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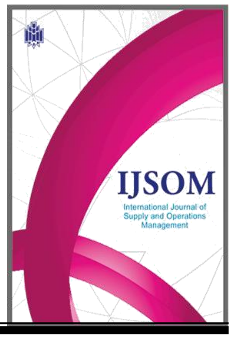

A Chance-constrained Fuzzy Programming Approach for a Sustainable Supply Chain Network Design under Multiple Sources of Uncertainty

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Abstract
This paper aims to propose a multi-period multi-product supply chain network design which takes the sustainability dimensions into consideration in both strategic and operational decisions. Several critical issues in planning of supply chain networks are considered in the model such as the capacity of facilities, the minimum acceptable rate for the social score of manufacturing plants and distribution centers, the maximum coverage radius, and the limited budget. In order to obtain an effective and efficient network design, different categories of uncertainty are also taken into account, including the provider-side uncertainty reflected in the capacity of constructed facilities, as well as the economic, environmental, social, and technical parameters, the receiver-side uncertainty reflected in the demand, and the in-between uncertainty reflected in the transportation cost and the maximum coverage radius. To deal with different sources of uncertainty in the concerned problem, a chance constrained fuzzy programming approach is employed. Several test problems are used to analyze the characteristics of the proposed problem. The computational results can help decision makers to design supply chain networks from economic, environmental, and social perspectives.

Keywords: Supply chain management, Network design, Sustainability, Uncertainty, Coverage radius, Chance constraint fuzzy programming.

1. Introduction

Supply chain management has received significant attention from academics since the early 1980s. A supply chain involves all the events related to the flow and transformation of goods and services from the source point to the usage point (Büyüközkan and Çifçi, 2011). In todays' competitive world, most organizations attempt to meet demands by several strategic and operational decisions with economic, environmental, and social concerns. The economic aspects of supply chain networks are investigated in a large body of literature. However, it is crucial to consider environmental and social aspects in the design. As of now, numerous researches have been developed for designing supply chain networks. The reader can find some recent studies in the works of Mokhtar *et al*. (2019), Hu (2019), Dominguez *et al*. (2019), Hasanov *et al*. (2019), Ottemöller and Friedrich (2019), Jajja *et al*. (2018), Bugert and Lasch (2018), Jahani *et al*. (2018), and Hu *et al*. (2018). Since this study focuses on the consideration of sustainability in the design of supply chain network, the relevant literature on environmental and social aspects of supply chain management is presented below.

Regarding the environmental aspects of designing supply chain networks, a multi-objective model for a green supply chain network design was introduced by Wang *et al*. (2011) in which the environmental level of facilities and carbon emissions from transportation of final products are considered. Chaabane *et al*. (2011) investigated the economic and environmental dimensions of sustainability in a supply chain design problem by considering carbon emissions and total logistics costs including production cost, transportation cost, raw material purchasing cost, and fixed cost of using production technologies. Jin *et al*. (2014) examined the impact of different carbon policies including carbon emission tax, inflexible cap, and cap-and-trade on the supply chain network design. Fahimnia *et al*. (2015) developed a tactical supply chain planning model to consider economic and environmental objectives under a carbon tax policy scheme. Nouira *et al*. (2016) investigated the correlation between the environmental performance of a product in terms of carbon emissions, customer demands, and supply chain decisions. A robust environmental closed-loop supply chain network under uncertainty was presented by Ruimin *et al*. (2016) to study the trade-off between total costs and environmental

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influences. Chibeles-Martins *et al*. (2016) developed a supply chain network design problem in which the minimization of the environmental effects generated by diesel and electricity consumption over the entire supply chain and the maximization of profit obtained by selling the final products are considered as two conflicting objectives. Ding *et al*. (2016*a*) addressed the economic performance of a sustainable supply chain from the perspectives of firms and government by considering the environmental externalities and stakeholders' environmental interests. A profit maximization model for a closed-loop supply chain network design was introduced by Keyvanshokooh *et al*. (2016) in which locations and capacities of facilities, inventory levels, production amounts, and the shipment among the network entities are determined. A collaborative supply chain decision making framework with environmental constraints and carbon caps is proposed by Ding *et al*. (2016*b*) in which the government subsidy is considered to invest in producing environmentally-friendly products. Talaei *et al*. (2017) proposed a robust fuzzy programming approach to deal with the uncertainty in a carbon-efficient closed-loop supply chain network design problem and used the ε-constraint method to solve it. Kadambala *et al*. (2017) developed a closed-loop supply chain model to maximize profit, optimize customer surplus, and minimize energy use. They employed a multi-objective particle swarm optimization approach and a non-dominated sorted genetic algorithm (NSGAII) to solve their proposed model. Azadeh *et al*. (2017) presented a multi-objective mathematical model for integrating upstream and midstream segments of crude oil supply chain regarding the environmental emission, the energy consumption, and the produced wastewater. Rahmani and Mahoodian (2017) introduced a reliable and robust model for a green supply chain network design by considering the uncertainty risk of parameters and the risk caused by disrupted facilities. A mathematical model for a tire remanufacturing supply chain is addressed by Saxena *et al*. (2018) in which carbon tax-reward and carbon-tax-reward-forex polices are considered. Zhang *et al*. (2018) proposed a model for the carbon capture, utilization and storage system in a supply chain network which evaluates different scenarios for CO_2 reduction levels. Halat and Hafezalkotob (2019) investigated the inventory management decisions and carbon policies such as carbon cap, carbon tax, carbon trade, and carbon offset in a multi-stage green supply chain. They used a leader-follower game model in which the government wants to maximize social welfare and the supply chain designer wants to minimize the inventory cost and carbon emissions. Daryanto *et al*. (2019) proposed a three-echelon supply chain model in which carbon emissions from transportation, warehousing, and disposing of the deteriorated items are considered.

There are some studies that consider three dimensions of sustainability simultaneously. In this regard, Mota *et al*. (2015) applied the ReCiPe life cycle assessment approach to determine the environmental impact of production and transportation of final products of a sustainable supply chain design. A real case-study based on a Portuguese battery producer and distributor was also proposed to evaluate the applicability of their model. Soleimani *et al*. (2017) introduced a sustainable closed-loop supply chain network design in which environmental considerations, total profit optimization, and reduction of lost working days due to occupational accidents are taken into account. Yu *et al*. (2018) investigated the impact of different environmental tax policies on equilibrium product demands, prices, and the firm profit to design a sustainable supply chain network competition. Sahebjamnia *et al*. (2018) proposed several hybrid meta-heuristic algorithms based on the genetic algorithm, simulated annealing, tabu search, red deer algorithm, and water wave optimization to solve a sustainable tire closed-loop supply chain network. They used the life cycle assessment methodology to estimate the sustainability dimensions. Das (2018) integrated applications of lean systems in the design of a supply chain network to improve sustainability performances of the overall business. A sustainable supply chain model for switchgrass-based bioenergy production is proposed by Rabbani *et al*. (2018) in which a two-stage algorithm based on AUGMECON and TOPSIS methods was utilized to handle the trade-off between sustainable factors. Zhan *et al*. (2018) investigated the impact of financing mechanisms on the sustainable development and supply chain efficiency and described the equilibrium strategies between the supplier and retailer in each financing mechanism. Rohmer *et al*. (2019) presented a sustainable food supply chain design with the goal of minimizing environmental impacts and total costs. The social pillar of the supply chain design is addressed by the dietary health and the environmental indicators are considered by climate change, water use, land use, and fossil fuel depletion criteria. Taleizadeh *et al*. (2019) proposed a multi-echelon sustainable closed loop supply chain in which the discount offer is applied to return used products. Chalmardi and Camacho-Vallejo (2019) presented a bi-level programming for designing a sustainable supply chain network in which different strategies of incentives are offered to the companies for utilizing cleaner technologies.

This paper aims to propose a multi-period multi-product sustainable supply chain network which includes suppliers, manufacturing plants, distribution centers, and demand zones. To develop the model, the capacity of facilities, the maximum coverage radius, the limited budget, and the minimum acceptable rate for the social score of manufacturing plants and distribution centers are considered. The proposed model captures the uncertain nature of input data. As declared by Shen *et al*. (2011), the uncertainty can be classified into *provider-side*, *receiver-side*, and *in-between* uncertainties. The *provider-side uncertainty* captures the randomness in the capacity and the reliability of facilities. The *receiver-side uncertainty* includes the randomness within the demands, and the *in-between uncertainty* is related to the uncertainty in the travel time, the transportation cost, etc. In this study, three categories of uncertainty are considered to obtain an efficient supply chain network. To deal with different categories of uncertainty, the chance constrained fuzzy programming approach is employed. To evaluate the performance of the proposed model, different test problems are used.

The organization of this paper is as follows. The model formulation is presented in Section 2. Section 3 develops the chance constrained fuzzy programming approach to deal with uncertainty. In Section 4, results of the computational experiments are presented. Finally, some conclusions and possible directions for future research are drawn in Section 5.

2. Model description and formulation

In this section, the description and formulation of a sustainable supply chain network design is presented. The schematic view of the proposed model is shown in Figure 1. As it can be seen, there are four infrastructure layers geographically distributed in the network, including the suppliers, manufacturing plants, distribution centers, and demand zones. The forward supply chain network is considered in which the manufacturing plants supply raw materials from suppliers to produce new products. Then, new products are sent to distribution centers to satisfy demands. To capture the dynamic situations, the model is developed over multiple periods.

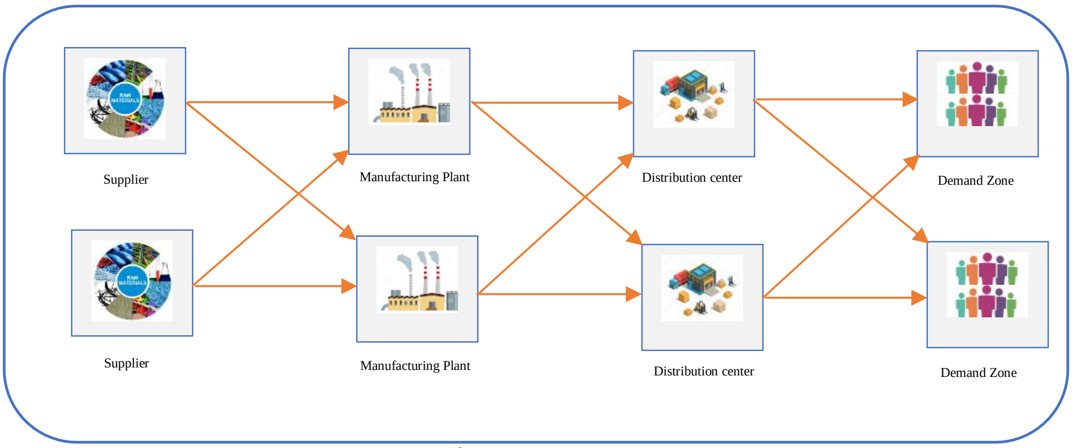


Figure 1.The schematic view of proposed sustainable supply chain network

The proposed model incorporates practical limitations in real-world decision making contexts such as the service capacity of manufacturing plants in producing products and the capacity of distribution centers. The available budget for investing in manufacturing plants and distribution centers is limited. The maximum coverage radius is also considered in the model which reflects whether distribution centers and demand zones can be served or covered in the network. Note that a demand zone can be covered if it lies within, not outside of, the maximum coverage radius of distribution centers. All three dimensions of sustainability are involved in the model, simultaneously. To consider the economic aspects of the designed supply chain network, different types of cost such as investment cost, transportation cost, variable manufacturing and distributing costs, as well as purchasing cost are taken into account. The environmental issues are addressed in the model in such a way as to minimize the environmental costs of emissions through strategic and operational processes. In this regard, the emission from opening manufacturing plants and distribution centers, the emission from processing products in manufacturing plants and distribution centers, the emission from transportation between manufacturing plants and distribution centers, and the emission from transportation between distribution centers and market zones are considered. Note that in different echelons of a supply chain, different types of greenhouse gases are emitted into the air, including CO_2, SO_2, NO_x, Methane, and the like. Therefore, the proposed model captures different kinds of emissions. The number of job opportunities created by opening and operating manufacturing plants and distribution centers are considered to reflect the social aspects of the supply chain network design. Since the supply chain network designs are significantly affected by a great degree of uncertainty, three categories of uncertainty are also regarded in the model. The provider-side uncertainty is reflected in the capacity of constructed facilities as well as economic, environmental, social, and technical parameters. The receiver-side uncertainty captures the randomness in the demand, and in-between uncertainty is reflected in the transportation costs and maximum coverage radius.
The sets, parameters, and decision variables used in the proposed model are defined as follows:

Sets

O Set of suppliers
I Set of candidate locations for manufacturing plants
J Set of candidate locations for distribution centers
K Set of demand zones
L Set of products
R Set of raw materials
N Set of types of emission into the air
T Set of time periods

Economic parameters
f_{it} Fixed installation cost of opening manufacturing plant i at time period t
g_{jt} Fixed installation cost of opening distribution center j at time period t
v_{ot} Fixed cost of evaluating and selecting supplier o at time period t
Em_{nt} Environmental cost per unit of emission of type n at time period t
$\widetilde{Tcs}_{roit}$ Transportation cost per unit of raw material r from supplier o to manufacturing plant i at time period t
$\widetilde{Tcm}_{lijt}$ Transportation cost per unit of product l from manufacturing plant i to distribution center j at time period t
$\widetilde{Tcd}_{ljkt}$ Transportation cost per unit of product l from distribution center j to demand zone k at time period t
$\widetilde{pm}_{lit}$ Variable manufacturing cost per unit of product l at manufacturing plant i at time period t
$\widetilde{pd}_{ljt}$ Variable distributing cost per unit of product l at distribution center j at time period t
$\widetilde{mc}_{roit}$ Variable purchasing cost per unit of raw material r from supplier o to manufacturing plant i at time period t
$\widetilde{bm}_{t}$ Maximum available budget for investing in manufacturing plants at time period t
$\widetilde{bd}_{t}$ Maximum available budget for investing in distribution centers at time period t

Environmental parameters
λm_{nit} Amount of emission of type n generated by establishing manufacturing plant i at time period t
λd_{njt} Amount of emission of type n generated by establishing distribution center j at time period t
$\widetilde{\mu m}_{nlit}$ Amount of emission of type n generated by manufacturing per unit of product l from manufacturing plant i at time period t
$\widetilde{\mu d}_{nljt}$ Amount of emission of type n generated by distributing per unit of product l from distribution center j at time period t
$\widetilde{\varphi m}_{nlijt}$ Amount of emission of type n generated by the shipment per unit of product l from manufacturing plant i to distribution center j at time period t
$\widetilde{\varphi d}_{nljkt}$ Amount of emission of type n generated by the shipment per unit of product l from distribution center j to demand zone k at time period t
$\widetilde{\varphi s}_{nroit}$ Amount of emission of type n generated by the shipment per unit of raw material r from supplier o to manufacturing plant i at time period t

Social parameters
ξ_{it} Number of job opportunities created by opening manufacturing plant i at time period t
θ_{it} Number of job opportunities created by working manufacturing plant i at time period t
Ω_{jt} Number of job opportunities created by distribution center j at time period t
ϑ_{jt} Number of job opportunities created by working distribution center j at time period t
$\tilde{\mathcal{L}}_{i}$ Minimum acceptable rate for the social score of manufacturing plant i
$\tilde{\tau}_{j}$ Minimum acceptable rate for the social score of distribution center j

Technical parameters
$\widetilde{D}_{klt}$ Demand of customer k for product l at time period t
$\tilde{\varsigma}_{il}$ Capacity of manufacturing plant i for product l
$\tilde{a}_{jl}$ Capacity of distribution center j for product l
$\tilde{b}_{or}$ Capacity of supplier o for raw material r
m_{rl} Amount of raw material r for producing per unit of product l
d_{oi} Shortest distance between supplier o and manufacturing plant i
d_{ij} Shortest distance between manufacturing plant i and distribution center j
d_{jk} Shortest distance between distribution center j and demand zone k
$\widetilde{Rm}$ The maximum coverage radius of manufacturing plants to serve distribution centers
$\widetilde{Rd}$ The maximum coverage radius of distribution centers to serve demand zones
M A large number

Decision variables
z_{it} 1 if a manufacturing plant is located at candidate location i at time period t, 0 otherwise
w_{jt} 1 if a distribution center is located at candidate location j at time period t, 0 otherwise
x_{ot} 1 if supplier o is selected at time period t, 0 otherwise
om_{ijt} 1 if manufacturing plant i serves distribution center j at time period t
od_{jkt} 1 if distribution center j serves demand zone k at time period t
q_{lit} Quantity of product l produced by manufacturing plant i at time period t
y_{roit} Quantity of raw material r shipped from supplier o to manufacturing plant i at time period t
s_{lijt} Quantity of product l shipped from manufacturing plant i to distribution center j at time period t
u_{ljkt} Quantity of product l shipped from distribution center j to demand zone k at time period t

Regarding the aforementioned assumptions and definitions, the formulation of the proposed supply chain network design can be stated as follows:

$$
\begin{aligned}
Min\ Z = & \sum_{t\in T}\sum_{i\in I} f_{it} z_{it} + \sum_{t\in T}\sum_{j\in J} g_{jt} w_{jt} + \sum_{t\in T}\sum_{o\in O} v_{ot} x_{ot} + \sum_{t\in T}\sum_{r\in R}\sum_{o\in O}\sum_{i\in I} \widetilde{mc}_{roit} y_{roit} + \sum_{t\in T}\sum_{l\in L}\sum_{i\in I} \widetilde{pm}_{lit} q_{lit} \\
& + \sum_{t\in T}\sum_{l\in L}\sum_{j\in J}\sum_{k\in K} \widetilde{pd}_{ljt} u_{ljkt} + \sum_{t\in T}\sum_{r\in R}\sum_{o\in O}\sum_{i\in I} \widetilde{Tcs}_{roit} y_{roit} + \sum_{t\in T}\sum_{l\in L}\sum_{i\in I}\sum_{j\in J} \widetilde{Tcm}_{lijt} s_{lijt} \\
& + \sum_{t\in T}\sum_{l\in L}\sum_{j\in J}\sum_{k\in K} \widetilde{Tcd}_{ljkt} u_{ljkt} + \sum_{t\in T}\sum_{n\in N}\sum_{i\in I} Em_{nt} \lambda m_{nit} z_{it} + \sum_{t\in T}\sum_{n\in N}\sum_{l\in L}\sum_{i\in I} Em_{nt} \widetilde{\mu m}_{nlit}\, q_{lit} \\
& + \sum_{t\in T}\sum_{n\in N}\sum_{l\in L}\sum_{i\in I}\sum_{j\in J} Em_{nt} \widetilde{\varphi m}_{nlijt} d_{ij} s_{lijt} + \sum_{t\in T}\sum_{n\in N}\sum_{j\in J} Em_{nt}\, \lambda d_{njt} w_{jt} \\
& + \sum_{t\in T}\sum_{n\in N}\sum_{l\in L}\sum_{j\in J}\sum_{k\in K} Em_{nt} \widetilde{\mu d}_{nljt}\, u_{ljkt} + \sum_{t\in T}\sum_{n\in N}\sum_{l\in L}\sum_{j\in J}\sum_{k\in K} Em_{nt} \widetilde{\varphi d}_{nljkt}\, d_{jk} u_{ljkt} \\
& + \sum_{t\in T}\sum_{n\in N}\sum_{r\in R}\sum_{o\in O}\sum_{i\in I} Em_{nt} \widetilde{\varphi s}_{nroit} d_{oi} y_{roit} \qquad (1)
\end{aligned}
$$

$s.t.$

$$\sum_{o\in O} y_{roit} = \sum_{l\in L} m_{rl} q_{lit}, \qquad \forall r \in R, i \in I, t \in T, \qquad (2)$$

$$q_{lit} = \sum_{j\in J} s_{lijt}, \qquad \forall l \in L, i \in I, t \in T, \qquad (3)$$

$$\sum_{i\in I} s_{lijt} = \sum_{k\in K} u_{ljkt}, \qquad \forall l \in L, j \in J, t \in T, \qquad (4)$$

$$\sum_{j\in J} u_{ljkt} \ge \tilde{D}_{klt}, \qquad \forall l \in L, k \in K, t \in T, \qquad (5)$$

$$\sum_{i\in I} y_{roit} \le \tilde{b}_{or} x_{ot}, \qquad \forall r \in R, o \in O, t \in T, \qquad (6)$$

$$\sum_{j\in J} s_{lijt} \le \tilde{\varsigma}_{il} z_{it}, \qquad \forall l \in L, i \in I, t \in T, \qquad (7)$$

$$\sum_{k\in K} u_{ljkt} \le \tilde{a}_{jl} w_{jt}, \qquad \forall l \in L, j \in J, t \in T, \qquad (8)$$

$$\sum_{i\in I} f_{it} z_{it} \le \widetilde{bm}_t, \qquad \forall t \in T, \qquad (9)$$

$$\sum_{j\in J} g_{jt} w_{jt} \le \widetilde{bd}_t, \qquad \forall t \in T, \qquad (10)$$

$$\xi_{it} z_{it} + \sum_{j\in J}\sum_{l\in L} \theta_{it}\ s_{lijt} \ge \tilde{\mathcal{L}}_i, \qquad \forall i \in I, t \in T, \qquad (11)$$

$$\Omega_{jt} w_{jt} + \sum_{l\in L}\sum_{k\in K} \vartheta_{jt}\, u_{ljkt} \ge \tilde{\tau}_j, \qquad \forall j \in J, t \in T, \qquad (12)$$

$$d_{ij} om_{ijt} \le \widetilde{Rm}, \qquad \forall i \in I, j \in J, t \in T, \qquad (13)$$

$$s_{lijt} \le Mom_{ijt}, \qquad \forall l \in L, i \in I, j \in J, t \in T, \qquad (14)$$

$$om_{ijt} \le z_{it}, \qquad \forall i \in I, j \in J, t \in T, \qquad (15)$$

$$d_{jk} od_{jkt} \le \widetilde{Rd}, \qquad \forall j \in J, k \in K, t \in T, \qquad (16)$$

$$u_{ljkt} \le Mod_{jkt}, \qquad \forall l \in L, j \in J, k \in K, t \in T, \qquad (17)$$

$$od_{jkt} \le w_{jt}, \qquad \forall j \in J, k \in K, t \in T, \qquad (18)$$

$$x_{ot} \in \{0,1\}, \qquad \forall o \in O, t \in T, \qquad (19)$$

$$z_{it} \in \{0,1\}, \qquad \forall i \in I, t \in T, \qquad (20)$$

$$w_{jt} \in \{0,1\}, \qquad \forall j \in J, t \in T, \qquad (21)$$

$$om_{ijt} \in \{0,1\}, \qquad \forall i \in I, j \in J, t \in T, \qquad (22)$$

$$od_{jkt} \in \{0,1\}, \qquad \forall j \in J, k \in K, t \in T, \qquad (23)$$

$$y_{roit} \ge 0, \qquad \forall r \in R, o \in O, i \in I, t \in T, \qquad (24)$$

$$q_{lit} \ge 0, \qquad \forall l \in L, i \in I, t \in T, \qquad (25)$$

$$s_{lijt} \ge 0, \qquad \forall l \in L, i \in I, j \in J, t \in T, \qquad (26)$$

$$u_{ljkt} \ge 0, \qquad \forall l \in L, j \in J, k \in K, t \in T. \qquad (27)$$

The objective function in (1) minimizes fixed installation costs of opening manufacturing plants and distribution centers, fixed costs of evaluating the suppliers, manufacturing costs, distributing costs, purchasing costs, transportation costs, and environmental costs. Constraint (2) guarantees that raw materials of each product must be satisfied. Constraints (3) and (4) ensure the flow balance at manufacturing plants and distribution centers, respectively. Constraint (5) guarantees the fulfilment of demands for each product. Constraints (6) to (8) are the capacity limitation constraints for suppliers, manufacturing plants, and distribution centers, respectively. Constraints (9) and (10) define the budget limitation for investing in manufacturing plants and distribution centers, respectively. Constraints (11) and (12) specify the minimum acceptable rates for the social score of manufacturing plants and distribution centers, respectively. Constraints (13) to (15) state that distribution centers can be served by manufacturing plants based on the maximum coverage radius. Constraints (16) to (18) define the maximum coverage radius for distribution centers to transport products to demand zones. Constraints (19) to (27) enforce the binary and non-negativity constraints on the corresponding decision variables.

3. The chance constrained fuzzy programming model

As of now, several methods have been developed in the literature to cope with the uncertainty associated with parameters. In this study, the chance constrained fuzzy programming approach proposed by Inuiguchi and Ramik (2000) is used in which all imprecise parameters are assumed to have the pattern of trapezoidal fuzzy distribution. This approach enables system designers to control the conservatism level of satisfying constraints. Following the approach proposed by Inuiguchi and Ramik (2000), the equivalent deterministic model can be stated as follows:

$$\begin{aligned}
Min\ Z = &\sum_{t\in T}\sum_{i\in I} f_{it} z_{it} + \sum_{t\in T}\sum_{j\in J} g_{jt} w_{jt} + \sum_{t\in T}\sum_{o\in O} v_{ot} x_{ot} \\
&+ \sum_{t\in T}\sum_{r\in R}\sum_{o\in O}\sum_{i\in I}\left(\frac{mc_{roit(1)}+mc_{roit(2)}+mc_{roit(3)}+mc_{roit(4)}}{4}\right) y_{roit} \\
&+ \sum_{t\in T}\sum_{l\in L}\sum_{i\in I}\left(\frac{pm_{lit(1)}+pm_{lit(2)}+pm_{lit(3)}+pm_{lit(4)}}{4}\right) q_{lit} \\
&+ \sum_{t\in T}\sum_{l\in L}\sum_{j\in J}\sum_{k\in K}\left(\frac{pd_{ljt(1)}+pd_{ljt(2)}+pd_{ljt(3)}+pd_{ljt(4)}}{4}\right) u_{ljkt} \\
&+ \sum_{t\in T}\sum_{r\in R}\sum_{o\in O}\sum_{i\in I}\left(\frac{Tcs_{roit(1)}+Tcs_{roit(2)}+Tcs_{roit(3)}+Tcs_{roit(4)}}{4}\right) y_{roit} \\
&+ \sum_{t\in T}\sum_{l\in L}\sum_{i\in I}\sum_{j\in J}\left(\frac{Tcm_{lijt(1)}+Tcm_{lijt(2)}+Tcm_{lijt(3)}+Tcm_{lijt(4)}}{4}\right) s_{lijt} \\
&+ \sum_{t\in T}\sum_{l\in L}\sum_{j\in J}\sum_{k\in K}\left(\frac{Tcd_{ljkt(1)}+Tcd_{ljkt(2)}+Tcd_{ljkt(3)}+Tcd_{ljkt(4)}}{4}\right) u_{ljkt} \\
&+ \sum_{t\in T}\sum_{n\in N}\sum_{i\in I} Em_{nt}\lambda m_{nit} z_{it} \\
&+ \sum_{t\in T}\sum_{n\in N}\sum_{l\in L}\sum_{i\in I} Em_{nt}\left(\frac{\mu m_{nlit(1)}+\mu m_{nlit(2)}+\mu m_{nlit(3)}+\mu m_{nlit(4)}}{4}\right) q_{lit} \\
&+ \sum_{t\in T}\sum_{n\in N}\sum_{l\in L}\sum_{i\in I}\sum_{j\in J} Em_{nt}\left(\frac{\varphi m_{nlijt(1)}+\varphi m_{nlijt(2)}+\varphi m_{nlijt(3)}+\varphi m_{nlijt(4)}}{4}\right) d_{ij} s_{lijt} \\
&+ \sum_{t\in T}\sum_{n\in N}\sum_{j\in J} Em_{nt}\,\lambda d_{njt} w_{jt} \\
&+ \sum_{t\in T}\sum_{n\in N}\sum_{l\in L}\sum_{j\in J}\sum_{k\in K} Em_{nt}\left(\frac{\mu d_{nljt(1)}+\mu d_{nljt(2)}+\mu d_{nljt(3)}+\mu d_{nljt(4)}}{4}\right) u_{ljkt} \\
&+ \sum_{t\in T}\sum_{n\in N}\sum_{l\in L}\sum_{j\in J}\sum_{k\in K} Em_{nt}\left(\frac{\varphi d_{nljkt(1)}+\varphi d_{nljkt(2)}+\varphi d_{nljkt(3)}+\varphi d_{nljkt(4)}}{4}\right) d_{jk} u_{ljkt} \\
&+ \sum_{t\in T}\sum_{r\in R}\sum_{o\in O}\sum_{i\in I} Em_{nt}\left(\frac{\varphi s_{nroit(1)}+\varphi s_{nroit(2)}+\varphi s_{nroit(3)}+\varphi s_{nroit(4)}}{4}\right) d_{oi} y_{roit} \qquad (28)
\end{aligned}$$

$s.t.\ (2)-(4), (14), (15), (17)-(27)$

$$\sum_{j\in J} u_{ljkt} \geq (1-\alpha_1)\mathrm{D}_{\mathrm{klt}(3)} + \alpha_1 \mathrm{D}_{\mathrm{klt}(4)}, \qquad \forall l\in L, k\in K, t\in T, \qquad (29)$$

$$\sum_{i\in I} y_{roit} \leq \left[(1-\alpha_2) b_{or(2)} + \alpha_2 b_{or(1)}\right] x_{ot}, \qquad \forall r\in R, o\in O, t\in T, \qquad (30)$$

$$\sum_{j\in J} s_{lijt} \leq \left[(1-\alpha_3)\varsigma_{il(2)} + \alpha_3 \varsigma_{il(1)}\right] z_{it}, \qquad \forall l\in L, i\in I, t\in T, \qquad (31)$$

$$\sum_{k\in K} u_{ljkt} \leq \left[(1-\alpha_4) a_{jl(2)} + \alpha_4 a_{jl(1)}\right] w_{jt}, \qquad \forall l\in L, j\in J, t\in T, \qquad (32)$$

$$\sum_{i\in I} f_{it} z_{it} \leq (1-\alpha_5) bm_{t(2)} + \alpha_5 bm_{t(1)}, \qquad \forall t \in T, \tag{33}$$

$$\sum_{j\in J} g_{jt} w_{jt} \leq (1-\alpha_6) bd_{t(2)} + \alpha_6 bd_{t(1)}, \qquad \forall t \in T, \tag{34}$$

$$\xi_{it} z_{it} + \sum_{l\in L} \theta_{it}\, q_{lit} \geq (1-\alpha_7)\mathcal{L}_{\mathrm{i}(3)} + \alpha_7 \mathcal{L}_{\mathrm{i}(4)}, \qquad \forall i \in I, t \in T, \tag{35}$$

$$\Omega_{jt} w_{jt} + \sum_{l\in L}\sum_{k\in K} \vartheta_{jt}\, u_{ljkt} \geq (1-\alpha_8)\tau_{\mathrm{j}(3)} + \alpha_8 \tau_{\mathrm{j}(4)}, \qquad \forall j \in J, t \in T, \tag{36}$$

$$d_{ij} om_{ijt} \leq (1-\alpha_9) Rm_{(2)} + \alpha_9 Rm_{(1)}, \qquad \forall i \in I, j \in J, t \in T, \tag{37}$$

$$d_{jk} od_{jkt} \leq (1-\alpha_{10}) Rd_{(2)} + \alpha_{10} Rd_{(1)}, \qquad \forall j \in J, k \in K, t \in T. \tag{38}$$

It should be noted that α_1 to α_{10} denote the conservatism level of satisfying constraints.

4. Computational study

In this section, some numerical examples are presented in order to examine the performance of the proposed model. To this end, three test problems are designed. The characteristics and size of test problems are presented in Table 1. The values of parameters are shown in Table 2. The proposed model is coded in GAMS23.4 optimization software and evaluated on a personal computer equipped with an INTEL Core 2 CPU with 2.4 GHz clock speed and 2 GB of RAM.

Table 1. The size of test problems

problem	$\|I\|$	$\|K\|$	$\|J\|$	$\|O\|$	$\|L\|$	$\|R\|$	$\|N\|$	$\|T\|$
1	5	5	4	3	2	2	2	2
2	10	8	7	5	4	5	3	3
3	15	11	10	8	6	7	4	4

Table 2. The values of parameters for the computational studies

Parameters	Values	Parameters	Values
f_{it}	[6000000,7000000]	$\widetilde{bd}_t$	[10000000,20000000]
g_{jt}	[1000000,2000000]	$\widetilde{bm}_t$	[20000000,40000000]
v_{ot}	[20000,30000]	m_{rl}	[10,30]
Em_{nt}	[700,1000]	$d_{oi}/d_{ij}/d_{jk}$	[10,100]
$\widetilde{Tcs}_{roit}/\widetilde{Tcm}_{lijt}/\widetilde{Tcd}_{ljkt}$	[50,100]	$\lambda m_{nit}/\lambda d_{njt}$	[1000000,2000000]
$\widetilde{pm}_{lit}$	[400,600]	$\widetilde{\mu m}_{nlit}$	[300,350]
$\widetilde{pd}_{ljt}$	[100,200]	$\widetilde{\mu d}_{nljt}$	[80,120]
$\widetilde{mc}_{roit}$	[1200,1500]	$\widetilde{\varphi m}_{nlijt}/\widetilde{\varphi d}_{nljkt}/\widetilde{\varphi s}_{nroit}$	[400,500]
$\widetilde{D}_{klt}$	[300,500]	ξ_{it}/θ_{it}	[5,40]
$\tilde{\varsigma}_{il}$	[2500,5000]	$\Omega_{jt}/\vartheta_{jt}$	[3,20]
$\tilde{a}_{jl}$	[1500,3000]	$\tilde{\mathcal{L}}_i/\tilde{\tau}_j$	[5,30]
$\tilde{b}_{or}$	[10000,20000]	$\widetilde{Rm}/\widetilde{Rd}$	[30,70]

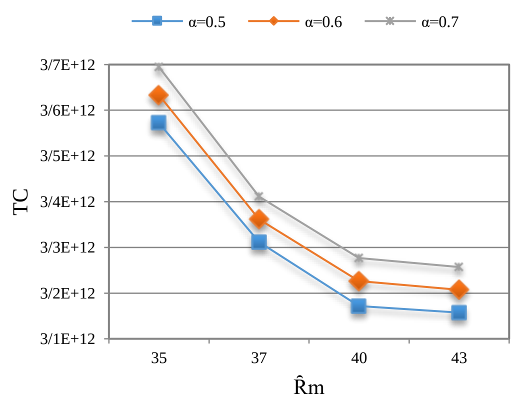
The numerical results of the generated instances are summarized in Table 3. Note that the conservatism level of satisfying constraints is assumed to be more than 0.5. As it can be seen, the total cost of system is strongly affected by α values. For example, by comparing the solutions obtained for test problem 2, it can be seen that the system under $\alpha = 1$ incurs 12.6% much more cost than the one with $\alpha = 0.5$ but a more conservative solution can be obtained. Moreover, the uncertainty associated with parameters plays a significant role in determining the system costs such that the system costs in the chance constrained fuzzy programming model are higher than the system costs in the determinist model.

A sensitivity analysis is carried out to test the impact of key parameters on the model results. A test problem with $|I| = 5, |K| = 5$, $|J| = 4$, $|O| = 3, |L| = 2, |R| = 2, |N| = 2$, and $|T| = 2$ is considered. Figure 2 shows how values of several parameters affect the system cost. Note that the average value of uncertain parameters is shown in the figure. Figures (2a) and (2b) illustrate the impact of maximum coverage radius of manufacturing plants and distribution centers on the system cost, respectively. When the maximum coverage radius increases, the constructed facilities can serve demands in much farther locations. Thus, the transportation cost grows but the fixed installation cost drops significantly, leading to a reduction in the total cost.

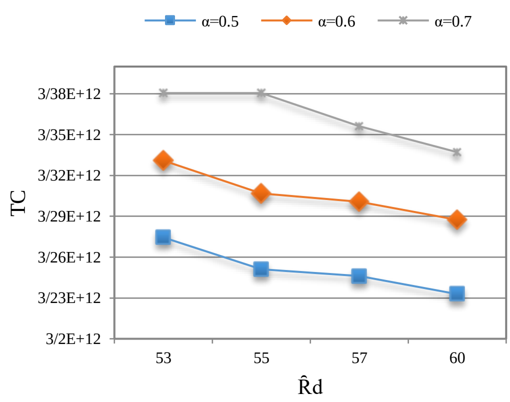
Figure (2c) shows how the demand for each product can affect the total costs. As shown in the figure, the system cost rises when the demand of each product increases. Moreover, the increasing trend of system cost becomes considerably conspicuous in a more conservative situation when the value of α is 0.9. Figures (2d) to (2f) depict the impacts of capacity of manufacturing plants, distribution centers, and suppliers, respectively. As it can be seen, the total cost drops significantly as the capacity of each facility increases. Note that when facilities have sufficient capacities to serve demands, the demands can be satisfied with the closest facilities, and therefore, the decrease in transportation costs leads to the decrease in total system cost.

Table 3. The results under different conservatism levels

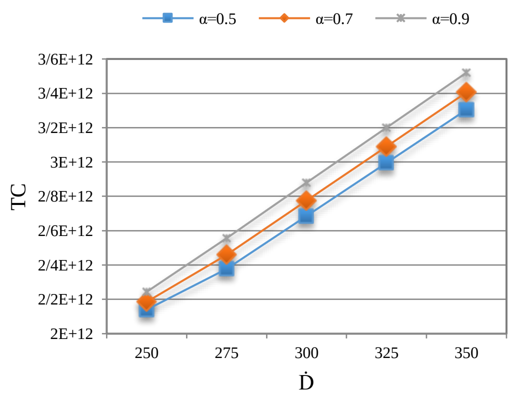
Test problem	α	Objective Value	
		Deterministic model	Chance constrained fuzzy programming model
1	0.5	2.09218E12	3.10560E12
	0.6		3.15562E12
	0.7		3.20564E12
	0.8		3.25566E12
	0.9		3.31217E12
	1		3.36089E12
2	0.5	3.15978E13	4.64972E13
	0.6		4.73466E13
	0.7		4.81970E13
	0.8		4.90500E13
	0.9		4.99049E13
	1		5.23537E13
3	0.5	1.14252E14	1.56614E14
	0.6		1.59643E14
	0.7		1.62674E14
	0.8		1.65706E14
	0.9		1.68740E14
	1		1.71773E14



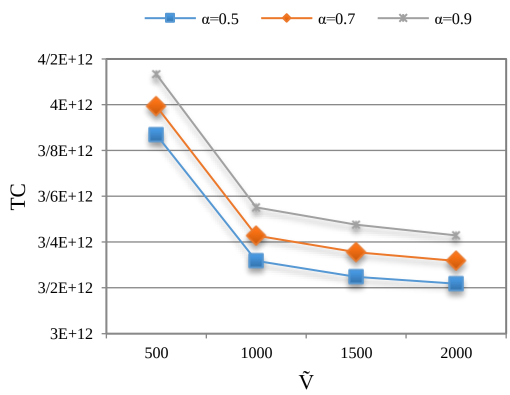
a) The impact of $\widetilde{Rm}$ on the system cost



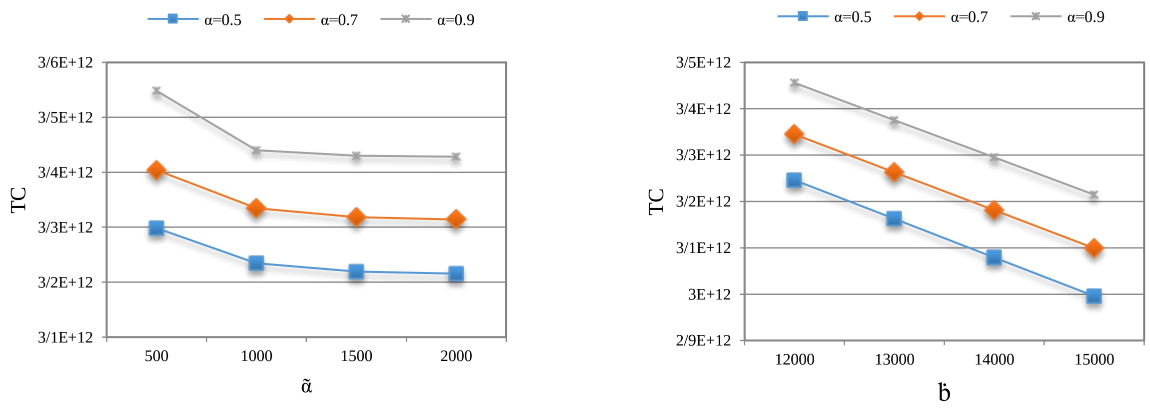
b) The impact of $\widetilde{Rd}$ on the system cost



c) The impact of $\widetilde{D}_{klt}$ on the system cost



d) The impact of $\tilde{v}_{il}$ on the system cost



e) The impact of $\tilde{a}_{jl}$ on the system cost

f) The impact of $\tilde{b}_{or}$ on the system cost

Figure 2. Sensitivity analysis

5. Conclusion

In this paper, a novel multi-period multi-product supply chain network design is developed that optimizes the economic, environmental, and social concerns, simultaneously. The model aims to minimize the total system cost including fixed installation, transportation, manufacturing, purchasing, distributing, and environmental costs. Several aspects of supply chain network design such as the capacity of facilities, the maximum coverage radius, the limited budget, and the minimum acceptable rate for the social score of manufacturing plants and distribution centers are considered in the model. The model captures different categories of uncertainty, including the provider-side, the receiver-side, and the in-between uncertainties. To deal with uncertain parameters, the chance constrained fuzzy programming approach is applied. Several test problems are used to analyze the characteristics of the proposed problem. The computational results indicate that considering different categories of uncertainty is crucial to designing an efficient and effective supply chain network. Several interesting research topics motivated by the present work could be worth investigating for future researches. It would be interesting to consider the capacity of each facility as an endogenous factor. The proposed model can be extended in the disruption situations in which manufacturing plants are affected by the unexpected natural disasters or man-made hazards. It might be also appealing to investigate how insights would change if the carbon tax policy is considered in the proposed model.

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