supply chain (CLSC) network. The proposed model is a mixed-integer linear programming model considering total cost minimization, environment impact maximization, and total revenue maximization. The obtained model helps in assessing the trade-off among different objectives and guides the decision maker to choose the preferred plan among the Pareto optimal solutions. The utilities of the proposed models were examined using application of a copier remanufacturing. A valuable sensitivity analyses were conducted to show the effect of variation of demand, return, and disposal rate on the model performances. In this study, a model was developed under the assumption of fixed and known parameters. However, the effect of uncertainty on the model needs to be considered in future works. Another future direction for research is using and establishing meta-heuristic algorithms for solving large CLSC problems.

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