A Multi-Objective Model for Optimization of a Green Closed-Loop Supply Chain Network under Uncertain Demand

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Abstract

Fierce competition in the market has forced companies to study their supply chain networks more. Due to increased social awareness and stricter governmental laws and legislation, the green closed-loop supply chain (GCLSC) has been reviewed more recently. The main goal of this study is to propose a multi-objective model for optimization of a comprehensive green closed-loop supply chain network with a multi-period multi-stage network, including the manufacturer, distributor, customer market, collection, recovery, and disposal centers under uncertain demand. To handle the uncertain parameter, we utilized chance constraint fuzzy programming. We considered different objective functions, consisting of maximizing income, minimizing total supply chain cost, and minimizing total CO_2 emissions (i.e., CO_2 emitted from facility centers and various transportation modes). Aimed at achieving optimal values, we utilized a carbon-pricing approach to transform the problem into a single objective function. A numerical example coupled with a sensitivity analysis has been conducted to validate the proposed model and formulation. The results show the suitability of the model and the formulation.

Keywords
Green closed-loop supply chain, Multi-objective optimization, Environmental, Chance constraint fuzzy programming

1. Introduction

Economic factors, governmental laws and legislation, and increased expectations of customers have made for a fierce competition in the market, forcing companies and agencies to focus more on their supply chain networks and integrated logistics (Melo et al., 2009). The integration of both forward and reverse supply change networks into a unified structure results in a closed-loop supply chain (CLSC) (Moritz Fleischmann et al., 2001), and brings significant beneficial business incentives. However, an increased number of network nodes and, in turn, more operational facility centers alongside increased inter-nodal transportation leads to an increase in greenhouse gas emissions. Thus, a green closed-loop supply chain (GCLSC) network design can be one of the initial steps in the creation of the sustainable supply chain.

Copious literature related to supply chain network design has been published. Fleischmann et al. (2001) designed an integrated forward/reverse logistic system for the first time and formulated the model in mixed-integer linear programming (MILP). In the presented network, returned products were collected first from the customers and then redistributed after remanufacturing. A multi-product closed-loop logistics network design problem with hybrid manufacturing/remanufacturing facilities and capacitated hybrid distribution/collection centers was developed by Easwaran and Üster (2010) to serve a set of retail locations. Özceylan, Paksoy, and Bektas (2014) presented an integrated mixed-integer non-linear programming (MINLP) model to optimize both strategic decisions (e.g., the flow of products in the forward and reverse supply chains) and tactical decisions (e.g., to balance the production line in the reverse supply chain).

Alongside facility location decisions in supply chain configuration (e.g., location of manufacturers, as well as distribution, collection, recovery, and recycling centers), some researchers considered supplier selection in their model. Not only can this approach result in the minimization of cost, but it can also bring other benefits such as customer satisfaction (Nobar et al., 2011) and/or competitive advantages (Sahraeian et al., 2010). Additionally, aimed at reducing the cost of transportation and managing the truck congestion at warehouses, Fallahtafti et al. (2019) proposed a supply chain network in such a way that a third party logistic (3PL) selection decision was made for transporting the products from the selected suppliers to a manufacturer. Ko and Evans (Ko & Evans, 2007) proposed a MINLP model for the design of an integrated logistic network while keeping in consideration the 3PL service providers. Some researchers examined different parameters of the model, such as cost coefficients, demand, rate of return, and capacity in uncertain conditions, and proposed either fuzzy programming (e.g., (Alamdar et al., 2018; Fallah-tafti et al., 2019; Ghahremani Nahr et al., 2018; Talaei et al., 2016)) or stochastic programming (e.g., (Farrokh et al., 2018; Zhen et al., 2019; Amin & Zhang, 2013)). Concerning objective functions, most related papers have considered only a single objective function that mostly is a minimization of monetary cost. However, in real-life problems, decision-makers (DM) generally should deal with more than one objective function. For this reason, multi-objectivity in optimization models is gaining more attention by considering objectives such as minimizing risk (Dai & Dai, 2016), maximizing responsiveness to customers (Rad & Nahavandi, 2018; Soleimani et al., 2017), minimizing risk (Vahdat Zad, 2018), reducing delivery time (Fallah-Tafti et al., 2014), and/or maximizing social responsibility through increased job opportunities and decreased waste production (Pishvaee et al., 2012).

Additionally, in most developed countries today, corporations must comply with government regulations to reduce their carbon emissions. A GCLSC can deal with the challenge of environmentally friendly manufacturing by recycling the used products for reproducing/reducing the waste, finding the optimal location-allocation of facility centers and transportation modes, and establishing the optimal quantity of products in forward and reverse flows. Perhaps one of the earliest efforts to identify green reverse logistics was performed by Fleischmann et al. (2000). Quariguasi Frota Neto et al. (2010) proposed a CLSC network design for a recycling system by exploring some environmental strategies. To solve the model, a carbon-sensitive supply chain network problem with green procurements was studied by Alfonso-Lizarazo et al. (2013). Amin and Zhang (2013) studied the effects of uncertainties in demand and return products in a stochastic multi-objective integrated forward/reverse logistics network. They considered two qualitative factors regarding the environment (i.e., environment-friendly materials and clean technology). Talaei et al. (2016) designed a multi-objective MINLP model for a closed-loop green supply chain network to simultaneously minimize both the total network costs and carbon dioxide emission rates. To address the effects of uncertainty parameters, they used a robust fuzzy programming approach in their problem. A multi-objective logistics model in the gold industry, including four echelons in the forward direction and three stages in reverse, was presented by Zohal and Soleimani (2016). Then, an ant colony metaheuristic algorithm was developed for the solution method. They considered the minimization of both the total network costs and the carbon emission rates as objective functions. Soleimani et al. (2017) studied a multi-objective GCLSC. Three objectives including maximizing profit, maximizing responsiveness to customer demand, and minimizing lost working days due to occupational accidents were considered in the problem. They applied a genetic algorithm (GA) and multiple scenarios with different aspects to solve the problem. Liu et al. (2017) studied closed-loop orientation (CLO) and concluded it was the appropriate strategic orientation to implement green supply chain management practices effectively; they then developed a valid measurement of CLO. The structural equation modeling method was used to examine the relationships among CLO, green supply chain management (GSCM) practices, and environmental and economic performance. The results showed that both CLO and GSCM have positive effects on the environmental and economic performance. The issue of reduction of the environmental burden of a CLSC—consisting of a pallet provider, a manufacturer, and several retailers—was addressed by Bottani and Casella (2018). They developed a simulation model to solve a real problem with multiple objectives, which included economic metrics, as well as some relevant environmental key performance indicators. A GCLSC with multiple objectives consisting of the total cost, environmental emissions, and customer satisfaction was presented by Rad and Nahavandi (2018). In order to solve the model, an ant colony optimization algorithm was developed. Zhao et al. (2018) redesigned the supply chain of agricultural. They took advantage of a system dynamics simulation by using carbon emissions per product as an indicator in order to obtain the optimal scenario for managerial practice and design an incentive mechanism to drive supply chain operations. Liu et al. (2018) proposed a bi-objective GCLSC problem with uncertain demand so that the locations and number of manufacturer and customer points are pre-known, and several possible candidate locations for the facilities are available. Alongside minimizing the total cost, they considered maximizing the satisfaction, which consists of the logistics speed, quality of goods, and the number of recycling products. To solve the problem, they used two heuristic algorithms, NSGA-II and MOSA, for middle- and large-scale instances. Ghomi-Alavi et al. (2018) presented a bi-objective, bi-level model with a price-dependent demand for the network design of a green closed-loop supply chain with random disruptions from suppliers with uncertain demand. Chun and Ulya (2019) considered greening efforts of both the retailer and the manufacturer with government intervention through the reward-penalty mechanism under the game-theoretical settings in GCLSC.

Recently, Mohtashami et al. (2020) utilized a queuing system to optimize the transportation and waiting time and, in turn, reduce the environmental impact in a CLSC network.

Considering the papers mentioned earlier and some related exhaustive literature review papers (e.g., (Ciccullo et al., 2018; Fang & Zhang, 2018)), it can be observed that there is a significant trend towards considering more comprehensive and integrated problems. This approach, however, makes the formulation and solution more difficult. For instance, although the objective function of the most published papers has been defined as "single," and parameters as "certain," the newly published articles mainly consider those features as multi-objective, and uncertain parameters to make it more realistic. Additionally, in regards to the reduction of CO/CO_2 emissions, most papers in the literature considered only a single-type vehicle as a transportation mode, and discharge of carbon only during production and transportation. The main goal of this study is to propose a multi-objective model for the optimization of a comprehensive green closed-loop supply chain network. The proposed GCLSC is a multi-period multi-stage network, and includes the manufacturer, distributor, customer market, collection, recovery, and disposal centers. This model integrates network design decisions into both forward and reverse flows. To make the model more applicable and close to a real-world situation, three objectives—including minimizing cost, maximization of income, and minimization of pollutants—will be considered simultaneously under uncertainty in demand. Some decision variables of the model that should be optimized are the amount of products in forward/reverse flow and the location/allocation of facilities.

2. Problem description and model formulation

2.1 Problem definition

The proposed model is based on the models in (Talaei et al., 2016; Zohal & Soleimani, 2016). The proposed GCLSC is a multi-objective, multi-echelon, multi-transportation mode, multi-period network includingsuppliers, manufacturers, distribution centers, customers, collection centers, recycling, and disposal centers, and which integrates the network design decisions in both forward and reverse flows. Figure 1 depicts the schematic view of the model. As is shown, raw materials are transferred to the manufacturer in forward flows. Then, the manufacturing centers produce final products and ship these products to the distribution centers. Finally, the products are delivered to the customers through distribution centers. In the backward direction, the returned products are bought from the customers and sent back to the collection centers. After a quality inspection, if the returned products can be repaired/restored, they are sent back to the manufacturing centers; otherwise, they are shipped to recycling centers. Finally, the return products are disassembled, and those that can be reused are sold to the suppliers, while the rest are transferred to the disposal centers. The proposed supply chain network in this project has a general structure and so can be applied to different industries.

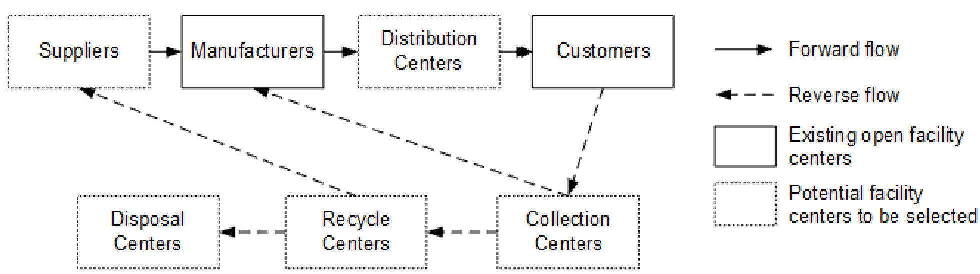

Figure 1. The proposed GCLSC logistics network

The model has been proposed by assuming the following:

- All demands of customers must be satisfied in the same period, and all the returned products from customers must be collected.
- In the forward flow, products are transferred through a pull mechanism of the network, while in the reverse flow, returned products are shipped through a push mechanism.
- One manufacturer produces the products.
- The location of suppliers, manufacturers, and customers are fixed and known.
- The location of candidate facilities to be opened is pre-identified; such facilities are available and should be selected.

- The flows are permitted to move only between two consecutive centers, and the flow between the facilities in the same state is prohibited.
- Since the customers and collection centers are far from the other facility centers, different transportation modes are considered for associated links between these facility centers and others.
- The amount of CO_2 emission per mile for each type of transportation mode is constant.

2.2 Model formulation

The proposed model can be formulated in MILP as follows:

Sets and index

s	sets of suppliers ($s = 1, \dots, s$)
j	sets of candidate location for distribution centers ($j = 1, \dots, j$)
k	sets of fixed locations of customers ($k = 1,\dots, k$)
l	sets of candidate locations for collection centers ($l = 1,\dots, l$)
m	sets of candidate locations for recycle centers ($m = 1, \dots, m$)
n	sets of candidate locations for disposal centers ($n = 1, \dots, n$)
v	sets of transportation modes ($v = 1, \dots, v$)
t	index related to time periods ($t = 1, \dots, t$)

Parameters

d_{kt}	the demand of customer k at period t
α_s	processing cost per unit of raw materials at supplier s
β	processing cost per unit of a product at the manufacturer
γ_j	processing cost per unit of a product at distribution center j
δ_k	repurchase cost per unit of a returned product from customer k
ζ_l	processing cost per unit of a returned product at collection center l
η_m	processing cost per unit of a returned product at recycle center m
θ_s	the selling price per unit of a returned product to supplier s
fj_j	fixed cost of opening distribution center j
fl_l	fixed cost of opening collection center l
fm_m	fixed cost of opening recycle center m
fn_n	fixed cost of opening disposal center n
cx_s	transportation cost per unit of raw materials from supplier s to the manufacturer
co_j	transportation cost per unit of product from the manufacturer to distribution center j
cu_{jk}^v	transportation cost per unit of product from distribution center j to customer k by transportation mode v
cq_{kl}	transportation cost per unit of returned products from customer k to collection center l
cs_{lm}^v	transportation cost per unit of returned products from collection center l to recycle center m
ch_l^v	transportation cost per unit of returned products from collection center l to the manufacturer by transportation mode v
cr_{mn}	transportation cost per unit of products from recycling center m to disposal center n
cs_c	maximum capacity of supplier s at each period
ca	maximum capacity of the manufacturer at each period
cj_j	maximum capacity of distribution center j at each period
cl_l	maximum capacity of collection center l at each period
cm_m	maximum capacity of recycling center m at each period
cn_n	maximum capacity of disposal center n at each period
cv^v	maximum capacity of transportation mode v at each period

rkl	rate of return of products from customers
rla	rate of recovery and repair products from collection center l to the manufacturer
rms	rate of recycled products from recycling center m to supplier s
pri	the selling price per unit of the product to customer k
dsa_s	the distance between supplier s and the manufacturer
daj_j	the distance between the manufacturer and distribution center j
djk_{jk}	the distance between distribution j and customer k
dkl_{kl}	the distance between customer k and collection center l
dla_l	the distance between collection center l and the manufacturer
dlm_{lm}	the distance between collection center l and recycling center m
dms_{ms}	the distance between recycling center m and supplier s
dmn_{mn}	the distance between recycling center m and disposal center n
pv^v	the amount of CO2 emitted from transportation mode v per mile
ps_s	the average amount of CO_2 emitted from supplier s
pa	the average amount of CO_2 emitted from the manufacturer
pj_j	the average amount of CO_2 emitted from distribution center j
pl_l	the average amount of CO_2 emitted from collection center l
pm_m	the average amount of CO_2 emitted from recycling center m
pn_n	the average amount of CO_2 emitted from disposal center n
evv	the effective loading percentage of transportation mode v
ef	the effective capacity percentage at facility centers
ω	the CO_2 cost per ton of emission

Decision variables

x_{st}	the amount of material transported from supplier s to manufacturer at period t
o_{jt}	the amount of products transported from the manufacturer to distribution center j at period t
u^v_{jkt}	the amount of products transported from distribution center j to customer k by transportation mode v at period t
q_{klt}	the amount of returned products from customer k to collection center l at period t
r^v_{lmt}	the amount of returned products from collection center l to recycling center m at period t
p^v_{lt}	the amount of returned products from collection center l to the manufacturer at period t
y_{mst}	the amount of recycled products from recycling center m to supplier s at period t
z_{mnt}	the amount of recycled products from recycling center m to disposal center n at period t
λ_s	1 if supplier s is selected, otherwise 0
μ_j	1 if distribution center j is opened, otherwise 0
ρ_l	1 if collection center l is opened, otherwise 0
φ_m	1 if recycling center m is opened, otherwise 0
χ_n	1 if disposal center n is opened, otherwise 0

Regarding these notations, the closed-loop supply chain network design is formulated as follows:

$$\max Z = Z_1 - (Z_2 + \omega Z_3) \quad (1)$$

$$Z_1 = \sum_t \sum_k d_{kt} \times pri \quad (2)$$

$$Z_2 = \left[\begin{array}{l} \left(\begin{array}{l} \sum_t \sum_s (cx_s + \alpha_s)\, x_{st} + \sum_t \sum_j (co_j + \beta)\, o_{jt} + \sum_t \sum_j \sum_k \sum_v (cu^v_{jk} + \gamma_j)\, u^v_{jkt} \\ + \sum_t \sum_k \sum_l (cq_{kl} + \delta_k)\, q_{klt} + \sum_t \sum_l \sum_m \sum_v (cs^v_{lm} + \varsigma_l)\, r^v_{lmt} + \sum_t \sum_l \sum_v (ch^v_l + \varsigma_l)\, p^v_{lt} \\ + \sum_t \sum_s \sum_m (cy_{ms} + \eta_m - \theta_s)\, y_{mst} + \sum_t \sum_n \sum_m (cr_{mn} + \eta_m)\, z_{mnt} \end{array} \right) \\ + \left(\sum_j fj_j\, \mu_j + \sum_l fl_l\, \rho_l + \sum_m fm_m\, \varphi_m + \sum_n fn_n\, \chi_n \right) \end{array} \right] \quad (3)$$

$$Z_3 = \left[\begin{array}{l} \left(\begin{array}{l} \sum_t \sum_s pv^{v_1}\, dsa_s \frac{x_{st}}{cv^{v_1}\, ev^{v_1}} + \sum_t \sum_j pv^{v_1}\, daj_j \frac{o_{jt}}{cv^{v_1}\, ev^{v_1}} + \sum_t \sum_j \sum_k \sum_v pv^v\, djk_{jk} \frac{u^v_{jkt}}{cv^v\, ev^v} \\ + \sum_t \sum_k \sum_l pv^{v_1}\, dkl_{kl} \frac{q_{klt}}{cv^{v_1}\, ev^{v_1}} + \sum_t \sum_l \sum_m \sum_v pv^v\, dlm_{lm} \frac{r^v_{lmt}}{cv^v ev^v} + \sum_t \sum_l \sum_v pv^v\, dla_l \frac{p^v_{lt}}{cv^v\, ev^v} \\ + \sum_t \sum_s \sum_m pv^{v_1}\, dms_{ms} \frac{y_{mst}}{cv^{v_1}\, ev^{v_1}} + \sum_t \sum_n \sum_m pv^{v_1}\, dmn_{mn} \frac{z_{mnt}}{cv^{v_1}\, ev^{v_1}} \end{array} \right) \\ + \left(\begin{array}{l} \sum_t \sum_s ps_s \frac{x_{st}}{cs_s\, ef} + \sum_t \sum_j pa \frac{o_{jt}}{ca\, ef} + \sum_t \sum_j \sum_k \sum_v pj_j \frac{u^v_{jkt}}{cj_j\, ef} + \sum_t \sum_l \sum_m \sum_v pl_l \frac{(r^v_{lmt} + p^v_{lt})}{cl_l\, ef} \\ + \sum_t \sum_s \sum_m pm_m \frac{(y_{mst} + z_{mnt})}{cm_m\, ef} + \sum_t \sum_n \sum_m pn_n \frac{z_{mnt}}{cn_n\, ef} \end{array} \right) \end{array} \right] \quad (4)$$

S.t.,

$$\sum_j \sum_v u^v_{jkt} \ge d_{kt} \quad ; \forall k, t \quad (5)$$

$$\sum_s x_{st} + \sum_l \sum_v p^v_{lt-1} = o_{jt} \quad ; \forall t \quad (6)$$

$$o_{jt} = \sum_k \sum_v u^v_{jkt} \quad ; \forall j, t \quad (7)$$

$$\sum_j \sum_v u^v_{jkt} \times rrp = \sum_l q_{klt} \quad ; \forall k, t \quad (8)$$

$$\sum_k q_{klt} \times rla = \sum_v p^v_{lt} \quad ; \forall l, t \quad (9)$$

$$\sum_k q_{klt} \times (1 - rla) = \sum_m \sum_v r^v_{lmt} \quad ; \forall l, t \quad (10)$$

$$\sum_l \sum_v r_{lmt} \times rms = \sum_s y_{mst} \quad ; \forall m, t \quad (11)$$

$$\sum_l \sum_v r^v_{lmt} \times (1 - rms) = \sum_n z_{mnt} \quad ; \forall m, t \quad (12)$$

$$x_{st} \le cs_s \lambda_s \quad ; \forall s, t \quad (13)$$

$$\sum_j o_{jt} \le ca \quad ; \forall t \quad (14)$$

$$\sum_v \sum_k u^v_{jkt} \le cj_j \mu_j \quad ; \forall j, t \quad (15)$$

$$\sum_v p^v_{lt} + \sum_m \sum_v r^v_{lmt} \le cl_l \rho_l \quad ; \forall l, t \quad (16)$$

$$\sum_s y_{mst} + \sum_n z_{mnt} \le cm_m \varphi_m \quad ; \forall m, t \quad (17)$$

$$\sum_m z_{mnt} \le cn_n \chi_n \quad ; \forall n, t \quad (18)$$

$$x_{st} \le cv^{v_1} \quad ; \forall s, t \quad (19)$$

$$o_{jt} \le cv^{v_1} \quad ; \forall j, t \quad (20)$$

$$u^v_{jkt} \le cv^v \quad ; \forall j, k, v, t \quad (21)$$

$$p^v_{lt} \le cv^v \quad ; \forall l, v, t \quad (22)$$

$$r^v_{lmt} \le cv^v \quad ; \forall l, m, v, t \quad (23)$$

$$y_{mst} \le cv^v \quad ; \forall m, s, t \quad (24)$$

$$z_{mnt} \le cv^v \quad ; \forall m, n, t \quad (25)$$

$$\lambda_s, \mu_j, \rho_l, \varphi_m, \chi_n \in \{0,1\} \quad ; \forall s, j, l, m, n \quad (26)$$

$$x_{st}, o_{jt}, u^v_{jkt}, q_{klt}, p^v_{lt}, r^v_{lmt}, y_{mst}, z_{mnt} \ge 0 \quad ; \forall s, k, j, v, l, m, n, t \quad (27)$$

The problem consists of several objectives: (1) maximization of income (Z_1), (2) minimization of total supply chain costs (Z_2), and (3) minimization of CO_2 emissions (Z_3). The first objective is achieved through total products sold to customers by multiplying the selling price and total demands. The second objective is the minimization of the total costs, including the processing cost, transportation cost, fixed cost of opening the facilities, and the cost of buying the returned products. The last objective is associated with the CO_2 emission that is calculated via two main expressions. The first is the total amount of CO_2 emitted in the environment, which is done by considering capacity and the effective loading percentage of different transportation modes in the network. The second is the total CO_2 emitted in the environment due to processing the product in various facility centers; this is calculated by considering the capacity and the effective capacity percentage at these facility centers. Constraint (5) imposes the total demand of customers at each period that should be fulfilled. Equations (6)-(12) guarantee the flow balance at manufacturing facilities, distribution centers, collection centers, recycling centers, and disposal centers. For example, constraint (6) ensures that the total amount of products that are sent to the distribution centers at each period are equal to the summation of the total amount of products sold by suppliers in the same period and the amount of returned products that are sent back to the manufacturer from collection centers from the previous period. Constraints (13)-(25) are related to capacity restrictions. Constraints (13)-(18) are the capacity of facilities prohibiting the overload flow, while constraints (19)-(25) are the capacity of transportation modes that move the product. Finally, constraints (26) and (27) express the binary and non-negativity constraints on decision variables.

2.3 Uncertainty Modeling

The chance constraint fuzzy programming (CCFP) method can deal with uncertain parameters in problems in which at least one of the parameters in constraints and/or objective functions is a fuzzy random variable. The CCFP approach is a well-founded approach relying on insightful mathematical concepts, which transforms the fuzzy mathematical model into an equivalent crisp model. The CCFP approach comprises the expected value of a fuzzy number; and such measures as Necessity (Nec), Possibility (Pos), and Credibility (Cr). The interested reader is referred to papers presented by Inuiguchi and Ramık (2000) and Duboise et al. (2000). In this study, we assumed that satisfying the customers' demand is of exceeding importance for decision-makers and, in turn, we utilized the Necessity approach to tackle the ambiguous demand parameter in the associated objective function and constraint. Moreover, we used a triangular fuzzy number for modeling in which demand is defined as $\tilde{d} = (\tilde{d}_{(1)}, \tilde{d}_{(2)}, \tilde{d}_{(3)})$. The equivalent CCFP formula for the objective function Z_1 in Eq. (2) and constraint (5) can be formulated in equations (28) and (29) respectively:

$$Max\, E[Z_1] = E\left[\sum_t \sum_k \tilde{d}_{kt}\right] \times pri \tag{28}$$

$$Nes\left\{\sum_j \sum_v u^v_{jkt} \geq \tilde{d}_{kt}\right\} \geq \alpha \qquad ;\forall k,t \tag{29}$$

where constraint with an ambiguous parameter is molded with at least a satisfaction level $\alpha \in [0.5, 1.0]$. The equivalent crisp formulas for these two equations are as follows:

$$Max\, E[Z_1] = \sum_t \sum_k (w_1\tilde{d}_{(1)kt} + w_2\tilde{d}_{(2)kt} + w_3\tilde{d}_{(3)kt}) \times pri \tag{30}$$

$$\sum_j \sum_v u^v_{jkt} \geq (1-\alpha)\tilde{d}_{(2)kt} + \alpha\tilde{d}_{(3)kt} \qquad ;\forall k,t \tag{31}$$

where, considering the concept of most likely values proposed in some relevant papers (e.g., (Fallah-Tafti et al., 2014; Listeş & Dekker, 2005)), the weights of w_i is set as $w_1 = w_3 = 1/6$, $w_2 = 4/6$. Therefore, the deterministic model can be formulated as follows:

$$Max\, E[Z] = \left[\sum_t \sum_k \left(\frac{\tilde{d}_{(1)kt} + 4\tilde{d}_{(2)kt} + \tilde{d}_{(3)kt}}{6}\right) \times pri\right] - (Z_2 + \omega Z_3) \tag{32}$$

Equations (6)-(27) and (31).

3. Solution method

To solve such multi-objective decision making (MODM) problems, numerous methods have been used. For instance, the ε-constraint method is one of the most commonly used approaches, thanks to its ability to solve such problems without a need to provide scaling of the objective functions that can affect the results in the ε-constraint method, and its possibility to change ε and to find diverse optimum solutions. In the ε-constraint method, the higher priority function is considered to be the objective function, and other functions are the ε-based constraints. However, the minimization of CO_2 in the environment (Z_3) can be economically valued. Hence, for the proposed multi-objective GCLSC network, having monetary objectives—including maximization of income (Z_1) and minimization of supply chain cost (Z_2)—and a non-monetary objective of minimization of CO_2 emissions in the environment (Z_3), we can solve the problem in a single objective function. We can do this without converting the objective functions with a lower priority into constraints. This approach can help DMs integrate the third objective function (Z_3) with other objectives and make the model a single objective function, enabling them to achieve the optimum values. In this regard, several techniques can be used to quantify and monetize non-market impacts (Litman, 2009). Carbon pricing can be defined into two different main types as follows (World Bank Board, 2019):

- Emission Trading System (ETS): in ETS - sometimes referred to as a cap-and-trade system- the government sets an emissions cap on the total amount of certain greenhouse gases that can be emitted by installations covered by the system. Within the cap, companies sell or buy emission allowances that they can trade with one another as needed. This market establishes an emission price.
- Carbon tax: directly sets a price on carbon by defining a tax rate on greenhouse gas emissions. In this approach, CO_2 is economically valued based on the cost of control, prevention, or compensation. For example, climate change that refers to global warming.

Considering our proposed model, we used the second approach for quantifying the third objective that is the cost of CO_2 emission. However, estimates of the environmental cost of carbon emissions are sensitive to scientific and economic assumptions and, thus, vary greatly. Researchers participating in the Stanford Energy Modeling Forum (DIAMOND & ZODROW, 2020) modeled 39 different carbon tax scenarios for the US, with carbon prices of $25 or $50 per metric ton (1.1 tons) starting in 2020 and rising at 1 percent or 5 percent per year until 2050. One of the techniques is control/prevention cost, which estimates the associated cost based on prevention, control, or mitigation expenses. For instance, if the industry is required to spend $1,000 per ton to reduce pollutant emissions, we can infer that society considers those emissions to impose costs at least that high. In some references, this approach is called carbon tax as a price on CO_2 and other greenhouse gas emissions, encouraging people, businesses, and governments to produce less of them.

4. Numerical Experiment

In this section, a numerical experiment coupled with results are presented in order to demonstrate the validity and practicality of the proposed model. According to (Litman, 2009), the cost of CO_2 emissions—considering the control cost approach—is estimated to be about $40 per ton of emission in the environment. We used this value as the parameter (pc), because this value is quite similar to other reputable references. For instance, according to a rough estimate developed by an interagency working group of the United States government, carbon dioxide emissions impose about $40 cost per metric ton (Tax Policy Center Board, 2019). This price is considered to calculate the average amount of CO_2 emission from the facility centers and from the transportation modes by considering their capacities and the associated effective coefficients.

The proposed GCLSC network model was coded using GAMS 26.1 software and the CPLEX 12.0 solver optimization software on a personal computer with a 64-bit operating system, 1.8 GHz CPU Intel core i5-3337(U) processor and 6 GB RAM memory. Table 1 shows the size of this problem, and Tables 2 through 4 represent the values of the model parameters.

Table 1. Size of numerical experiments

No. of suppliers	No. of plants	No. of candidate distribution centers	No. of customers	No. of candidate collection centers	No. of candidate recycle centers	No. of candidate disposal centers	No. of transportation modes	No. of time periods
5	1	3	4	2	2	2	2	5

Table 2. Capacity data for the example network in each period

Suppliers, s = (1-5)	Manufacturer	Distribution center, j = (1-3)	Transportation Mode, v = (1-2)	Collection center, l = (1-2)	Recycle center, m = (1-2)	Disposal center, n = (1-2)
(400, 350, 300, 200, 400)	(600)	(300, 200, 200)	(8000, 5000)	(100, 50)	(100, 50)	(100, 50)

Table 3. The demand of customer k at time period t

	$\tilde{d}_{(1)}$	$\tilde{d}_{(2)}$	$\tilde{d}_{(3)}$
$\tilde{d}_{kt}$	$\sim U(100{,}150)$	$\sim U(150{,}200)$	$\sim U(200{,}250)$

Table 4. Other model parameters

Parameter	Parameter range	Parameter	Parameter range	Parameter	Parameter range
fj	[2000, 2500]	θ_s	[300, 330]	ps_s	[25, 40]
fl	[1200, 1500]	cs_s	[200, 400]	pa	350
fm	[2000, 2500]	cj_j	[200, 300]	pj_j	[30, 40]
fn	[1200, 1500]	cl_l	[50, 100]	pl_l	[30, 30]
α_s	[300, 400]	cm_m	[50, 100]	pm_m	[25, 30]
β	10	cn_n	[50, 100]	pn_n	[20, 30]
γ_j	[2, 3]	cv_v	[60, 200]	pv_n	[150, 400]
δ_k	[330, 350]	rrp	0.05	pri	400
ζ_l	[2, 3]	rla	0.50	rv_v	50
η_m	[2, 3]	rms	0.90	ω	40

4.1. Discussion

The results of solving this comprehensive model reports that the optimum value (i.e., net income) after five years is $22,185 *k*. Figure 2 illustrates the cumulative net income during a time period of five years. As is shown, in the first year, the total net income is negative because of the enormous amount of money spent on opening new facilities, but then the net income gradually increases.

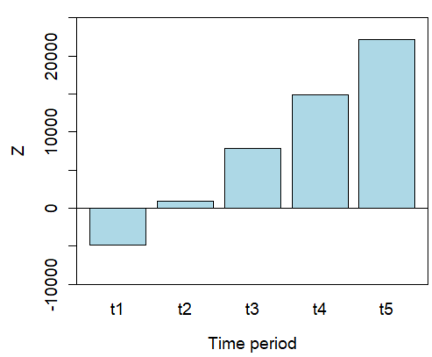

Figure 2. The accumulated value of the objective function (Z)

4.2. Sensitivity Analysis

To ensure the mathematical formulation and associated coding are correct, a sensitivity analysis is performed by changing values of the model parameters, and the results are presented in Figure 3. As can be observed, an increase in the selling price of products (pri) and the amount of recycled products sent back to the suppliers (rms) will result in increasing the income (Z_1) and decreasing the total supply chain cost (Z_2), respectively. Moreover, an increase in the processing cost per unit of products at the manufacturer (β) and the pollutant cost per ton of emission (ω) leads to an increase in the value of the supply chain cost (Z_2) and monetary value of carbon dioxide emissions (Z_3), respectively. These results validate the formulation and coding of the presented model.

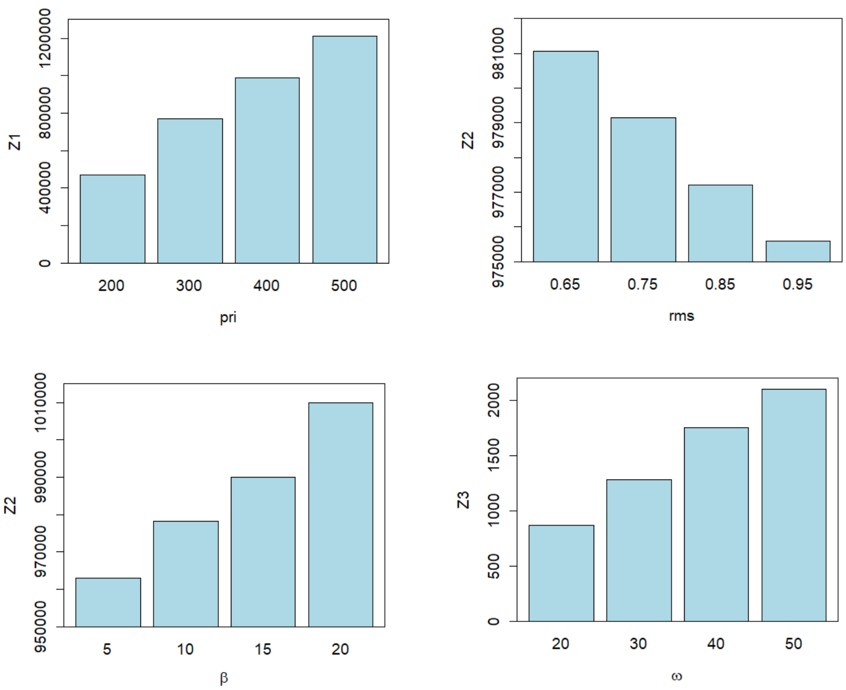

Figure 3. The effect of changing different parameters on each objective

5. Conclusion and future research

In this study, an effort has been made to develop a multi-objective, mixed-integer linear programming model in a green closed-loop supply chain network. The proposed network consists of multi-objective, multi-echelon, multi-period, and multi-transportation modes. This model includes almost all possible entities and flows in an integrated forward and reverse network, which simultaneously incorporates strategic decisions (e.g., facility location and supplier selection) and tactical decisions (e.g., transportation mode). The objective is to maximize the net income that is achieved through maximizing income while minimizing the cost of production, transportation, and pollutant emission. Then, to integrate the cost of emission into a net-income objective, the carbon-tax approach was applied to quantify and monetize the associated objective function. The results demonstrated the applicability and reliability of the formulation and solution approach.

Finally, there are some topics that can be suggested for future research. The researchers can develop the model (e.g., considering uncertain parameters such as cost, return rate, and/or incorporating a multi-product network) and then apply a suitable solution approach for uncertainty modeling (e.g., robust fuzzy programming, stochastic programming). Also, since this model is a comprehensive model, it can be applied to various industries. As a result, other objective functions in regards to the characteristics of the problem (e.g., maximizing customer satisfaction, minimizing risk for hazardous material) can be defined. Moreover, the model can be used for a real large-scale case and, thus, suitable solution approaches (e.g., heuristic and meta-heuristic methods) and new solution methodologies—or even simulation-based optimization techniques—can be applied, and the performance of different solution methods can be evaluated.

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