Design of a Closed Supply Chain with regards to the Social and Environmental Impacts under Uncertainty

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Abstract
In recent years, the decrease of resources and the increase of environmental concerns regarding the burial of industrial waste have led to developing the integrated green supply chain. In this study, a multi-product, multi-level multi-objective closed-loop supply chain network is formulated in a way that considers the total profit, social responsibility, and environmental impacts. To overcome the innate uncertainty in some parameters such as transportation cost, operational costs, and customer demand, a robust counterpart based on the Bental-Nimrovski approach is developed. Finally, the performance of the deterministic and robust models evaluated by implementing the different experiments. The result shows the superiority of the deterministic model based on the mean of all objective functions and the robust model's superiority based on standard deviations.

Keywords: Closed Loop Supply Chain Network, Uncertainty, Multi-Objective Model

1 Introduction

Designing the supply chain network is considered one of the most critical strategic decisions in the last few decades. On the other hand, environmental concerns related to the supply chain network is growing, which leads researchers to focus more on reusing the defective products and prevent further waste to reduce environmental pollution and achieve profitability by considering social and commercial considerations [1, 2, 3]. Another concept that has been highlighted by researchers is considering corporate social responsibility (CSR) throughout the supply chain [4, 19-25]. This paper considers these aspects for a closed-loop supply chain through three objective functions: total profit, social responsibility, and environmental effects. The most important novelty of this paper is (I) considering the three aspects of economic, social, and environmental impacts simultaneously, (II) considering the robust approach (Bental-Nimrovski) to design a CLSC, (III) considering all levels of forward and reverse supply chain, and (IV) using the goal-achieving technique to solve the problem as a single-objective.

This paper is organized as follows: the literature review is presented precisely in Section 2. The mathematical model is described and formulated in Section 3. The numerical example and comparisons based on two criteria are presented in Section 4. Finally, conclusions and future research are demonstrated in Section 5.

2 Literature Review

According to studies in the literature, designing the reverse and closed-loop supply chain network based on mixed-integer programming is a widely used approach [5]. Over the past decade, many reverse supply chain network design models have been developed as closed-loop supply chains. Wang and Hsu proposed a nonlinear model for the closed-loop supply chain network design. In this model, the potential locations of factories, distributors, and disposal centers are determined while the total cost was minimized [6]. Uster et al., designed a multi-product CLSC network that contains the collection and remanufacturing facilities in a forward and reverse loop. They used the Benders approach to minimize the fixed cost of locating facilities as well as transportation costs and processing costs [7]. Shih presented a mixed-integer programming model for the reverse logistics system. In this model, the transportation costs, fixed construction costs, and disposal costs of non-recoverable products were minimized [8]. Data uncertainty is an inevitable phenomenon in the supply chain field that needs to be addressed [9]. A probabilistic approach has been used in many studies to deal with this uncertainty [10, 11]. Lickens et al., presented a mixed-integer nonlinear programming model that considered the returned product rate as an uncertain parameter. They used the genetic algorithm to solve the model based on the differential evolution technique [12]. Recently, the green supply chain concepts and social responsibility in designing the supply chain network are highlighted. For example, Millet evaluated the criteria to achieve a robust supply chain that considered the economic, social, and environmental impacts simultaneously [13]. In the following section, the proposed mathematical model is presented.

3 Proposed Mathematical Model

The designed CLSC network in this paper is a multi-objective, multi-product, multi-level network that maximizes the total profit, social effects, and minimizes the environmental impacts simultaneously. In the following subsections, the sets, parameters, and decision variables are described.

3.1 Sets

v The fixed supplier location
c The fixed first market location
q The fixed second market location
d The fixed locations of disposal center
i The potential locations for establishing the factory
j The potential locations for establishing the distribution center
k The potential locations for establishing the collection center
l The potential locations for establishing the repair center
s The potential locations for establishing the redistribution center
r The potential locations for establishing the recycling center
p Products
e Raw material
h Capacity levels for potential locations

3.2 Parameter

Pr_{cp}	The purchasing cost of product *p* in the first market *c*
Prr_{qp}	The purchasing cost of product *p* in the second market *q*
DE_{cp}	The amount of demand for product *p* in the first market *c*
DDE_{qp}	The amount of demand for product *p* in the second market *q*
FX_{ih}	The fixed cost for establishing the factory *i* with capacity level *h*
FY_{jh}	The fixed cost for establishing the distribution center *j* with capacity level *h*
FH_{kh}	The fixed cost for establishing the collection center *k* with capacity level *h*
FW_{lh}	The fixed cost for establishing the repair center *l* with capacity level *h*
FO_{sh}	The fixed cost for establishing the redistribution center *s* with capacity level *h*
FU_{rh}	The fixed cost for establishing the recycling center *r* with capacity level *h*
SC_{ve}	The purchasing cost of raw material *e* from supplier *v*
MC_{ip}	The production cost of product *p* in factory *i*
RMC_{ip}	The reproduction cost of product *p* in factory *i*
DC_{jp}	The holding cost of product *p* in distribution center *j*
CC_{kp}	The inspection cost of product *p* in collection center *j*
DPC_{dp}	The disposal cost of product *p* in disposal center *d*
RPC_{lp}	The repair cost of product *p* in repair center *l*
RDC_{sp}	The redistribution cost of product *p* in redistribution center *s*
RC_{rp}	The recycling cost of product *p* in recycling center *r*
TVI_{vie}	The cost of transporting raw material *e* from supplier *v* to factory *i*
TIJ_{ijp}	The cost of transporting product *p* from factory *i* to distribution center *j*
TJC_{jcp}	The cost of transporting product *p* from distribution center *j* to the first market *c*
TCK_{ckp}	The cost of transporting product *p* from the first market *c* to the collection center *k*
TKI_{kip}	The cost of transporting product *p* from collection center *k* to the factory *i* for reproduction
TKD_{kdp}	The cost of transporting product *p* from collection center *k* to the disposal center *d*
TKL_{klp}	The cost of transporting product *p* from collection center *k* to the repair center *l*
TKR_{krp}	The cost of transporting product *p* from collection center *k* to the recycling center *i*
TLS_{lsp}	The cost of transporting product *p* from repair center *l* to the recycling center *s*
TSQ_{sqp}	The cost of transporting product *p* from redistribution center *s* to the second market *q*
TRV_{rve}	The cost of transporting raw material *e* from recycling center *r* to the supplier *v*
$CapV_{v}$	The maximum capacity of supplier *v*
$CapI_{ih}$	The maximum capacity of factory *i* with capacity level *h*
$CapJ_{jh}$	The maximum capacity of distribution center *j* with capacity level *h*

$CapK_{kh}$	The maximum capacity of collection center *k* with capacity level *h*
$CapL_{lh}$	The maximum capacity of repair center *l* with capacity level *h*
$CapS_{sh}$	The maximum capacity of redistribution center *s* with capacity level *h*
$CapR_{rh}$	The maximum capacity of recycling center *r* with capacity level *h*
RT	The rate of returned products from the first market to the collection center
RM	The rate of reproduction in factory
RS	The rate of recycling in recycling centers
RD	The disposal rate in disposal center
RR	The rate of repair in repair centers
θ_{JO}	The normalized weighted factor for the created job opportunities in facility
θ_{LD}	The normalized weight factor for the total number of lost working days due to workplace injury at the facility
JOI_{ih}	The number of created job opportunity in case of establishing factory *i* with capacity level *h*
JOJ_{jh}	The number of created job opportunity in case of establishing distribution center *j* with capacity level *h*
JOK_{kh}	The number of created job opportunity in case of establishing collection center *k* with capacity level *h*
JOL_{lh}	The number of created job opportunity in case of establishing repair center *i* with capacity level *h*
JOS_{sh}	The number of created job opportunity in case of establishing reproduction center *s* with capacity level *h*
JOR_{rh}	The number of created job opportunity in case of establishing recycling center *r* with capacity level *h*
LDI_{ih}	Average lost working days due to the work injury in case of establishing the factory *i* with capacity level *h*
LDL_{lh}	Average lost working days due to workplace injury in case of establishing the repair center l with capacity level h
LDR_{rh}	Average lost working days due to the workplace injury in case of establishing the recycling center *r* with capacity level *h*
$ETVI_{vie}$	The carbon emission rate for shipping the raw material *e* from supplier *v* to factory *i*
$ETIJ_{ijp}$	The amount of carbon emission for shipping product *p* from factory *i* to distribution center *j*
$ETJC_{jcp}$	The amount of carbon emission for shipping product *p* from distribution center *j* to first market *c*
$ETCK_{ckp}$	The amount of carbon emission for shipping product *p* from the first market *c* to collection center *k*
$ETKI_{kip}$	The amount of carbon emission for shipping product *p* from the first market *c* to factory *i* for reproduction
$ETKD_{kdp}$	The amount of carbon emission for shipping product *p* from the collection center *k* to disposal center *d*
$ETKL_{klp}$	The amount of carbon emission for shipping product *p* from the collection center *k* to repair center *l*
$ETKR_{krp}$	The amount of carbon emission for shipping product *p* from the collection center *k* to recycling center *r*
$ETLS_{lsp}$	The amount of carbon emission for shipping product *p* from repair center *l*

	to redistribution center *s*
$ETSQ_{sqp}$	The amount of carbon emission for shipping product *p* from redistribution center *s* to the second market *q*
$ETRV_{rvp}$	The amount of carbon emission for shipping raw material *e* from recycling center *r* to the supplier *v*
EM_{ip}	The amount of carbon emission for producing product *p* in factory *i*
ERM_{ip}	The amount of carbon emission for reproducing product *p* in factory *i*
ERP_{lp}	The amount of carbon emission for repairing product *p* in repair center *l*
ERC_{rp}	The amount of carbon emission for recycling product *p* in recycling center *l*
NX	The maximum number of factory for establishment
NY	The maximum number of distribution center for establishment
NH	The maximum number of collection center for establishment
NW	The maximum number of repair center for establishment
NO	The maximum number of redistribution center for establishment
NU	The maximum number of recycling center for establishment

3.3 Decision Variable

QVI_{vie}	The amount of raw material *e* transported from supplier *v* to factory *i*
QIJ_{ijp}	The amount of product *p* transported from factory *i* to distribution center *j*
QJC_{jcp}	The amount of product *p* transported from distribution center *j* to first market *c*
QCK_{ckp}	The amount of product *p* transported from the first market *c* to collection center *k*
QKI_{kip}	The amount of product *p* transported from the collection center *k* to factory *i* for reproduction
QKD_{kdp}	The amount of product *p* transported from the collection center *k* to disposal center *d*
QKL_{klp}	The amount of product *p* transported from the collection center *k* to repair center *l*
QKR_{krp}	The amount of product *p* transported from the collection center *k* to recycling center *r*
QLS_{lsp}	The amount of product *p* transported from the repair center *l* to redistribution center *s*
QSQ_{sqp}	The amount of product *p* transported from the redistribution center *s* to the second market *q*
QRV_{rve}	The amount of product *p* transported from the recycling center *r* to supplier *v*
X_{ih}	If factory *i* with capacity level *h* is established, otherwise 0
Y_{jh}	If distribution center *j* with capacity level *h* is established, otherwise 0
T_{kh}	If collection center *k* with capacity level *h* is established, otherwise 0
W_{lh}	If repair center *l* with capacity level *h* is established, otherwise 0
O_{sh}	If redistribution center *s* with capacity level *h* is established, otherwise 0
U_{rh}	If recycling center *r* with capacity level *h* is established, otherwise 0

$$Max\ \ Z_1 = \left(\sum_j \sum_c \sum_p \Pr_{cp} QJC_{jcp} + \sum_s \sum_q \sum_p \Pr r_{qp} QSQ_{sqp} \right) - \tag{1}$$

$$\left(\begin{array}{l} \sum_i \sum_h FX_{ih} X_{ih} + \sum_j \sum_h FY_{jh} Y_{jh} + \sum_k \sum_h FH_{kh} T_{kh} + \\ \sum_l \sum_h FW_{lh} W_{lh} + \sum_s \sum_h FO_{sh} O_{sh} + \sum_r \sum_h FU_{rh} U_{rh} \end{array} \right) -$$

$$\left(\begin{array}{l} \sum_v \sum_i \sum_e TVI_{vie} QVI_{vie} + \sum_i \sum_j \sum_p TIJ_{ijp} QIJ_{ijp} + \sum_j \sum_c \sum_p TJC_{jcp} QJC_{jcp} + \\ \sum_c \sum_k \sum_p TCK_{ckp} QCK_{ckp} + \sum_k \sum_i \sum_p TKI_{kip} QKI_{kip} + \sum_k \sum_d \sum_p TKD_{kdp} QKD_{kdp} + \\ \sum_k \sum_l \sum_p TKL_{klp} QKL_{klp} + \sum_k \sum_r \sum_p TKR_{krp} QKR_{krp} + \sum_l \sum_s \sum_p TLS_{lsp} QLS_{lsp} + \\ \sum_s \sum_q \sum_p TSQ_{sqp} QSQ_{sqp} + \sum_r \sum_v \sum_e TRV_{rve} QRV_{rve} \end{array} \right) -$$

$$\left(\begin{array}{l} \sum_v \sum_i \sum_e SC_{ve} QVI_{vie} + \sum_i \sum_j \sum_p MC_{ip} QIJ_{ijp} + \sum_j \sum_c \sum_p DC_{jp} QJC_{jcp} + \\ \sum_c \sum_k \sum_p CC_{kp} QCK_{ckp} + \sum_k \sum_i \sum_p RMC_{ip} QKI_{kip} + \sum_k \sum_d \sum_p DPC_{dp} QKD_{kdp} + \\ \sum_k \sum_l \sum_p RPC_{lp} QKL_{klp} + \sum_i \sum_j \sum_p RC_{rp} QKR_{krp} + \sum_l \sum_s \sum_p RDC_{sp} QLS_{lsp} \end{array} \right)$$

$$Max\ \ Z_2 = \theta_{JO} \left(\begin{array}{l} \sum_i \sum_h JOI_{ih} X_{ih} + \sum_j \sum_h JOJ_{jh} Y_{jh} + \sum_k \sum_h JOK_{kh} T_{kh} + \\ \sum_l \sum_h JOL_{lh} W_{lh} + \sum_s \sum_h JOS_{sh} O_{sh} + \sum_r \sum_h JOR_{rh} U_{rh} \end{array} \right) - \tag{2}$$

$$\theta_{LD} \left(\sum_i \sum_h JDI_{ih} X_{ih} + \sum_l \sum_h LDL_{lh} W_{lh} + \sum_r \sum_h LDR_{rh} T_{rh} \right)$$

$$Min\ Z_3 = \sum_v \sum_i \sum_e ETVI_{vie} QVI_{vie} + \sum_i \sum_j \sum_p (ETIJ_{ijp} + EM_{ip}) QIJ_{ijp} + \sum_j \sum_c \sum_p ETJC_{jcp} QJC_{jcp} + \tag{3}$$

$$\sum_c \sum_k \sum_p ETCK_{ckp} QCK_{ckp} + \sum_k \sum_i \sum_p (ETKI_{kip} + ERM_{ip}) QKI_{kip} + \sum_k \sum_d \sum_p ETKD_{kdp} QKD_{kdp} +$$

$$\sum_k \sum_l \sum_p (ETKL_{klp} + ERP_{lp}) QKL_{klp} + \sum_k \sum_r \sum_p (ETKR_{krp} + ERC_{rp}) QKR_{krp} + \sum_l \sum_s \sum_p ETLS_{lsp} QLS_{lsp} +$$

$$+ \sum_s \sum_q \sum_p ETSQ_{sqp} QSQ_{sqp} + + \sum_r \sum_v \sum_p ETRV_{rve} QRV_{rve}$$

The first objective function (Equation 1) maximizes the profits (total revenue minus total costs) from establishing the facilities in four parts. In the first part, the revenue obtained from the product's sale in the first and second market is computed. The fixed costs of establishing factory, distribution, collection, repair, redistribution, and recycling center are calculated in the second part. In the third part, the transportation cost between facilities is shown. Finally, in the fourth part, the operating cost of the supply chain is presented. The second objective function (Equation 2) maximizes the social effects of the supply chain network by maximizing the created job opportunities as well as minimizing the average lost days due to workplace injury. The third objective function (Equation 3) minimizes the environmental impacts, CO_2 emission resulted from transportation, production, reproduction, repair, and recycling throughout the supply chain.

Constraint

$$\sum_j \sum_p QIJ_{ijp} = \sum_v \sum_e QVI_{vie} + \sum_k \sum_p QKI_{kip} \qquad \forall i \tag{4}$$

$$\sum_i QIJ_{ijp} = \sum_c QJC_{jcp} \qquad \forall j, p \tag{5}$$

$$\sum_j QJC_{jcp} \geq DE_{cp} \qquad \forall c, p \tag{6}$$

$$\sum_k QCK_{ckp} = DE_{cp} \times RT \qquad \forall c, p \tag{7}$$

$$\sum_d QKD_{kdp} = \sum_c QCK_{ckp} \times RD \qquad \forall k, p \tag{8}$$

$$\sum_l QKL_{klp} = \sum_c QCK_{ckp} \times RR \qquad \forall k, p \tag{9}$$

$$\sum_r QKR_{krp} = \sum_c QCK_{ckp} \times RS \qquad \forall k, p \tag{10}$$

$$\sum_i QKI_{kip} = \sum_c QCK_{ckp} \times RM \qquad \forall k, p \tag{11}$$

$$\sum_c QCK_{ckp} = \sum_d QKD_{kdp} + \sum_i QKI_{kip} + \sum_l QKL_{klp} + \sum_r QKR_{krp} \qquad \forall k, p \tag{12}$$

$$\sum_k QKL_{ckp} = \sum_s QLS_{lsp} \qquad \forall l, p \tag{13}$$

$$\sum_l QLS_{lsp} = \sum_q QSQ_{sqp} \qquad \forall s, p \tag{14}$$

$$\sum_s QSQ_{sqp} \geq DDE_{qp} \qquad \forall q, p \tag{15}$$

$$\sum_k \sum_p QKR_{krp} = \sum_v \sum_e QRV_{rve} \qquad \forall r \tag{16}$$

$$\sum_i \sum_e QVI_{vie} \leq CapV_v \qquad \forall v \tag{17}$$

$$\sum_j \sum_p QIJ_{ijp} \leq \sum_h CapI_{ih} X_{ih} \qquad \forall i \tag{18}$$

$$\sum_c \sum_p QJC_{jcp} \leq \sum_h CapJ_{jh} Y_{jh} \qquad \forall j \tag{19}$$

$$\sum_c \sum_p QCK_{ckp} \leq \sum_h CapK_{kh} T_{kh} \qquad \forall k \tag{20}$$

$$\sum_k \sum_p QKL_{klp} \leq \sum_h CapL_{lh} W_{lh} \qquad \forall l \tag{21}$$

$$\sum_l \sum_p QLS_{lsp} \leq \sum_h CapL_{sh} W_{sh} \qquad \forall s \tag{22}$$

$$\sum_k \sum_p QKR_{krp} \leq \sum_h CapR_{rh} U_{rh} \qquad \forall r \tag{23}$$

$$\sum_h X_{ih} \leq 1 \qquad \forall i \tag{24}$$

$$\sum_h Y_{jh} \le 1 \qquad \forall j \tag{25}$$

$$\sum_h T_{kh} \le 1 \qquad \forall k \tag{26}$$

$$\sum_h W_{lh} \le 1 \qquad \forall l \tag{27}$$

$$\sum_h O_{sh} \le 1 \qquad \forall s \tag{28}$$

$$\sum_h U_{rh} \le 1 \qquad \forall r \tag{29}$$

$$\sum_h X_{ih} \le NX \qquad \forall i \tag{30}$$

$$\sum_h Y_{jh} \le NY \qquad \forall j \tag{31}$$

$$\sum_h T_{kh} \le NH \qquad \forall k \tag{32}$$

$$\sum_h W_{lh} \le NW \qquad \forall l \tag{33}$$

$$\sum_h O_{sh} \le NO \qquad \forall s \tag{34}$$

$$\sum_h U_{rh} \le NU \qquad \forall r \tag{35}$$

$$X_{ih},\ Y_{jh},\ T_{kh},\ W_{lh},\ O_{sh},\ U_{rh} \in \{0,1\} \tag{36}$$

$$QVI_{vie},\ QIJ_{ijp},\ QJC_{jcp},\ QCK_{ckp},\ QKI_{kip},\ QKD_{kdp},\ QKL_{klp},\ QKR_{krp},\ QLS_{lsp},\ QSQ_{sqp},\ QRV_{rve} \ge 0 \tag{37}$$

Constraint 4 guarantees that the summation of inflows to each factory from all suppliers and collection centers is equal to the center's outflows. Constraint 5 ensures that the summation of the inflows to each distribution center from all production centers is equal to the summation of the outflows from these distribution centers. Constraint 6 ensures that the demand of all customers in the first market area is satisfied. Constraint 7 indicates the relationship between customer demand in first market areas and the returned products to collection centers. Constraint 8 shows that the outflows from the collection centers to all disposal centers are equal to the inflows to each collection center from all first market customers multiplied by the disposal ratio. Constraint 9 shows that the outflows from the collection centers to all repair centers are equal to the inflows to each collection center from all first market customers multiplied by the repair ratio. Constraint 10 shows that for each product, the outflows from the collection centers to all recycling centers are equal to the inflows to each collection center from all first market customers multiplied by the recycling ratio. Constraint 11 shows that the outflows from the collection centers to all factories are equal to the inflows to each collection center from all first market customers multiplied by the reproduction ratio. Constraint 12 shows that the inflows to each collection center from all the first market customers are equal to the sum of the outflows from this center to the repair, reproduction, recycling, and disposal centers. Constraint 13 ensures that the sum of the inflows to each repair center from all collection centers is equal to the summation of the outflows from these repair centers. Constraint 15 ensures that the demand of all customers in the second market is satisfied. Constraint 16 ensures that for each raw material, the sum of inflows to each recycling center from all collection centers is equal to the sum of the outflows from these recycling centers. Constraint 17 ensures that the sum of outflows from each supplier to all factories does not exceed the supplier's capacity for each raw material. Constraint 18 ensures that the total output from each factory to all distribution centers does not exceed the factories' capacity for each product. Constraint 19 ensures that the sum of the outflows from each distribution center to all first market customers does not exceed the distribution center's capacity for each product. Constraint 20 ensures that the total inflows to the collection centers from all customers in the first market do not exceed the collection centers' capacity. Constraint 21 ensures that the total inflows to the repair centers from all collection centers do not exceed the capacity's repair centers. Constraint 22 ensures that the total inflows to the redistribution centers from all collection centers do not exceed the redistribution centers' capacity. Constraint 23 ensures that the total inflows to recycling centers from collection centers do not exceed recycling centers' capacity. Constraints 24 to 29 ensure that the factories, distribution, collection, repair, redistribution, and recycling centers are built with at most one capacity level, respectively. Constraints 30 to 35 limit the maximum number of facilities, including factories, distribution, collection, repair, redistribution, and recycling centers for the establishment, respectively. Constraints 36 and 37 show the binary and positive variables of the model, respectively.

4 Numerical Examples

In this section, five different scenarios are defined to evaluate the proposed deterministic model. To solve the model, GAMS, solver CPLEX with a system of Cori7 and RAM 16 GIG is used. In addition, to overcome the innate uncertainty, the Bental-Nimrovski approach is implemented. To compare the obtained results from deterministic and robust models, two criteria are defined, standard deviation and mean of solutions which are summarized in Table 1 [17, 18]. As was expected, the results demonstrate the superiority of the deterministic model in terms of the first criteria (mean) in most cases, which is due to implementing the Bental Nimrovski approach, which provides the worst optimized solutions. On the other hand, the robust model shows a better solution than the deterministic model in terms of standard deviation.

Table 1. Mean and standard deviation of the objective functions under different numerical examples

Test	Level of uncertainty	Mean of the objective functions under tests						Standard deviation of the objective functions under tests					
		Certain			Robust			Certain			Robust		
		Z_1	Z_2	Z_3	Z_1	Z_2	Z_3	Z_1	Z_2	Z_3	Z_1	Z_2	Z_3
1	0.20	1471389	1425	4979	1443491	1395	6391	23280	14	105	12827	6	66
	0.50	1438239	1429	4971	1410900	1376	6559	53807	42	142	20108	3	25
	1	1468308	1437	4908	1372803	1365	6615	33885	24	63	18554	2	19
2	0.20	1802385	1778	13362	1950852	1777	17169	95885	137	157	41117	20	102
	0.50	1897217	1798	13571	1873418	1671	17376	157140	103	328	37141	37	46
	1	1848915	1744	13663	1757935	1618	17871	125590	130	110	43065	12	72
3	0.20	2530859	2297	13003	2522298	2436	17383	70324	161	513	15913	8	24
	0.50	2491791	2342	12954	2484593	2401	17561	37530	220	798	23407	33	105
	1	2469014	2357	12825	2411694	2107	17849	40128	109	1030	16067	73	94
4	0.20	2894264	2500	13692	2719786	2575	18318	78356	107	133	31941	28	22
	0.50	2902641	2560	13834	2629353	2465	18472	81214	110	273	18249	14	150
	1	2854546	2475	13437	2548031	2415	18788	65352	111	256	33258	31	91
5	0.20	2729494	3208	16491	3613648	3005	14937	334308	226	2262	108021	4	937
	0.50	2333410	2846	15638	3414474	2933	16726	252544	136	1354	162274	46	399
	1	3284102	3020	16285	2956161	2757	18772	211693	139	1825	105276	24	705

5 Conclusion

In this paper, a multi-objective robust optimization model for the closed-loop supply chain was presented. According to the multidimensional concept of sustainability, the goals of maximizing profits and social effects as well as minimizing the environmental impacts were considered. To formulate the problem, a mixed-integer linear programming model was proposed to design a closed-loop supply chain network. To extend the proposed model under uncertainty, some model parameters, such as first and second market customer demand, transportation costs between facilities, as well as operating costs related to each facility, were considered uncertain. Then, based on the Bental-Nimrovski approach, the robust counterparts presented. Finally, five different scenarios were defined to evaluate the deterministic and robust model's performance based on two criteria (mean and standard deviation of the objective functions). The results demonstrated the superiority of the deterministic model in most cases in terms of objective function's means, while the robust method had better performance in terms of standard deviation. In conjunction with the potential factories, distribution, collection, repair, redistribution, and recycling centers, as well as the number of products transported between facilities, were determined. Since the proposed robust model is NP-hard, it requires considerable solving time for the large dimension problems, so as future studies implementing the heuristic methods are recommended.

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