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A Possibilistic Reliable and Responsive Closed Loop Supply Chain Network Design Model under Uncertainty

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Reliability of supply chain networks is an important issue affecting customer satisfaction and profitability of organizations. However, occurrence of disruptions such as flood, earthquake and fire could ruin performance of supply chains. Uncertainty of parameters is another important factor that could lower quality of long-term plans of companies. Hence, uncertainty of parameters and disruption strike are important issues adversely influencing reliability of networks. Also, responsiveness of supply chains is a significant matter that should be considered carefully while designing distribution networks. Responsiveness could increase customer loyalty and satisfaction that could result in increasing market share of companies and their long-term planned benefit. Regarding alluded matters, the aim of this paper is designing a reliable forward-reverse supply chain network that minimizes total costs of network design along with maximization of total responsiveness of distribution network. Extended closed-loop network is capable of considering environmental issues by caring about end-of-life products. Designing reverse supply chain network aside with forward ones could decrease bad environmental impact of end-of-life products. Notably, to cope with adverse effects of disruptions, a scenario-based approach is suggested that enables considering partial and complete disruption of capacity of facilities. Additionally, an effective possibilistic programming method is applied to appropriately control uncertainty of parameters. As quality of raw materials is important to produce high-quality products, minimum acceptable quality level of raw materials is considered in extended model to maximize customer satisfaction. Finally, it should be noted that designed test problems show appropriate performance of suggested model and its applicability in real world case studies. Extended model is solved regarding different risk-aversion levels and sensitivity analysis is performed for different parameters of network design that shows effectual performance of proposed model.

Keywords: Supply chain; reliability; network design; responsiveness; possibilistic programming.

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1. Introduction

Nowadays, there are many factors that guarantee proper design and performance of supply chains and each of them could make long-term competitive advantage for companies. One of these factors is reliability of supply chain networks.[39] Reliability can be defined as capability of supply chain echelons to cope with adverse effect of different types of risks threatening whole performance of network named as disruptions.[4,35] In other words, disruption strike may ruin the performance of supply chain echelons and beget great losses for company stakeholders and decrease market share of companies.[19] Furthermore, it could lower responsiveness of supply chains and decrease customer satisfaction that could be regarded as a negative point in performance of worldwide expanded companies.[43,27] In this regard, paying attention to reliability factors in the design of networks helps to improve customer satisfaction. Also, it increases long-term benefit of company business.[33,34] Planning and integrated management of different echelons of supply chains could also help to achieve aforementioned goals (see Refs. 1, 5–7, 11, 30).

Generally, uncertainties affecting the performance of supply chains could be classified into two categories called as business-as-usual uncertainty and man-made disruptions. Uncertainty of parameters of network design is an inseparable part of nature of supply chains that is available in all echelons of networks. Uncertainty of parameters decreases quality of decisions made by company decision makers via changing the trend of planning parameters.[19,42] In other words, availability of uncertain parameters such as demand and different types of costs could affect output decisions based on risk-averseness and degree of uncertainty of parameters.[9,13,23,30] Hence, many researchers have extended appropriate methods to control adverse effects of this type of uncertainty. One of these methods is stochastic programming. This method has some deficiencies owing to its need to large amount of data to generate different uncertainty scenarios. Furthermore, increment of number of uncertain parameters results in time-consuming simulations to generate probability distribution of each uncertain parameter.[16,25,29]

Another method that could cope with uncertainty of parameters is possibilistic programming that is able to control the risk averseness degree of output decisions by applying opinion of company decision makers. Notably, possibility distribution of uncertain parameters could be defined based on experts' opinion which relies on their experience.[18,20,22,44] This method has solved aforementioned deficiencies by application of possibility distribution and confidence level of uncertain parameters.[3,21,28,31]

The other type of uncertainty is disruption strike that could be the result of man-made natural disasters such as terrorist attack, flood, fire and earthquake. This kind of uncertainty ruins a part or whole processing capacity of facilities of supply chains that could adversely affect the responsiveness of supply chains. Noted matters could result in customer dissatisfaction and make great losses for different echelons of networks.[10,15,37] To control and cope with the adverse effects of disruptions, reliable programming models are extended by researchers. These methods seek to lower the risk of disruption strikes by application of different methods such as outsourcing, back-ordered sales and cooperation with competitors.[17,19,24,32] Each of these methods has some deficiencies such as penalty cost of customer dissatisfaction and also dependence on competitors that could make some other risks for companies regarding their business.[12,26,38,41] Accordingly, development and application of appropriate methods to strengthen networks against disruptions could be regarded as an interesting research line.

As it was mentioned, responsiveness of supply chain networks to customer demand is an important subject that could result in customer loyalty and decrease of back-ordered sales.[2,8,25] Notably, responsiveness could be defined as capability of delivering products to customer zones on time. Therefore, late delivery of products would result in lost or backlogged sales and early delivery of products could result in inventory holding cost. Both the noted matters are negative points for companies.[36,40] Accordingly, caring about noted matters in the design of logistics networks should be regarded by planners of organizations while designing their network.

Based on enumerated matters, the aim of this paper is designing a multi-objective linear programming closed loop supply chain network model that minimizes total costs of network aside with minimization total earliness/tardiness of supply chain networks. Also, it is capable of coping with different types of uncertainties which makes the model and its output results unreliable. Reliable programming models are applied to control adverse effects of disruptions and also possibilistic programming method is employed to control uncertainty of parameters and level of risk-aversion of outputs based on opinion of company's decision makers. Finally, it is worth mentioning that extended closed loop supply chain model cares about environmental issues by extending the backward side of network to recycle and recover end-of-life products. Notably, the suggested model is a general one that could be employed to optimize the performance of different real-world industrial cases.

With regard to enumerated matters, the aim of this paper is to design a reliable multi-echelon closed loop supply chain network such that its differences from other available researches in literature is as follows:

- Extending a bi-objective reliable closed loop supply chain network design (SCND) model that minimizes total variable processing and transportation costs of network aside with fix cost of opening facilities at different echelons of network and also minimizes earliness/tardiness of products delivery to customer zones,
- Suggesting a mixed integer linear programming model that copes with adverse effects of partial or complete disruptions by application of stochastic programming and accordingly scenario-based modeling,
- Extending a possibilistic programming model that controls uncertainty of parameters based on opinion of field experts and company managers,

- Designing a general supply chain network model that consists of different echelons in forward and backward directions of network that is applicable to real-world problems such as paper and electronic appliances recycling.

Remainder of this paper is organized as follows. Comprehensive problem definition and extended model's assumptions are presented in Sec. 2. Model formulation and definition of constraints and objective functions of suggested model are rendered in Sec. 3. Possibilistic programming method and suggested equivalent crisp model are presented in Sec. 4. Some test problems and sensitivity analysis performed based on output results of extended model are presented in Sec. 5. Future research directions and some managerial suggestions are presented along with conclusion in Sec. 6.

2. Problem Definition

Extended multi-echelon closed loop supply chain network is single product and single period as shown in Fig. 1. There are two kinds of suppliers which provide raw materials for plants in the forward side of network. First kind of suppliers provide raw materials that are produced from their original natural resources and are not recycled raw materials. Second type of suppliers provide recycled raw materials for plants. Obviously, recycled raw materials are cheaper than the other kind of raw materials. However, quality of recycled raw materials is lower than the other type of raw materials that are produced from natural resources. After producing final products at different plants, they are transferred to customer zones via different distribution centers. At the backward side of network, end-of-life products (i.e. a percent of products delivered to customer zones at previous time period) are collected via collection center. A percent of collected products are recoverable and they would

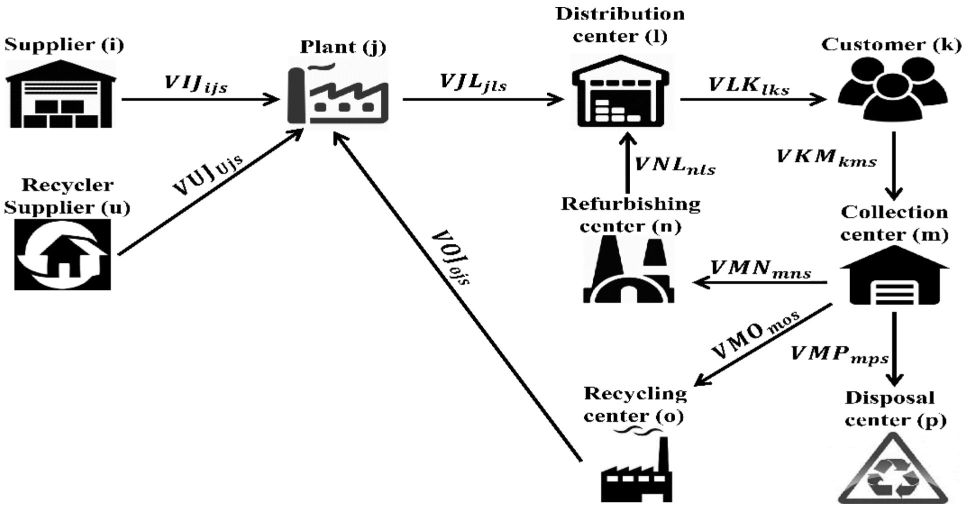

Fig. 1. Proposed closed loop supply chain network structure.

be sent to recovery centers. Recovered products would be sent to distribution centers for satisfying demand of customer zones aside with products produced at manufacturing plants. A percent of collected products are useless and they should be sent to disposal centers for safe disposal. Finally, a percent of collected products are recyclable and they should be sent to recycling centers. Products at recycling centers would be recycled and separated to their raw materials. Then, raw materials would be sent to production plants for producing new products. Recycled raw materials have lower quality in comparison with non-recycled raw materials; however, recycling cost is lower than the price of extracting raw materials from their natural resources.

It is assumed that distribution centers are in danger of disruption strikes as they are the most important stakeholder of supply chain with regard to their important role in delivering products to customer zones. To model disruptions and appropriately reduce adverse effect of disruptions, different disruption scenarios are defined. Each scenario has an occurrence probability which determines non-operating distribution centers and percentage of disrupted capacity of each distribution center at each scenario. Defined scenarios help to choose the best set of opened distribution centers that work properly regarding different disruption scenarios and also lower the risk of cost enhancement via disruption strike.

The other important point is that each customer zone defines a predefined delivery lead time for different distribution centers. Late delivery of products would cause customer dissatisfaction. Also, early delivery of products to customer zones would cause product holding cost at customer zones. In this regard, total earliness and tardiness of products delivery to customer zones is minimized as an objective function along with minimization of total costs of network design.

With regard to enumerated matters, following assumptions are presented to extend the suggested model.

- Demand of customer zones should be fully satisfied,
- Number and capacity of suppliers, collection and recovery centers is predefined,
- Number and capacity of plants, distribution and recycling centers is not predetermined and should be defined based on flow of products between different echelons of network,
- All end-of-life products should be collected via different collection centers,
- Each raw material provided by suppliers and recycling centers has a predefined quality level where the total amount of provided raw materials should meet the minimum acceptable quality level defined by company managers.

Noteworthy, the extended network minimizes total costs of network design along with total earliness and tardiness of products delivery to customer zones. Also, optimal number and location of opened plants, distribution and recycling centers and products flow between consecutive echelons of network would be determined as decision variables.

3. Model Formulation

To formulate elucidated closed loop supply chain network with regard to noted assumptions, following indices, parameters and decision variables should be presented.

Indices:

I	Index of suppliers $(i = 1, 2, \ldots, I)$
U	Index of suppliers or recycled raw materials $(u = 1, 2, \ldots, U)$
J	Index of plants $(j = 1, 2, \ldots, J)$
L	Index of distribution centers $(l = 1, 2, \ldots, L)$
K	Index of customer zones $(k = 1, 2, \ldots, K)$
N	Index of refurbishing centers $(n = 1, 2, \ldots, N)$
M	Index of collection/inspection centers $(m = 1, 2, \ldots, M)$
O	Index of recycling centers $(o = 1, 2, \ldots, O)$
P	Index of disposal centers $(p = 1, 2, \ldots, P)$
Z	Index of capacity levels of plants $(z = 1, 2, \ldots, Z)$
T	Index of capacity levels of distribution centers $(q = 1, 2, \ldots, Q)$
Q	Index of capacity levels of recycling centers $(s = 1, 2, \ldots, S)$
S	Index of scenarios

Parameters:

FJ_{jz}	Fixed cost of establishing a factory at potential location j with capacity level z
FL_{lt}	Fixed cost of establishing a distribution center at potential location l with capacity level t
FO_{oq}	Fixed cost of establishing a recycling center at potential location o with capacity level q
CI_i	Cost of purchasing each unit of raw material from supplier i
CU_u	Cost of purchasing each unit of recycled raw material from supplier u
CJ_j	Production cost each unit of final product at factory j
CL_l	Holding cost of each unit of product at distribution center l
CMN_m	Processing and packaging cost of each unit of product for recovery at collection center m
CMO_m	Processing and packaging cost of each unit of product for refurbishing at collection center m
CMP_m	Processing and packaging cost of each unit of product for disposal at collection center m
CNL_n	Refurbishment cost of each unit of product at refurbishing center n
COJ_o	Recycling cost of each unit of product at recycling center o
CP_p	Disposal cost of each unit of product at disposal center p
TIJ_{ij}	Transferring cost per unit of raw material from supplier i to factory j

TUJ_{uj}	Transferring cost per unit of recycled raw material from supplier u to factory j
TJL_{jl}	Transferring cost per unit of final product from factory j to distribution center l
TLK_{lk}	Transferring cost per unit of final product from distribution center l to customer zone k
TKM_{km}	Transferring cost per unit of final product from customer zone k to collection center m
TMN_{mn}	Transferring cost per unit of final product from collection center m to refurbishing center n
TMO_{mo}	Transferring cost per unit of final product from collection center m to recycling center o
TMP_{mp}	Transferring cost per unit of final product from collection center m to disposal center p
TNL_{nl}	Transferring cost per unit of final product from refurbishing center n to distribution center l
TOJ_{oj}	Transferring cost per unit of raw material from recycling center o to factory j using transportation mode b
DE_k	Demand of customer zone k

ζ_k	Percent of returned end-of-life products at customer zone k
λ_1	Percent of returned products to each collection center that should be disposed
λ_2	Percent of returned products to each collection center that should be recycled
λ_3	Percent of returned products to each collection center that should be refurbished
$CAPJ_{jz}$	Maximum production capacity of factory j established with capacity level z
$CAPL_{lt}$	Maximum storage capacity of distribution center l established with capacity level t
$CAPO_{oq}$	Maximum product recycling capacity of recycling center o established with capacity level q
$CAPI_i$	Maximum capacity of supplier i for providing raw material for factories
$CAPU_u$	Maximum capacity of supplier u for providing recycled raw material for factories
$CAPM_m$	Maximum product processing capacity of collection center m
$CAPN_n$	Maximum product recovery capacity of refurbishing center n
$CAPP_p$	Maximum product safe disposal capacity of disposal center p
DIS_{js}	Percentage of disrupted capacity of plant j at scenario s
A_s	Probability of scenario s

$DTLK_{lk}$	Delivery time of products from distribution center l to customer zone k
$EDTK_k$	Expected delivery time of products to customer zone k
EQJ_j	Expected quality of raw materials provided by different suppliers to plant j
EQI_i	Quality of each unit of raw material provided by supplier i
EQU_u	Quality of each unit of raw material provided by recycler supplier u
EQO_o	Quality of each unit of raw material provided by recycling center o

Decision variables:

XJ_{jz}	1: If a factory is established at potential location j with capacity level z; 0: otherwise
XL_{lt}	1: If a distribution center is established at potential location l with capacity level t; 0: otherwise
XO_{oq}	1: If a recycling center is established at potential location o with capacity level q; 0: otherwise
VIJ_{ijs}	Number of transferred raw material from supplier i to factory j at scenario s
VUJ_{ujs}	Number of transferred recycled raw material from supplier i to factory j at scenario s
VJL_{jls}	Number of transferred final products from factory j to distribution center l at scenario s
VLK_{lks}	Number of transferred final products from distribution center l to customer zone k at scenario s
VKM_{kms}	Number of transferred final returned products from customer zone k to collection center m at scenario s
VMN_{mns}	Number of transferred final returned products collection center m to refurbishing center n at scenario s
VMO_{mos}	Number of transferred final returned products from collection center m to recycling center o at scenario s
VMP_{mps}	Number of transferred final returned products from collection center m to disposal center p at scenario s
VNL_{nls}	Number of transferred final recovered products from refurbishing center n to distribution center l at scenario s
VOJ_{ojs}	Number of transferred final recycled raw material from recycling center o to factory j at scenario s
$TTDT_{lks}$	Total tardiness of delivering products to customer zone k via distribution center l regarding scenario s
$TEDT_{lks}$	Total earliness of delivering products to customer zone k via distribution center l regarding scenario s

Described closed loop supply chain based on enumerated problem definition and presented indices, parameters and decision variables could be formulated as follows:

$$\begin{aligned}
\textbf{Min } \boldsymbol{Z_1} = {} & \sum_j \sum_z FJ_{jz} XJ_{jz} + \sum_l \sum_t FL_{lt} XL_{lt} + \sum_o \sum_q FO_{oq} XO_{oq} \\
& + \sum_s A_s \Bigg[\sum_i \sum_j (CI_i + TIJ_{ij}) VIJ_{ijs} \\
& + \sum_u \sum_j (CU_u + TUJ_{uj}) VUJ_{ujs} + \sum_j \sum_l (CJ_j + TJL_{jl}) VJL_{jls} \\
& + \sum_l \sum_k (CL_l + TLK_{lk}) VLK_{lks} + \sum_k \sum_m TKM_{km} VKM_{kmst} \\
& + \sum_m \sum_n (CMN_m + TMN_{mn}) VMN_{mns} \\
& + \sum_m \sum_o (CMO_m + TMO_{mo}) VMO_{mos} \\
& + \sum_m \sum_p (CMP_m + TMP_{mp}) VMP_{mps} \\
& + \sum_n \sum_l (CNL_n + TNL_{nl}) VNL_{nls} \\
& + \sum_o \sum_j (COJ_o + TOJ_{oj}) VOJ_{ojs} + \sum_m \sum_p CP_p VMP_{mps} \Bigg], \qquad (1)
\end{aligned}$$

$$\textbf{Min } \boldsymbol{Z_2} = \sum_s A_s \left[\sum_l \sum_k (TTDT_{lks} + TEDT_{lks}) \right] \qquad (2)$$

s.t.

$$\sum_l VLK_{lks} \geq DE_k \qquad \forall k, s, \qquad (3)$$

$$\sum_m VKM_{kms} \geq \zeta_k DE_k \qquad \forall k, s, \qquad (4)$$

$$\sum_o VOJ_{ojs} + \sum_u VUJ_{ujs} + \sum_i VIJ_{ijs} = \sum_l VJL_{jls} \qquad \forall j, s, \qquad (5)$$

$$\sum_j VJL_{jls} + \sum_n VNL_{nls} = \sum_k VLK_{lks} \qquad \forall l, s, \qquad (6)$$

$$\sum_k VKM_{kms} = \sum_n VMN_{mns} + \sum_o VMO_{mos} + \sum_p VMP_{mps} \qquad \forall m, s, \qquad (7)$$

$$\lambda_1 \sum_k VKM_{kms} = \sum_p VMP_{mps} \qquad \forall m, s, \qquad (8)$$

$$\lambda_2 \sum_k VKM_{kms} = \sum_p VMO_{mos} \qquad \forall m, s, \qquad (9)$$

$$\lambda_3 \sum_k VKM_{kms} = \sum_n VMN_{mns} \qquad \forall m, s, \qquad (10)$$

$$\sum_m VMN_{mns} = \sum_l VNL_{nls} \qquad \forall n, s, \qquad (11)$$

$$\sum_m VMO_{mos} = \sum_j VOJ_{ojs} \qquad \forall o, s, \tag{12}$$

$$\sum_l VJL_{jls} \leq \sum_z CAPJ_{jz}(1 - DIS_{js})XJ_{jz} \qquad \forall j, s, \tag{13}$$

$$\sum_k VLK_{lks} \leq \sum_t CAPL_{lt}XL_{lt} \qquad \forall l, s, \tag{14}$$

$$\sum_m VMO_{mos} \leq \sum_q CAPO_{oq}XO_{oq} \qquad \forall o, s, \tag{15}$$

$$\sum_j VIJ_{ijs} \leq CAPI_i \qquad \forall i, s, \tag{16}$$

$$\sum_j VUJ_{ujs} \leq CAPU_u \qquad \forall u, s, \tag{17}$$

$$\sum_k VKM_{kms} \leq CAPM_m \qquad \forall m, s \tag{18}$$

$$\sum_m VMN_{mns} \leq CAPN_n \qquad \forall n, s, \tag{19}$$

$$\sum_m VMP_{mps} \leq CAPP_p \qquad \forall p, s, \tag{20}$$

$$\sum_z XJ_{jz} \leq 1 \qquad \forall j, \tag{21}$$

$$\sum_t XL_{lt} \leq 1 \qquad \forall l, \tag{22}$$

$$\sum_t XO_{oq} \leq 1 \qquad \forall o, \tag{23}$$

$$VLK_{lks}(DTLK_{lk} - EDTK_k) = TTDT_{lks} - TEDT_{lks} \qquad \forall l, k, s, \tag{24}$$

$$\sum_i EQI_i VIJ_{ijs} + \sum_u EQU_u VUJ_{ujs} + \sum_o EQO_o VOJ_{ojs} \geq EQJ_j \qquad \forall j, s, \tag{25}$$

$$XJ_{jz}, XL_{lt}, XO_{oq} \in \{0, 1\} \qquad \forall j, z, l, t, o, q, \tag{26}$$

$$\begin{aligned} &VIJ_{ijs}, VUJ_{ujs}, VJL_{jls}, VLK_{lks}, VKM_{kms}, \\ &\quad VMP_{mps}, VMO_{mos}, VMN_{mns}, VNL_{nls}, VOJ_{ojs}, \\ &\quad VOR_{ors}, TEDT_{lks}, TTDT_{lks} \geq 0 \end{aligned} \qquad \begin{aligned} &\forall i, j, s, l, k, \\ &\quad m, p, o, n, r. \end{aligned} \tag{27}$$

Objective function (1) minimizes total costs of network design comprising opening cost of plants, distribution centers and recycling centers. Also, it includes the weighted sum of variable processing costs and transportation costs regarding different disruption scenarios. Objective function (2) minimizes the total weighted sum of earliness and tardiness of product delivery to customer zones. Constraint (3) assures full satisfaction of demand of customer zones. Constraint (4) guarantees that all end-of-life products should be collected via collection centers. Constraints (5) to (12) ensure flow balance at different echelons of supply chain network. Constraints

(13) to (20) assure that the total amount of products sent from each facility at each echelon of network to different facilities at the next level of network should be less than or equal to its maximum capacity level. Noteworthy, the demand of each customer zone is different regarding each defined scenario. Therefore, the amount of product flow from each distribution center to different customer zones would be different based on available capacity of distribution centers regarding each scenario. Constraints (21) to (23) guarantee that at most one capacity level should be opened for plants, distribution and recycling centers, respectively. Constraint (24) is an auxiliary constraint that guarantees linearity of second objective function. Also, it determines the amount of earliness or tardiness at each customer zones. Constraint (25) ensures that total amount of provided raw material via different channels should meet minimum acceptable quality level of company decision makers. Constraints (26) and (27) present binary and non-negative variables, respectively.

4. Extended Possibilistic Programming Model

To extend the suggested equivalent crisp model, the possibilistic programming model presented by Pishvaee and Torabi[20] and Jimenez *et al.*[14] is employed. Applied method uses expected value and expected interval of a fuzzy number to model uncertain parameters. The most important issue about employed method is that it has capability of controlling level of risk-averseness of output decisions. In other words, decision-makers would be able to adjust confidence level of uncertain parameters based on their level of risk-aversion. Noted matter is the biggest advantage of applied method. Notably, in this method, each uncertain parameter is presented as a triangular fuzzy number (i.e. $\tilde{C} = (c_p, c_M, c_0)$) that its membership function could be formulated as follows:

$$\mu_{\tilde{C}}(x) = \begin{cases} f_C(x) = \dfrac{x - C^P}{C^M - C^P} & \text{if } C^P \leq x \leq C^M \\ 1 & \text{if } x = C^M \\ g_C(x) = \dfrac{C^0 - x}{C^0 - C^M} & \text{if } C^M \leq x \leq C^0 \\ 0 & \text{if } x \leq C^P \textit{ or } x \geq C^0. \end{cases} \tag{28}$$

Now, the compact form of suggested reliable closed loop SCND model is presented to extend the equivalent crisp model as follows:

$$\begin{aligned} \textbf{Min} \quad & \boldsymbol{Z} = \tilde{f}y + \tilde{c}x \\ \textbf{s.t.} \quad & Bx \geq \tilde{d} \\ & Nx \leq \tilde{H}y \\ & Vx \leq \tilde{R} \\ & Kx \leq 0 \\ & y \in \{0,1\}, \quad x \geq 0 \end{aligned} \tag{29}$$

where y and x are decision variables of opening facilities at different echelons of network and product flow between consecutive echelons of network, respectively. Also, uncertain parameters of compact model are presented with a tilde on. Uncertain parameters $\tilde{f}$ and $\tilde{c}$ are fixed opening cost of facilities and variable processing costs, respectively. Uncertain parameters $\tilde{d}$, $\tilde{R}$ and $\tilde{H}$ present demand of customer zones and capacity of facilities at different echelons of network, respectively. Parameters B, N, V and K are coefficients of the decision variable. With regard to presented uncertain parameters and enumerated matters about the possibilistic programming method, equivalent crisp model could be formulated as follows:

$$
\begin{aligned}
\textbf{Min}\ \ \boldsymbol{Z} &= \left(\frac{f^p+f^m+f^o}{3}\right)y + \left(\frac{c^p+c^m+c^o}{3}\right)x \\
\textbf{s.t.}\qquad Bx &\geq \left[\alpha\cdot\left(\frac{d^o+d^m}{2}\right)+(1-\alpha)\left(\frac{d^m+d^p}{2}\right)\right] \\
Nx &\leq \left[\beta\cdot\left(\frac{H^p+H^m}{2}\right)+(1-\beta)\left(\frac{H^m+H^o}{2}\right)\right]y \qquad (30)\\
Vx &\leq \left[\gamma\cdot\left(\frac{R^p+R^m}{2}\right)+(1-\gamma)\left(\frac{R^m+R^o}{2}\right)\right] \\
Kx &\leq 0 \\
y &\in \{0,1\}, \quad x \geq 0,
\end{aligned}
$$

where uncertain parameters of objective function are modeled based on the expected value of triangular fuzzy numbers. In other words, objective function minimizes expected value of total costs. Also, parameters α, β and γ represent minimum satisfaction levels of uncertain parameters. Decision-makers should determine the value of confidence level of uncertain parameters based on their risk-aversion (i.e. $0.5 < \alpha, \beta, \gamma \leq 1$). Increasing value of satisfaction levels would result in risk-averse output decision. Notably, decision-makers change the value of confidence levels in an interactive procedure to achieve the best value of objective function based on optimized decision variables.

With regard to elucidated matters, bi-objective possibilistic reliable and responsive closed loop SCND model could be presented as follows:

$$
\begin{aligned}
\textbf{Min}\ \boldsymbol{Z_1} = &\sum_j\sum_z\left(\frac{FJ^p_{jz}+FJ^m_{jz}+FJ^o_{jz}}{3}\right)XJ_{jz} + \sum_l\sum_t\left(\frac{FL^p_{lt}+FL^m_{lt}+FL^o_{lt}}{3}\right)XL_{lt} \\
&+\sum_o\sum_q\left(\frac{FO^p_{oq}+FO^m_{oq}+FO^o_{oq}}{3}\right)XO_{oq}
\end{aligned}
$$

$$+\sum_s A_s \left[\sum_i \sum_j \left(\frac{CI_i^p + CI_i^m + CI_i^o + TIJ_{ij}^p + TIJ_{ij}^m + TIJ_{ij}^o}{3}\right) VIJ_{ijs}\right.$$

$$+\sum_u \sum_j \left(\frac{CU_u^p + CU_u^m + CU_u^o + TUJ_{uj}^p + TUJ_{uj}^m + TUJ_{uj}^o}{3}\right) VUJ_{ujs}$$

$$+\sum_m \sum_p \left(\frac{CP_p^p + CP_p^m + CP_p^o}{3}\right) VMP_{mps}$$

$$+\sum_i \sum_j \left(\frac{CJ_j^p + CJ_j^m + CJ_j^o + TJL_{jl}^p + TJL_{jl}^m + TJL_{jl}^o}{3}\right) VJL_{jls}$$

$$+\sum_k \sum_m \left(\frac{TKM_{km}^p + TKM_{km}^m + TKM_{km}^o}{3}\right) VKM_{kmst}$$

$$+\sum_l \sum_k \left(\frac{CL_l^p + CL_l^m + CL_l^o + TLK_{lk}^p + TLK_{lk}^m + TLK_{lk}^o}{3}\right) VLK_{lks}$$

$$+\sum_m \sum_n \left(\frac{\begin{array}{l} CMN_m^p + CMN_m^m + CMN_m^o + TMN_{mn}^p \\ \quad + TMN_{mn}^m + TMN_{mn}^o \end{array}}{3}\right) VMN_{mns}$$

$$+\sum_m \sum_o \left(\frac{\begin{array}{l} CMO_m^p + CMO_m^m + CMO_m^o + TMO_{mo}^p \\ \quad + TMO_{mo}^m + TMO_{mo}^o \end{array}}{3}\right) VMO_{mos}$$

$$+\sum_m \sum_p \left(\frac{\begin{array}{l} CMP_m^p + CMP_m^m + CMP_m^o + TMP_{mp}^p \\ \quad + TMP_{mp}^m + TMP_{mp}^o \end{array}}{3}\right) VMP_{mps}$$

$$+\sum_n \sum_l \left(\frac{\begin{array}{l} CNL_n^p + CNL_n^m + CNL_n^o + TNL_{nl}^p \\ \quad + TNL_{nl}^m + TNL_{nl}^o \end{array}}{3}\right) VNL_{nls}$$

$$\left.+\sum_o \sum_j \left(\frac{\begin{array}{l} COJ_o^p + COJ_o^m + COJ_o^o + TOJ_{oj}^p \\ \quad + TOJ_{oj}^m + TOJ_{oj}^o \end{array}}{3}\right) VOJ_{ojs}\right],$$

$$\textbf{Min } \boldsymbol{Z}_2 = \sum_s A_s \left[\sum_l \sum_k (TTDT_{lks} + TEDT_{lks}) \right]$$

$$\textbf{s.t.} \quad \sum_l VLK_{lks} \geq \alpha \cdot DE_k^o + (1-\alpha) \cdot DE_k^p \qquad \forall k, s$$

$$\sum_m VKM_{kms} \geq \beta \cdot \zeta_k^o \cdot DE_k^o + (1-\beta) \cdot \zeta_k^p \cdot DE_k^p \qquad \forall k, s$$

$$\sum_o VOJ_{ojs} + \sum_u VUJ_{ujs} + \sum_i VIJ_{ijs} = \sum_l VJL_{jls} \qquad \forall j, s$$

$$\sum_j VJL_{jls} + \sum_n VNL_{nls} = \sum_k VLK_{lks} \qquad \forall l, s$$

$$\sum_k VKM_{kms} = \sum_n VMN_{mns} + \sum_o VMO_{mos} + \sum_p VMP_{mps} \qquad \forall m, s$$

$$\lambda_1 \sum_k VKM_{kms} = \sum_p VMP_{mps} \qquad \forall m, s$$

$$\lambda_2 \sum_k VKM_{kms} = \sum_p VMO_{mos} \qquad \forall m, s$$

$$\lambda_3 \sum_k VKM_{kms} = \sum_n VMN_{mns} \qquad \forall m, s$$

$$\sum_m VMN_{mns} = \sum_l VNL_{nls} \qquad \forall n, s$$

$$\sum_m VMO_{mos} = \sum_j VOJ_{ojs} \qquad \forall o, s$$

$$\sum_l VJL_{jls} \leq \sum_z [\rho \cdot CAPJ_{jz}^p + (1-\rho) \cdot CAPJ_{jz}^m](1 - DIS_{js}) XJ_{jz} \quad \forall j, s$$

$$\sum_k VLK_{lks} \leq \sum_t [\tau \cdot CAPL_{lt}^p + (1-\tau) \cdot CAPL_{lt}^m] XL_{lt} \qquad \forall l, s$$

$$\sum_m VMO_{mos} \leq \sum_q [\sigma \cdot CAPO_{oq}^p + (1-\sigma) \cdot CAPO_{oq}^m] XO_{oq} \qquad \forall o, s$$

$$\sum_j VIJ_{ijs} \leq \varepsilon \cdot CAPI_i^p + (1-\varepsilon) \cdot CAPI_i^m \qquad \forall i, s$$

$$\sum_j VUJ_{ujs} \leq \vartheta \cdot CAPU_u^p + (1-\vartheta) \cdot CAPU_u^m \qquad \forall u, s$$

$$\sum_k VKM_{kms} \leq \theta \cdot CAPM_m^p + (1-\theta) \cdot CAPM_m^m \qquad \forall m, s$$

$$\sum_m VMN_{mns} \leq \mu \cdot CAPN_n^p + (1-\mu) \cdot CAPN_n^m \qquad \forall n, s$$

$$\sum_m VMP_{mps} \leq \omega \cdot CAPP_p^p + (1-\omega) \cdot CAPP_p^m \qquad \forall p, s$$

$$\sum_z XJ_{jz} \leq 1 \qquad \forall j$$

$$\sum_t XL_{lt} \leq 1 \qquad \forall l$$

$$\sum_t XO_{oq} \leq 1, \qquad \forall o$$

$$
\begin{aligned}
& VLK_{lks}\left(\left(\frac{DTLK_{lk}^{p}+DTLK_{lk}^{m}+DTLK_{lk}^{o}}{3}\right)-\left(\frac{EDTK_{k}^{p}+EDTK_{k}^{m}+EDTK_{k}^{o}}{3}\right)\right) && \\
& \quad = TTDT_{lks}-TEDT_{lks} && \forall l,k,s \\
& \sum_{i} EQI_{i}VIJ_{ijs}+\sum_{u} EQU_{u}VUJ_{ujs}+\sum_{o} EQO_{o}VOJ_{ojs} \geq EQJ_{j} && \forall j,s \\
& XJ_{jz}, XL_{lt}, XO_{oq} \in \{0,1\} && \forall, j,z,l,t,o,q \\
& VIJ_{ijs}, VUJ_{ujs}, VJL_{jls}, VLK_{lks}, VKM_{kms}, VMP_{mps}, VMO_{mos}, && \forall i,j,s,l,k, \\
& \quad VMN_{mns}, VNL_{nls}, VOJ_{ojs}, VOR_{ors}, TEDT_{lks}, TTDT_{lks} \geq 0 && m,p,o,n,r.
\end{aligned} \tag{31}
$$

5. Implementation and Evaluation

In this section, the generated test problem is inspired by a real industrial supply chain network of an Iranian holding of manufacturing electronic appliances. Generated data are applied to implement and evaluate extended model and show its effective performance. There are lots of certain and uncertain parameters in the proposed model and a lot of space is needed to present all of them. In this regard, noted parameters are not presented in this section. But, parameters of the extended model could be provided upon a request by interested readers. Notably, uncertain parameters of model are modeled by application of triangular possibility distribution that could be defined based on their three prominent points (i.e. $\tilde{r} = (\boldsymbol{r}_p, \boldsymbol{r}_m, \boldsymbol{r}_o)$).

In forward direction of extended supply chain network, demand of customer zones should be fulfilled via produced products at manufacturing plants. In this regard, raw materials are bought from suppliers and recycler suppliers. Buying recycled raw materials has lower buying price. However, it affects the quality of produced products. Produced products should be transferred to customer zones via different distribution centers. Finally, after using products, end-of-life products should be collected via different collection centers. Collected products should be inspected and categorized into three different types. First type of end-of-life products is the recoverable type via changing some parts or minor software recovery. Recovered products are distributed to customer zones via distribution centers. Second type of end-of-life products has recyclable ones. This type of products should be sent to recycling centers to recycle raw materials used in production of products. Then, recycled raw materials should be sent to production plants to produce new products. Third type of collected products are useless ones that do not have capability of recycling and recovery. This type of products should be disposed. This category of products should be sent to disposal centers for implementing disposal process on them. It is worthy to mention that number and location of plants, distribution and recycling centers are not predetermined and some of them should be opened based on flow of products in extended network. Three potential capacity levels are regarded

Table 1. Size of generated test problem.

Facility type	No. of facilities	Facility type	No. of facilities
Suppliers	3	Collection centers	5
Recycler suppliers	3	Recycling centers	5
Production plants	5	Recovery centers	5
Distribution centers	6	Disposal enters	3
Customer zones	8		

for each potential location of noted facilities. Size of generated test problem is presented in Table 1.

To evaluate the extended possibilistic bi-objective reliable SCND model, it is solved with CPLEX solver of GMAS optimization software. Firstly, to assess accurate performance of proposed model, it is solved under different satisfaction levels (i.e. 0.55, 0.65, 0.75, 0.85 and 0.95) as a single objective optimization model. Output results for cost minimization objective are presented in Fig. 2.

Presented results in Fig. 2 show that increment of satisfaction levels has led to increasing cost objective function. Notably, increasing satisfaction levels, in other words risk-aversion of model outputs, has led to cost objective function increase. Reason for this is the flow of more products in the network to satisfy customer needs. Flowing more products leads to more product transportations, opening more facilities and increasing processed products in different echelons of supply chain network. Noted matters show the accurate performance of the proposed model. Also, results related to number of opened facilities and their corresponding capacity level under different satisfaction levels are presented in Table 2. As it is obvious, increasing satisfaction levels have led to opening more facilities or opening facilities with bigger capacity levels that show appropriate output results of the proposed model.

Total transportation costs between different echelons of supply chain network are also presented in Fig. 3 regarding different satisfaction levels. As it could be

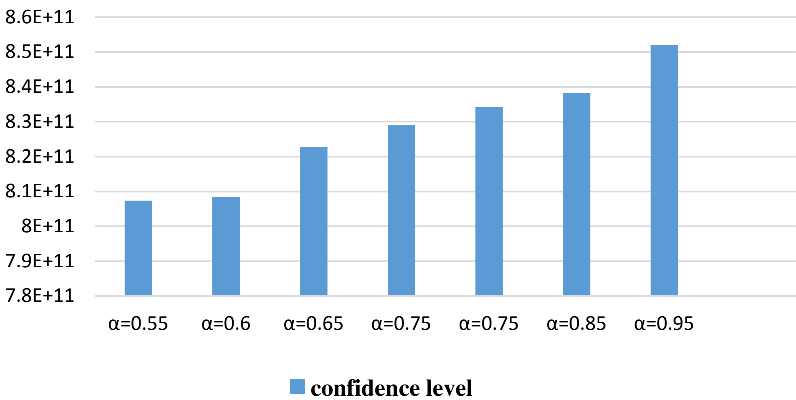

Fig. 2. Cost objective function regarding different satisfaction levels.

Table 2. Opened facilities and capacities in different echelons of network under different satisfaction levels.

Confidence level	Manufacturer			Distribute center			Recycling center		
	Capacity level z			Capacity level t			Capacity level q		
	1	2	3	1	2	3	1	2	3
$\boldsymbol{\alpha} = \mathbf{0.55}$	1,2,3,4	5		1	6		1,4		
$\boldsymbol{\alpha} = \mathbf{0.65}$	1,2,3,4	5			1,6		1		4
$\boldsymbol{\alpha} = \mathbf{0.75}$	1,2,4	3	5	1		6	1		4
$\boldsymbol{\alpha} = \mathbf{0.95}$	1,2,4	3	5	1,4,5			1,2		4

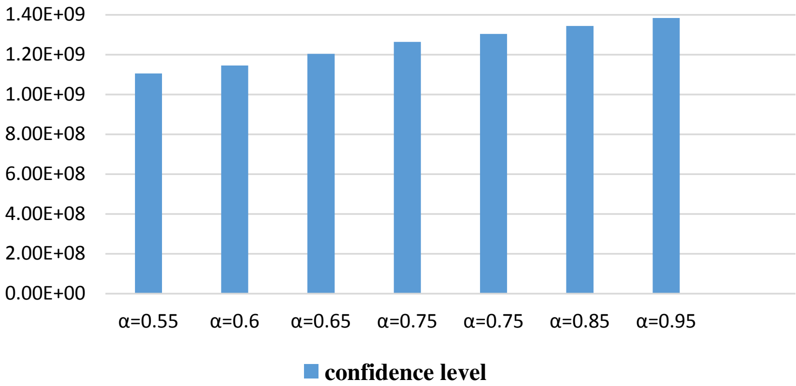

Fig. 3. Effect of different satisfaction levels on total transportation costs.

understood, increasing satisfaction levels have led to increment of transportation costs owing to flow of more products between consecutive echelons of network. Also, presented results show an accurate performance of presented bi-objective model.

To solve bi-objective model and find non-dominated optimal solutions, the epsilon constraint method is employed. In this method, the model should be solved as a single objective optimization model regarding each objective function. Therefore, the optimum value of each objective function should be found regarding defined constraints. Then, the optimum value of decision variables achieved from solving model by cost minimization objective should be put in earliness/tardiness objective to find the worst value of second objective function. Finally, the second objective function should be added to constraints as a constraint that its right-hand side should be changed between worst and best value of the second objective function to find the effect of changing earliness/tardiness objective on cost minimization objective function. Results of epsilon constraint method are presented in Fig. 4.

As it could be seen, point A presents the maximum value of total earliness and tardiness objective function and lowest value of the cost objective function. Lowering earliness/tardiness objective function should result in increment of cost objective

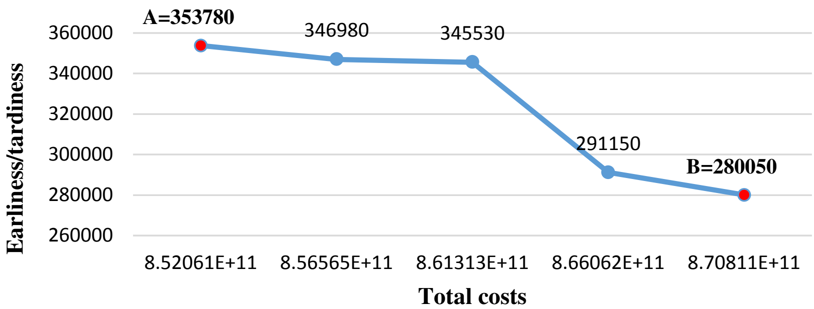

Fig. 4. Value of objective functions by application of epsilon constraint method.

function. Point B is representative of maximum cost objective function value and minimum earliness/tardiness objective function. Notably, the found points show conflicting solutions that means increasing cost objective function results in lowering earliness/tardiness objective function. Noted matters confirm the accurate performance of extended model regarding output value of conflicting objective functions. Notably, more facilities should be opened to minimize earliness/tardiness of extended network. In other words, the network should be decentralized. Also, minimization of total costs leads to opening less number of facilities or in other words centralized extended network. In this regard, production plants 1, 2, 3 and 4 are opened with their first potential capacity level at point A. Also, distribution centers 1, 4 and 5 are opened with first capacity level and only recycling center 4 is opened with its third potential capacity level. At point B, the network should be decentralized owing to minimization of earliness/tardiness objective function. Accordingly, distribution center 1 is opened with its third potential capacity level. Distribution center 2 is

Table 3. Results of solving bi-objective model under designed demand scenarios.

Scenario	Confidence level	Objective functions	
		Z_1	Z_2
1	$\alpha = 0.55$	792138655597	340425
	$\alpha = 0.75$	822105883788	562700
	$\alpha = 1$	851815856501	536600
2	$\alpha = 0.55$	857971390404	632880
	$\alpha = 0.75$	966722789509	867950
	$\alpha = 1$	1010855662260	947100
3	$\alpha = 0.55$	979213290708	953650
	$\alpha = 0.75$	1014490914527	831775
	$\alpha = 1$	1069504999130	1079750
4	$\alpha = 0.55$	1098558850578	1185898
	$\alpha = 0.75$	1209650081950	1287450
	$\alpha = 1$	1404413459492	1796550

opened with its second capacity level and distribution center 5 is opened with its first capacity level.

To evaluate the performance of extended model based on different values of demand of customer zones, they are increased based on a predefined percentage under different satisfaction levels and the results of each objective function are presented in Table 3.

As presented in Table 3, increasing demand of customer zones has led to increment of cost objective function and total earliness/tardiness objective function that is a result of flowing more products in extended supply chain network. Notably, increment of demand of customer zones leads to increment of number of opened facilities in different echelons of reliable supply chain network. Finally, it should be noted that alluded matters shows effective performance of the extended model and its applicability in real-world problems as a powerful decision-making tool.

6. Conclusion

Nowadays, there are many factors that can affect important aims of organizations. Consumer satisfaction, responsiveness of supply chain networks and high-quality produced products could be regarded as the most important noted aims. Uncertainty of input parameters and occurrence of disruptions are two important issues that could cause great losses and decrease the reliability of supply chain networks. Also, they can affect the level of achievement of the mentioned goals. Uncertainty of parameters is an inseparable part of supply chains owing to the dynamic nature of industrial cases. Also, disruptions are man-made or natural disasters such as floods, terrorist attacks and fire that could affect performance of supply chains. Notably, delivering products to customers on time is another important factor and is an important issue that could beget great benefit for company owners and stakeholders. Accordingly, a responsive reliable closed loop supply chain network is designed in this paper that maximizes customer loyalty by delivering products on time to customer zones along with minimizing fixed and variable costs of the network design. Extended model is capable of effective controlling of partial and complete disruptions by suggesting a scenario-based modeling approach. Uncertainty of parameters is controlled via employing an effectual possibilistic programming method. Finally, some test problems are generated that confirm the effectiveness of model outputs and also shows that extended model is practical and useable for real-world problems. The proposed model is solved and optimized based on different satisfaction levels of uncertain parameters that show its appropriate performance. Also, performed sensitivity analysis on important parameters of extended model shows accurate performance of model regarding different uncertainty scenarios.

As a future research guideline, it should be noted that for some other factors such as maximizing social responsibility, maximizing green operation of network and minimization of transfer risk could be regarded as a second objective beside cost minimization. Noteworthy, alluded matters could result in improved output decisions and customers' loyalty. Also, by considering global trade parameters such as tax, duty tariff and exchange rates, model would be changed to global supply chain network that could be used by worldwide expanded companies as a reliable decision-making tool. The other important point is that modelling and optimizing operational decisions along with tactical and strategic decisions could make the model more applicable in real-world problems.

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