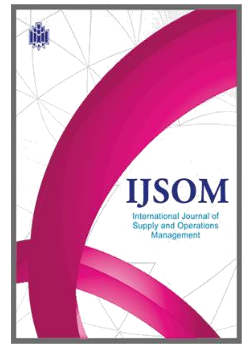
International Journal of Supply and Operations Management

IJSOM

2025, Volume 12, Issue 3, pp. 431-463
ISSN-Print: 2383-1359
ISSN-Online: 2383-2525
www.ijsom.com



Designing A Sustainable Closed Loop Supply Chain Network under Uncertainty: A Robust Possibilistic Programming Approach

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Abstract

This paper studies a comprehensive multi-objective closed loop supply chain network design problem by considering economic performance, environmental impacts, and social responsibilities as the most important concerns of a supply chain's stakeholders. Due to the unavailability of historical data, all uncertain parameters are represented as fuzzy numbers based on the subjective knowledge of experts. A novel multi-objective mixed integer programming model is developed to formulate the problem. Furthermore, a robust possibilistic counterpart model is derived to generate robust solutions under epistemic uncertainty of parameters. Because of the multi-objective nature of the problem an NSGA-II algorithm is designed to yield Pareto-optimal solutions. A case study in the automotive industry is provided to validate the developed model and its solution method. Finally, several sensitivity analyses are carried out to determine the impact of critical parameters.

Keywords: Closed Loop Supply Chain; Sustainability; Multi-Objective Programming; Robust Possibilistic Programming.

1. Introduction

A Closed Loop Supply Chain (CLSC) consists of both forward and backward supply chain flows. A typical forward supply chain's facilities includes: suppliers, manufacturing plants, Distribution Centers (DCs) and retailers (Fazli-Khalaf et al., 2017). End-Of-Life (EOL) products or End-Of-Use (EOU) products are collected from customers in the backward supply chain. Therefore, environmental damages of the supply chain will be reduced (Kumar et al., 2014; Rahimi & Fazlollahtabar, 2018). A backward supply chain's facilities consists of collection, inspection, recycling, recovery and disposal centers which collect EOLs and EOUs and return them to the production or consumption cycle as recycled raw parts/materials (Hu et al., 2016; Özceylan et al., 2017). Appropriate planning of a backward supply chain assists in the efficient management of energy resources and reduces air pollution that itself is a big problem in most industrial sectors (Paksoy et al., 2012). It is worth mentioning that the performance of forward and backward supply chains are highly interdependent and should be planned as an unified network (Fazli-Khalaf et al., 2017). Thus, integrated optimization of these two interrelated networks can prevent the sub-optimality of decisions obtained from separate optimization (Pishvaee & Razmi, 2012; Pishvaee & Torabi, 2010; Zohal & Soleimani, 2016). Closed Supply Chain Network Design (CLSCND) is a strategic decision making problem which determines the structure (i.e. location and capacity of facilities) through the supply chain and amount of aggregate material flows among them. These decisions impact on the long-term performance of companies. An effective and efficient supply chain network has the vital impact on the improvement of the stakeholders' satisfaction, profitability increment, location optimization and

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DOI: 10.22034/ijsom.2025.109454.2415

assignment of resources (Zhang et al., 2019). In other words, by designing, setting up and running of the material flows among centers of the supply chain, somehow economic, environmental and social goals of the stakeholders are achieved together and promoting and creating sustainable development in production, distribution and recycle of products are among the objectives of the sustainable closed loop supply chain network design (Zare Mehrjerdi & Lotfi, 2019). Over the last few decades given the increasing emphasize on the resources' scarcity and pollution of the environment, this problem has been an important field in the academia and industry (Govindan et al., 2015).

Considering economical aspect of decisions is common in modeling a CLSCND problem. However, economic dimension is not deniable, because if a supply chain network (except for non-for-profit cases like humanitarian supply chains) is not economically efficient, other aspects will not be highlighted (Nayeri et al., 2020). Nonetheless, with increasing concerns about destructive environmental effects, the green network was became a popular topic among researchers (Nayeri et al., 2020). The researches under this topic pay attention to air pollution and network environmental hazards. The pollutants produced by processes of different levels of the network can be taken as the most dangerous agents which affect human health (Mohammed et al., 2017). In the literature for modeling decisions related to the environment, four methods have been mentioned. These methods include Life Cycle Assessment (LCA), Green House Gas (GHG) emission, the amount of production waste and the amount of energy consumption (Vafaeenezhad et al., 2019). LCA is the measure for evaluating environmental impacts in all segments of the supply chain (from raw materials to the final product). For various reasons implementing this method is not possible. Care about environmental considerations is slowly understood in the companies, therefore evaluation only one piece of environmental factors may be considered as an intermediate stage of an integrated and complete method. So, until the time of environmental data acquisition, modeling of the whole supply chain will be hard (Luthra et al., 2014). Also, consumption of water as an important factor should be considered in the design of a supply chain (Ahi & Searcy, 2015). Therefore, in this study we have considered GHG emission, amount of energy and water consumptions as measurements related to environmental impacts of the supply chain.

Nowadays, the importance of social responsibility of the supply chain network to gain competitive advantages is clear for leaders of the supply chain network (Nayeri et al., 2020). Attention to social impact of the network leads to creating a good image of the organization among the public and can gain a competitive advantage for the company (Gholizadeh et al., 2020; Pishvaee et al., 2014). This aspect of a supply chain network involves different dimensions. The International Standardization Organization (ISO) in ISO26000 has classified these factors into six general groups, including human rights, workforce issues, the environment, suitable working conditions, customer care and societal development (Soleimani et al., 2017). The number of missed days of the workforce due to occupational accidents has been considered as one of the indicators related to social issues in ISO26000:2010 standard (Soleimani et al., 2017). Labor adjacency to parts of a supply chain enhances local employment and follows the prosperity of employees (as an instance by reduction in travel times) (Boukherroub et al., 2015). We decide on the location of facilities considering two above mentioned measurements under social responsibility in this study.

Because of the complex structure of a closed loop supply chain network, a CLSC problem is usually contaminated by uncertainties. In this regard, several researchers have used robust or stochastic optimization methods to design specific aspects of networks with uncertainties (Jiao et al., 2018). In cases like designing a new supply chain that has no historical data, determining stochastic distribution of parameters is not possible, consequently robust approach is used instead of stochastic optimization method (Rabbani et al., 2020). In this paper, all of the parameters are considered as triangular fuzzy numbers and a robust possibilistic counterpart is developed to yield the final robust solution.

2. Literature review

Devika et al., (2014) considered a Sustainable Closed Loop Supply Chain (SCLSC) for a glass industry. In the model environmental impacts were considered as an environmental objective function. Also, the authors modeled summation of the number of created job opportunities and the lost days caused from work's damages as a social objective. The authors designed three hybrid metaheuristic methods based on adapted Imperialist Competitive Algorithm (ICA) and Variable Neighborhood Search (VNS) for solving the problem. Pishvaee et al., (2014) proposed a chance-constraint fuzzy programming model to design a SCLSC for medical syringes and needles with economic, environmental and social objective functions. The authors by using a posteriori approach (Hwang & Masud, 2012), converted the problem into a single objective model and solved it by using Benders Decomposition (BD) method. Dubey et al., (2015) studied design of a SCLSC under uncertainty. They created an objective function of which composed three measures and proposed three robust mathematical models under different approaches. Saffari et al., (2015) developed a robust optimization model for the SCLSC network design. The paper had three distinct objectives including total cost, social impacts like recruitment and justice in creating job opportunities and environmental impacts like CO2 emissions. An efficient Non-dominated Sorting Genetic Algorithm-II (NSGA-II) is applied to determine the Pareto optimal solutions. Soleimani et al., (2017) proposed a fuzzy programming mathematical model for the SCLSC problem. The authors considered three objectives, profit maximization, minimizing the number of missed days of the workforce due to occupational accidents and maximizing the amount of satisfied customer needs. Also environmental considerations were modeled as a constraint in the model. A NSGA-II method was developed for solving the model. Mota et al., (2018) considered the design of a SCLSC under stochastic uncertainty and proposed a three objective Mixed Integer Linear Programming (MILP) model for the problem. The authors considered economical objective, via Net Present Value (NPV); environmental objective, via LCA method; and social objective, via an advanced measure based on Gross Domestic Product (GDP). The authors solved the problem using Cplex solver. Jiao et al., (2018) studied SCLSC under multi-uncertainties. The authors developed a distributed robust optimization model and an adaptive robust model addressing multi uncertainties. This study aimed to minimizing costs of the network and to keep GHG emissions lower than a previous specified upper bound. Implementing a Data Driven (DD) approach as a solution method was another contribution of the work. Govindan et al., (2019) studied a multi objective SCLSC problem and proposed a MILP model. The authors dealt with uncertainty and concurrently converted the multi objective model to a single one using a fuzzy approach. They applied the model to an automotive timing belt manufacturer. Finally, the authors solved the problem using Cplex solver. Zhen et al., (2019) considered a SCLSC design problem under uncertain demands. In other words, the authors considered the amount of demands in the form of predetermined stochastic scenarios. They proposed a bi-objective stochastic programming model consisting of CO2 emission and total operational cost minimization. Also, a Lagrangean Relaxation (LR) method is developed to solve the model. Rabbani et al., (2020) studied the design of a SCLSC in the presence of fuzzy uncertainty in travel costs, CO2 emissions, and the amount of customers demand. The authors proposed a multi-objectives robust possibilistic programming model. The model involves three objective functions to minimize the total costs, CO2 emissions, and the amounts of unsatisfied demand. The authors solved their case study by the Improved Augmented ε-Constraint (AUGMECON) method. Fathollahi-Fard et al., (2020) studied a SCLSC for an integrated water supply and wastewater collection system in stochastic environment. In the paper, the total cost and all environmental impacts were minimized. The number of job opportunities and work's damages were taken into account in social dimension of the problem. Another novelty of the study was to introduce an improved Multi objective Social Engineering Optimizer (MOSEO) to solve the problem. Nayeri et al., (2020) proposed a multi objective robust fuzzy optimization model to configure a SCLSC network for a water tank. In this three-objective model, minimizing total cost of the network, minimizing environmental impacts; sum of Asbestos and CO2 emission, and maximizing social effects; sum of fixed and variable job opportunities created minus damages to workers' health has been considered. Then, the proposed model was solved using the Goal Programming approach (GP). Mehrjerdi and Shafiee, (2020) studied design of a SCLSC network in tire industry. The authors proposed a multi objective integer programming model. This model consists of economic, environmental and social objectives. In the first one; costs, in the second one; the amount of pollutants emission, and in the third one; the amount of job opportunities created, have been considered. The authors implemented an improved version of the AUGMECON method as a solution technique. Moheb-Alizadeh et al., (2021) proposed a two-stage stochastic formulation for an efficient SCLSC network design problem. In this study efficiency is assessed using a bi-objective output-oriented data envelopment analysis model. The authors hybridized the GP method and the LR algorithm for solving the problem. Salehi-Amiri et al., (2021) designed a SCLSC for walnut industry. They proposed a new MILP formulation for the problem. The model only considers total cost of the network as an economic measure. The Simulated Annealing (SA), the SEO algorithm, the Keshtel algorithm, and hybrid of them were implemented as solution methods. Rafigh et al., (2021) proposed a SCLSC under uncertainty for the application of ventilators to create a response to the COVID-19 pandemic. In the paper in addition to the total cost, minimization of the social impacts and the amount of emitted GHG are considered in the form of stochastic parameters. A Hybrid Whale Optimization Algorithm (HWOA) was proposed to solve the problem. Gholizadeh et al.,(2021) proposed a SCLSC for dairy industry. In the model GHG emissions is included in the environmental objective function and maximization of the total profit is considered as an economic objective. The authors used an AUGMECON method for solving the problem. Tavana et al., (2022) considered an integrated tri-objectives MILP model to design SCLSC networks with various decision problems. The developed model minimized total costs and the amount of CO2 emissions while maximizing the created job opportunities. The authors proposed a fuzzy GP approach as a solution method. Akbari-Kasgari et al.,

(2022) presented a resilient SCLSC network for the copper industry. In the developed model, the economic objective was to maximize the profit; the environmental objective was to minimize water consumption and air pollutants; and the social objective was to maximize social desirability by considering security and unemployment rates. The authors used ε-Constraint (ε-C) and Weighted Sum (WS) methods for solving the problem. Seydanlou et al., (2023) considered an agricultural industry and proposed a SCLSC under uncertainty. The proposed problem minimized the expected total cost while considering energy consumption, CO2 emissions, and the number of employed jobs in constraints. The authors developed a customized SA using a tabu list for solving the problem. Abbasi et al., (2023) studied a green CLSCND problem during the COVID-19 pandemic. The model explained the trade-offs between minimizing CO2 emissions and minimizing total costs. The authors used the WS method for solving the problem. Hejazi and Khorshidvand, (2024) presented an uncertain SCLSC problem. As a contribution of this study, products were supplied with specific modules to meet customer demands and create product families. The objective functions of this paper are total costs, CO2 emissions, and created jobs. The proposed model was solved using ε-C method.

The survey of the related researches is presented in table 1.

Table 1. The survey of the related researches

Reference	Eco. Dimensions		Env. Dimensions				Soc. Dimensions			# Obj		Uncertainty		Solution method	Modeling
	Profit	Cost	Eng	GHG	Wat	CO2	# J.O	# M.D	Other	Single	Multi	Stc	Fuz		
(Devika et al., 2014)		✓		✓			✓	✓			✓			ICA & VNS	MILP
(Pishvaee et al., 2014)		✓									✓		✓	BD	MILP
(Dubey et al., 2015)		✓		✓	✓					✓		✓		Cplex	Robust
(Saffari et al., 2015)		✓		✓					✓		✓			NSGA-II	Robust
(Soleimani et al., 2017)	✓			✓				✓	✓		✓		✓	NSGA-II	MILP
(Mota et al., 2018)	✓				✓				✓		✓	✓		Cplex	MILP
(Jiao et al., 2018)		✓		✓						✓		✓		DD	Robust
(Govindan et al., 2019)		✓		✓						✓			✓	Cplex	MILP
(Zhen et al., 2019)		✓		✓							✓	✓		LR	MILP
(Rabbani et al., 2020)		✓				✓			✓		✓		✓	AUGMECON	Robust
(Fathollahi-Fard et al., 2020)		✓		✓			✓	✓		✓		✓		MOSEO	MILP
(Nayeri et al., 2020)		✓		✓		✓	✓		✓		✓		✓	GP	Robust
(Mehrjerdi & Shafiee, 2020)		✓	✓		✓	✓	✓				✓			AUGMECON	MILP
(Moheb-Alizadeh et al., 2021)		✓				✓	✓	✓			✓	✓		GP & LR	MINLP
(Salehi-Amiri et al., 2021)		✓								✓				SA & SEO & Keshtel	MILP
(Rafigh et al., 2021)		✓		✓			✓	✓	✓		✓	✓		HWOA	MINLP
(Gholizadeh et al., 2021)	✓			✓							✓	✓		AUGMECON	Robust
(Tavana et al., 2022)		✓				✓	✓				✓		✓	GP	MILP
(Akbari-Kasgari et al., 2022)	✓			✓	✓				✓	✓				ε-C & WS	MILP
(Seydanlou et al., 2023)		✓	✓			✓	✓				✓	✓		SA	MILP
(Abbasi et al., 2023)	✓					✓					✓			WS	MILP
(Hejazi & Khorshidvand, 2024)		✓				✓	✓				✓			WS	Robust
This paper		✓	✓	✓	✓		✓	✓			✓		✓		Robust

Eng: Amount of consumed Energy; GHG: Amount of generated GHG; Wat: Amount of consumed Water; # J.O: Number of created Job Opportunities; # M.D: Number of Missed Days
Obj: Number of Objectives; Stc: Stochastic environment; Fuz: Fuzzy environment; MINLP: Mixed Integer Non-Linear Programming

3. Problem formulation

The structure of the studied supply chain network is illustrated in Figure 1. Through the forward supply chain, required materials are shipped from suppliers to manufacturers and new products after production are sent to Distribution Centers (DCs) afterward they are distributed among retailers. In the reverse chain, the returned EOL products are first collected in Collection Centers (CCs) and then shipped to Repair Centers (RCs). The amount of returned products is determined as a predefined percent of demand of each retailer. Useful materials of returned products are moved to the manufacturing sites from RCs. Repaired products can be sold in Secondary Markets (SMs) and Disposal Centers (DCs) receive wastes of RCs. As mentioned in the introduction, in this paper all the parameters are represented using triangular fuzzy numbers. Also, by using robust possibilistic approach, developed by (Pishvaee et al., 2012), a robust counterpart of the model will be presented.

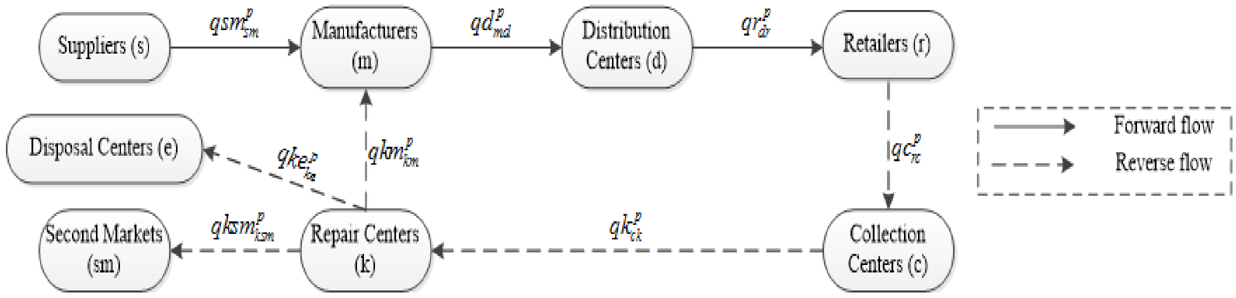

Figure 1.The structure of the studied supply chain network

3.1. Assumptions

- According to an automotive supply chain, a network with eight echelons is considered.
- The forward supply chain consists of suppliers, manufacturers, distributors, retailers and collection centers.
- The backward supply chain involves repair centers, second market customers and disposal centers.
- All of the parameters are tainted with epistemic uncertainty and thus represented as triangular fuzzy numbers.
- The number of missed days, due to occupational accidents, and the number of local employments are taken into account as a social responsibilities objective.
- Amounts of GHG emissions, water and energy consumptions are integrated into the environmental objective.
- Establishment of the new facilities for retailers is not allowed. Therefore, measurements related to the objectives in these facilities have not been calculated.

3.2. Indices

s	: Index of the suppliers
m	: Index of the manufacturers
d	: Index of the Distribution Centers (DCs)
e	: Index of the disposal centers
p	: Index of the products
r	: Index of the retailers
c	: Index of the collection centers
k	: Index of the repair centers
sm	: Index of the secondary market

3.3. Common parameters

d_r^p	: The demand of retailer r for the product type p
$caps_s^p$	: The capacity of supplier s to supply materials for manufacturing a product of type p
$capm_m^p$	: The capacity of manufacturer m for a product of type p
$capd_d^p$	: The capacity of DC d for a product of type p
$capc_c^p$	: The capacity of collection center c for the product of type p
$capk_k^p$	: The capacity of repair center k for the product of type p

$cape_e^p$: The capacity of disposal center e for the product of type p

αk^p : The salable percent of products of type p which entered to the repair centers

αe^p : The disposable percent of the product of type p which entered to the repair centers

βr^p : The percent of the product of type p returned from the collection centers to the repair centers

π_1, π_2, π_3 : The weights of different segments of the objective functions

3.4. Economical parameters

fcs_s : The fixed cost of opening supplier s

fcm_m : The fixed cost of opening manufacturer m

fcc_c : The fixed cost of opening collection center c

fcd_d : The fixed cost of opening DC d

fce_e : The fixed cost of opening disposal center e

fck_k : The fixed cost of opening repair center k

vcs_s^p : The supplying cost of requirements for one product of type p at supplier s

vcm_m^p : The production cost for a product of type p at manufacturer m

vcd_d^p : The inventory cost for a product of type p at distribution center d

vcc_c^p : The inventory cost for a product of type p at collection center c

vck_k^p : The repair cost for a product of type p at repair center k

vce_e^p : The disposal cost of a product of type p at disposal center e

vsm_{sm}^p : The transportation cost of requirements for one product of type p from supplier s to manufacturer m

vmd_{md}^p : The transportation cost of a product of type p from manufacturer m to DC d

vdr_{dr}^p : The transportation cost of a product of type p from DC d to retailer r

vrc_{rc}^p : The transportation cost of a product of type p from retailer r to collection center c

vck_{ck}^p : The transportation cost of a product of type p from collection center c to repair center k

vkm_{km}^p : The transportation cost of a product of type p from repair center k to manufacturer m

$vksm_{ksm}^p$: The transportation cost of a product of type p from repair center k to second market sm

vke_{ke}^p : The transportation cost of a product of type p from repair center k to disposal center e

3.5. Environmental parameters

ns_s^p : The amount of energy that consumed for supplying materials of one product of type p at supplier s

nm_m^p : The amount of energy that consumed by producing a product of type p in the manufacturer m

nd_d^p : The amount of energy that consumed by conserving a product of type p in the DC d

nc_c^p : The amount of energy that consumed by inventorying a product of type p in the collection center c

nk_k^p : The amount of energy that consumed by repairing a product of type p in the repair center k

ne_e^p : The amount of energy that consumed by disposing a product of type p in the disposal center e

nsm_{sm}^p : Energy consumption due to transporting all requirements for producing one product of type p from supplier s to manufacturer m

nmd_{md}^p : Energy consumption due to transportation of one product of type p from manufacturer m to DC d

ndr_{dr}^p : Energy consumption due to transportation of one product of type p from DC d to retailer r

nrc_{rc}^p : Energy consumption due to transportation of one product of type p from retailer r to collection center c

nck_{ck}^p : Energy consumption due to transportation of one product of type p from collection center c to repair center k

nkm_{km}^p : Energy consumption due to transportation of one product of type p from repair center k to manufacturer m

$nksm_{ksm}^p$: Energy consumption due to transportation of one product of type p from repair center k to second market sm

nke_{ke}^p : Energy consumption due to transportation of one product of type p from repair center k to disposal center e

es_s^p : Amount of GHG that emitted by supplying the requirements of a product of type p at supplier s

em_m^p : Amount of GHG that emitted by producing a product of type p at manufacturer m

ed_d^p : Amount of GHG that emitted by conserving a product of type p at DC d

ec_c^p : Amount of GHG that emitted by collecting a product of type p at center c

ek_k^p : Amount of GHG that emitted by repairing a product of type p at repair center k

ee_e^p : Amount of GHG that emitted by disposing a product of type p at disposal center c

esm_{sm}^p : GHG emission due to transportation of one product of type p from supplier s to manufacturer m

emd_{md}^p : GHG emission due to transportation of one product of type p from manufacturer m to DC d

edr_{dr}^p : GHG emission due to transportation of one product of type p from DC d to retailer r

erc_{rc}^p : GHG emission due to transportation of one product of type p from retailer r to collection center c

eck_{ck}^p : GHG emission due to transportation of one product of type p from collection center c to repair center k

ekm_{km}^p : GHG emission due to transportation of one product of type p from repair center k to manufacturer m

$eksm_{ksm}^p$: GHG emission due to transportation of one product of type p from repair center k to second market sm

eke_{ke}^p : GHG emission due to transportation of one product of type p from repair center k to disposal center e

ws_s^p : Amount of water that consumed by supplying the requirements of a product of type p at supplier s

wm_m^p : Amount of water that consumed by production of a product of type p at manufacturer m

wd_d^p : Amount of water that consumed by conserving of a product of type p at DC d

wc_c^p : Amount of water that consumed by collecting of a product of type p at collection center c

wk_k^p : Amount of water that consumed by repairing of a product of type p at repair center k

we_e^p : Amount of water that consumed by disposing of a product of type p at disposal center e

3.6. Social parameters

os_s^p : The number of direct and indirect local jobs which are created by the construction of supplier s for supplying materials of the product of type p

om_m^p : The number of direct and indirect local jobs which are created by the construction of manufacturer m for manufacturing of the product of type p

od_d^p : The number of direct and indirect local jobs which are created by the construction of DC d for distribution of the product of type p

oc_c^p : The number of direct and indirect local jobs which are created by the construction of collection center c for collection of the product of type p

ok_k^p : The number of direct and indirect local jobs which are created by the construction of repair center k for repairing of the product of type p

oe_e^p : The number of direct and indirect local jobs which are created by the construction of disposal center e for disposing the product of type p

ms_s^p : The number of missed days of the workforce due to occupational accidents at supplier s which has been constructed for supplying the requirements of the product of type p

mm_m^p : The number of missed days of the workforce due to occupational accidents at manufacturer m which has been constructed for manufacturing of the product of type p

md_d^p : The number of missed days of the workforce due to occupational accidents at DC d which has been constructed for distribution of the product of type p

mc_c^p : The number of missed days of the workforce due to occupational accidents at collection center c which has been constructed for collection of the product of type p

mk_k^p : The number of missed days of the workforce due to occupational accidents at repair center k which has been constructed for repairing of the product of type p

me_e^p : The number of missed days of the workforce due to occupational accidents at disposal center e which has been constructed for disposing of the product of type p

3.7. Decision variables

xs_s : 1, if supplier s is established; 0, otherwise

xm_m : 1, if manufacturer m is established; 0, otherwise

xd_d : 1, if DC d is established; 0, otherwise

xc_c : 1, if collection center c is established; 0, otherwise

xk_k	: 1, if repair center k is established; 0, otherwise
xe_e	: 1, if disposal center e is established; 0, otherwise
ysm_{sm}^p	: 1, if the requirements of product type p are moved from supplier s to manufacturer m ; 0, otherwise
ymd_{md}^p	: 1, if product type p is transported from manufacturer m to DC d ; 0, otherwise
ydr_{dr}^p	: 1, if product type p is transported from DC d to retailer r ; 0, otherwise
yrc_{rc}^p	: 1, if product type p is moved from retailer r to collection center c ; 0, otherwise
yck_{ck}^p	: 1, if product type p is transported from collection center c to repair center k ; 0, otherwise
ykm_{km}^p	: 1, if product type p is moved from repair center k to manufacturer m ; 0, otherwise
$yksm_{ksm}^p$	: 1, if product type p is transmitted from repairer k to second market zone sm ; 0, otherwise
yke_{ke}^p	: 1, if product type p is transported from repair center k to disposal center e ; 0, otherwise
qsm_{sm}^p	: Amount of transportation from supplier s to manufacturer m for the product of type p
qd_{md}^p	: Amount of transportation from manufacturer m to DC d for the product of type p
qr_{dr}^p	: Amount of transportation from DC d to retailer r for the product of type p
qc_{rc}^p	: Amount of transportation from retailer r to collection center c for the product of type p
qk_{ck}^p	: Amount of transportation from collection center c to repair center k for the product of type p
qkm_{km}^p	: Amount of transportation from repair center k to manufacturer m for the product of type p
$qksm_{ksm}^p$	: Amount of transportation from repair center k to second market sm for the product of type p
qke_{ke}^p	: Amount of transportation from repair center k to disposal center e for the product of type p

3.8. Economic objective function

The economic objective function is presented in equation 1. This objective function consists of three parts 1) fixed costs of the supply chain ($FixedCost$), 2) variable costs of the supply chain ($VariableCost$) and 3) inventory costs inside the supply chain members ($InventoryCost$). The fixed costs include the establishment costs of the supply chain components. The variable costs are related to the transportation costs among different sites of the supply chain. The inventory costs consist of holding costs of products at DCs, retailers, collection centers and the repairing costs at repair centers.

$$
\begin{aligned}
&Min\ TCost = FixedCost + VariableCost + InventoryCost \\
&FixedCost = \sum_s fcs_s\left(xs_s\right) + \sum_m fcm_m\left(xm_m\right) + \sum_d fcd_d\left(xd_d\right) + \sum_r fcr_r\left(xr_r\right) \\
&+\sum_c fcc_c\left(xc_c\right) + \sum_k fck_k\left(xk_k\right) + \sum_e fce_e\left(xe_e\right)
\end{aligned}
\tag{1}
$$

$$VariableCost = \sum_p \sum_s \sum_m \widetilde{vcs}_s^p \left(qsm_{sm}^p\right) + \sum_p \sum_m \sum_d \widetilde{vcm}_m^p \left(qd_{md}^p\right) + \sum_p \sum_s \sum_m \widetilde{vsm}_{sm}^p \left(qsm_{sm}^p\right) + \sum_p \sum_m \sum_d \widetilde{vmd}_{md}^p \left(qd_{md}^p\right) + \sum_p \sum_d \sum_r \widetilde{vdr}_{dr}^p \left(qr_{dr}^p\right) + \sum_p \sum_r \sum_c \widetilde{vrc}_{rc}^p \left(qc_{rc}^p\right) + \sum_p \sum_c \sum_k \widetilde{vck}_{ck}^p \left(qk_{ck}^p\right) + \sum_p \sum_k \sum_m \widetilde{vkm}_{km}^p \left(qkm_{km}^p\right) + \sum_p \sum_k \sum_{sm} \widetilde{vksm}_{ksm}^p \left(qksm_{ksm}^p\right) + \sum_p \sum_k \sum_e \widetilde{vke}_{ke}^p \left(qke_{ke}^p\right)$$

$$InventoryCost = \sum_p \sum_m \sum_d \widetilde{vcd}_d^p \left(qd_{md}^p\right) + \sum_p \sum_d \sum_r \widetilde{vcr}_r^p \left(qr_{dr}^p\right) + \sum_p \sum_r \sum_c \widetilde{vcc}_c^p \left(qc_{rc}^p\right) + \sum_p \sum_c \sum_k \widetilde{vck}_k^p \left(qk_{ck}^p\right)$$

3.9. Environmental objective function

This objective function will be in the form of equation 2. This objective function consists of three terms 1) the amount of energy consumed in the supply chain (Eng), 2) the amount of green-house gas emitted in the supply chain (Ems) and 3) the amount of water consumed in the supply chain (Wtr). Water and energy are consumed and green-house gas is emitted by the operations inside the facilities. In other words, the green-house gas is generated by transportations among the different sites.

$$\begin{aligned}
&Min\ TEnv = Eng + \pi_1(Ems) + \pi_2(Wtr) \\
&Eng = \sum_p \sum_s \sum_m \left(\widetilde{ns}_s^p + \widetilde{nsm}_{sm}^p\right) qsm_{sm}^p + \sum_p \sum_m \sum_d \left(\widetilde{nm}_m^p + \widetilde{nmd}_{md}^p\right) qd_{md}^p \\
&\quad + \sum_p \sum_d \sum_r \left(\widetilde{nd}_d^p + \widetilde{ndr}_{dr}^p\right) qr_{dr}^p + \sum_p \sum_r \sum_c \left(\widetilde{nrc}_{rc}^p\right) qc_{rc}^p \\
&\quad + \sum_p \sum_c \sum_k \left(\widetilde{nc}_c^p + \widetilde{nck}_{ck}^p\right) qk_{ck}^p + \sum_p \sum_m \sum_k \left(\widetilde{nm}_m^p + \widetilde{nkm}_{km}^p\right) qkm_{km}^p \\
&\quad + \sum_p \sum_k \sum_{sm} \left(\widetilde{nk}_k^p + \widetilde{nksm}_{ksm}^p\right) qksm_{ksm}^p + \sum_p \sum_e \sum_k \left(\widetilde{ne}_e^p + \widetilde{nke}_{ke}^p\right) qke_{ke}^p \\
&Ems = \sum_p \sum_s \sum_m \left(\widetilde{es}_s^p + \widetilde{esm}_{sm}^p\right) qsm_{sm}^p + \sum_p \sum_m \sum_d \left(\widetilde{em}_m^p + \widetilde{emd}_{md}^p\right) qd_{md}^p \\
&\quad + \sum_p \sum_d \sum_r \left(\widetilde{ed}_d^p + \widetilde{edr}_{dr}^p\right) qr_{dr}^p + \sum_p \sum_r \sum_c \left(\widetilde{erc}_{rc}^p\right) qc_{rc}^p \\
&\quad + \sum_p \sum_c \sum_k \left(\widetilde{ec}_c^p + \widetilde{eck}_{ck}^p\right) qk_{ck}^p + \sum_p \sum_m \sum_k \left(\widetilde{em}_m^p + \widetilde{ekm}_{km}^p\right) qkm_{km}^p \\
&\quad + \sum_p \sum_k \sum_{sm} \left(\widetilde{ek}_k^p + \widetilde{eksm}_{ksm}^p\right) qksm_{ksm}^p + \sum_p \sum_k \sum_e \left(\widetilde{ee}_e^p + \widetilde{eke}_{ke}^p\right) qke_{ke}^p
\end{aligned} \tag{2}$$

$$Wtr = \sum_p \sum_s \sum_m (\widetilde{ws}_s^p) qsm_{sm}^p + \sum_p \sum_m \sum_d (\widetilde{wm}_m^p) qd_{md}^p + \sum_p \sum_d \sum_r (\widetilde{wd}_d^p) qr_{dr}^p + \sum_p \sum_r \sum_c (\widetilde{wr}_r^p) qc_{rc}^p + \sum_p \sum_c \sum_k (\widetilde{wc}_c^p) qk_{ck}^p + \sum_p \sum_k \sum_c (\widetilde{wk}_k^p) qk_{ck}^p + \sum_p \sum_e \sum_k (\widetilde{we}_e^p) qke_{ke}^p$$

3.10. Social objective function

This objective function is related to the social responsibilities of the supply chain and is shown by equation 3. The objective function has two components 1) the total number of missed days of the workforce due to occupational accidents at active components and 2) the total number of local jobs created at established facilities in the supply chain.

$$Min\ SRes = \sum_s \sum_p \left((\pi_3) \widetilde{ms}_s^p - \widetilde{os}_s^p \right) xs_s + \sum_m \sum_p \left((\pi_3) \widetilde{mm}_m^p - \widetilde{om}_m^p \right) xm_m + \sum_d \sum_p \left((\pi_3) \widetilde{md}_d^p - \widetilde{od}_d^p \right) xd_d + \sum_c \sum_p \left((\pi_3) \widetilde{mc}_c^p - \widetilde{oc}_c^p \right) xc_c + \sum_k \sum_p \left((\pi_3) \widetilde{mk}_k^p - \widetilde{ok}_k^p \right) xk_k + \sum_k \sum_p \left((\pi_3) \widetilde{me}_e^p - \widetilde{oe}_e^p \right) xe_e \quad (3)$$

3.11. Constraints of the proposed model

Equation 4 satisfies demands of each retailer.

$$\sum_d qr_{dr}^p \geq \tilde{d}_r^p \quad ;\forall r, p \quad (4)$$

Equations 5-11, in addition to the capacity restriction, guarantee that arrival and departure of flows from (to) each facility is subject to its establishment.

$$qsm_{sm}^p \leq \left(caps_s^p \right) xs_s \quad ;\forall s, m, p \quad (5)$$

$$qd_{md}^p \leq \left(capm_m^p \right) xm_m \quad ;\forall m, d, p \quad (6)$$

$$qc_{rc}^p \leq \left(capc_c^p \right) xc_c \quad ;\forall r, c, p \quad (7)$$

$$qk_{ck}^p \leq \left(capk_k^p \right) xk_k \quad ;\forall c, k, p \quad (8)$$

$$qkm_{km}^p \leq \left(capk_k^p \right) xm_m \quad ;\forall k, \mathrm{m}, p \quad (9)$$

$$qksm_{ksm}^p \leq \left(capk_k^p \right) xm_k \quad ;\forall k, \mathrm{sm}, p \quad (10)$$

$$qke_{ke}^p \leq \left(cape_e^p \right) xe_e \quad ;\forall k, e, p \quad (11)$$

Equations 12-27 determine transportation of the products among established facilities.

$$qsm_{sm}^p \leq \left(caps_s^p \right) ysm_{sm}^p \quad ;\forall s, m, p \quad (12)$$

$$qsm_{sm}^p \geq caps_s^p \left(ysm_{sm}^p - 1 \right) \quad ;\forall s, m, p \quad (13)$$

$$qd^{p}_{md} \le \left(capm^{p}_{m}\right) ymd^{p}_{md} \quad ;\forall m,d,p \tag{14}$$

$$qd^{p}_{md} \ge capm^{p}_{m} \left(ymd^{p}_{md} - 1\right) \quad ;\forall m,d,p \tag{15}$$

$$qr^{p}_{dr} \le \left(capd^{p}_{d}\right) ydr^{p}_{dr} \quad ;\forall d,r,p \tag{16}$$

$$qr^{p}_{dr} \ge capd^{p}_{d} \left(ydr^{p}_{dr} - 1\right) \quad ;\forall d,r,p \tag{17}$$

$$qc^{p}_{rc} \le \left(capc^{p}_{c}\right) yrc^{p}_{rc} \quad ;\forall r,c,p \tag{18}$$

$$qc^{p}_{rc} \ge capc^{p}_{c} \left(yrc^{p}_{rc} - 1\right) \quad ;\forall r,c,p \tag{19}$$

$$qk^{p}_{ck} \le \left(capc^{p}_{c}\right) yck^{p}_{ck} \quad ;\forall c,k,p \tag{20}$$

$$qk^{p}_{ck} \ge capc^{p}_{c} \left(yck^{p}_{ck} - 1\right) \quad ;\forall c,k,p \tag{21}$$

$$qke^{p}_{ke} \le \left(capk^{p}_{k}\right) yke^{p}_{ke} \quad ;\forall k,e,p \tag{22}$$

$$qke^{p}_{ke} \ge capk^{p}_{k} \left(yke^{p}_{ke} - 1\right) \quad ;\forall k,e,p \tag{23}$$

$$qkm^{p}_{km} \le \left(capk^{p}_{k}\right) ykm^{p}_{km} \quad ;\forall k,\mathrm{m},p \tag{24}$$

$$qkm^{p}_{km} \ge capk^{p}_{k} \left(ykm^{p}_{km} - 1\right) \quad ;\forall k,\mathrm{m},p \tag{25}$$

$$qksm^{p}_{ksm} \le \left(capk^{p}_{k}\right) yksm^{p}_{ksm} \quad ;\forall k,\mathrm{sm},p \tag{26}$$

$$qksm^{p}_{ksm} \ge capk^{p}_{k} \left(yksm^{p}_{ksm} - 1\right) \quad ;\forall k,\mathrm{sm},p \tag{27}$$

Equations 28-35 guarantee service of each established facility is done completely by only one opened facility which is located in the lower level.

$$\sum_{s} ysm^{p}_{sm} \le 1 \quad ;\forall m,p \tag{28}$$

$$\sum_{m} ymd^{p}_{md} \le 1 \quad ;\forall d,p \tag{29}$$

$$\sum_{d} ydr^{p}_{dr} = 1 \quad ;\forall r,p \tag{30}$$

$$\sum_{c} yrc^{p}_{rc} = 1 \quad ;\forall r,p \tag{31}$$

$$\sum_{k} yck^{p}_{ck} \le 1 \quad ;\forall c,p \tag{32}$$

$$\sum_{m} ykm^{p}_{km} \le 1 \quad ;\forall k,p \tag{33}$$

$$\sum_{sm} yksm^{p}_{ksm} \le 1 \quad ;\forall k,p \tag{34}$$

$$\sum_{e} yke^{p}_{ke} \le 1 \quad ;\forall k,p \tag{35}$$

Equations 36-40 explain the flows balance limitation in two established facilities that are located on two consecutive echelons.

$$\sum_{d} qmd_{md}^{p} \le \sum_{s} qsm_{sm}^{p} \quad ;\forall m, p \tag{36}$$

$$\sum_{r} qr_{dr}^{p} \le \sum_{m} qmd_{md}^{p} \quad ;\forall d, p \tag{37}$$

$$\sum_{c} qc_{rc}^{p} \le \sum_{d} qr_{dr}^{p} \quad ;\forall r, p \tag{38}$$

$$\sum_{k} qk_{ck}^{p} \le \sum_{r} qc_{rc}^{p} \quad ;\forall c, p \tag{39}$$

$$\sum_{m} qkm_{km}^{p} + \sum_{e} qke_{ke}^{p} + \sum_{sm} qksm_{ksm}^{p} \le \sum_{c} qk_{ck}^{p} \quad ;\forall k, p \tag{40}$$

Equations 41-44 determine the output flows from each repair center to manufacturers, second market zones, and disposal centers and from each retailer to collection centers, respectively.

$$\sum_{m} qkm_{km}^{p} = \left(1 - \alpha k^{p} - \alpha e^{p}\right) \sum_{c} qk_{ck}^{p} \quad ;\forall k, p \tag{41}$$

$$\sum_{sm} qksm_{ksm}^{p} = \alpha k^{p} \sum_{c} qk_{ck}^{p} \quad ,\forall k, p \tag{42}$$

$$\sum_{e} qke_{ke}^{p} = \alpha e^{p} \sum_{c} qk_{ck}^{p} \quad ;\forall k, p \tag{43}$$

$$\sum_{c} qc_{rc}^{p} = \beta r^{p} \sum_{d} qr_{dr}^{p} \quad ;\forall r, p \tag{44}$$

Equation 45 shows domain of the decision variables.

$$\begin{aligned} & xs_s, xm_m, xd_d, xr_r, xc_c, xk_k, xe_e, ys_{ss'}^{psc}, ym_{mm'}^{psc}, ysm_{sm}^{psc}, ymd_{md}^{psc}, ydr_{dr}^{psc}, yrc_{rc}^{psc}, yck_{ck}^{psc} \\ & , ykm_{km}^{psc}, yksm_{ksm}^{psc}, yke_{ke}^{psc} \in \{0\, or\, 1\} \\ & qs_{ss'}^{psc}, qm_{mm'}^{psc}, qsm_{sm}^{psc}, qd_{md}^{psc}, qr_{dr}^{psc}, qc_{rc}^{psc}, qk_{ck}^{psc}, qke_{ke}^{psc}, qkm_{km}^{psc}, qksm_{ksm}^{psc} \ge 0 \end{aligned} \tag{45}$$

3.12. Developing the robust counterpart

As mentioned in the introduction section, all of the parameters except for amount of the capacities and the flow rates are shown by triangular fuzzy numbers. In such cases where the uncertainty level is high and as a result effectiveness of the strategic decisions is at risk, the robust possibilistic programming approach will be helpful (Habib et al., 2021).

Assume $\xi = (\xi 1, \xi 2, \xi 3)$ is a triangular fuzzy number. Membership function (μ) of the number is shown in figure 2.

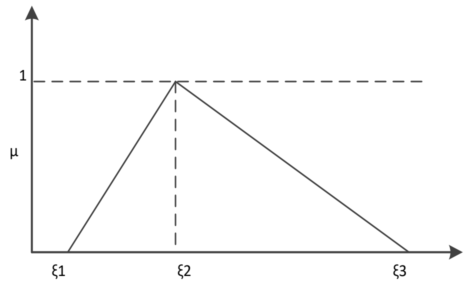

Figure 1. Membership function of a triangular fuzzy number

Consider a mathematical model according to equation 46 with triangular fuzzy number parameters $C = (C1, C2, C3)$ and $d = (d1, d2, d3)$.

$$
\begin{aligned}
& Min\, Z = Cx \\
& Ax \ge d \\
& x \ge 0
\end{aligned} \tag{46}
$$

According to (Pishvaee et al., 2012), the robust counterpart of the model is presented by equation 47.

$$
\begin{aligned}
& Min\, Z = E(Z) + \gamma\left(Z^{\max} - Z^{\min}\right) + \delta(1-\alpha)[d3 - d2] \\
& E(Z) = \left(\frac{C1 + 2C2 + C3}{4}\right)x \\
& Z^{\max} = (C3)x \\
& Z^{\min} = (C1)x \\
& Ax \ge (1-\alpha)d2 + \alpha d3 \\
& x \ge 0, 0.5 < \alpha \le 1
\end{aligned} \tag{47}
$$

In this model, $E(Z)$ shows the expected cost. Also, $Z^{\max}$ and $Z^{\min}$ represent the maximum and minimum cost, respectively. In this equation, γ is a parameter that shows the importance of the difference between $Z^{\max}$ and, compared to the two other terms of the objective function. Furthermore, $\delta(1-\alpha)[d3 - d2]$ shows the reliability level of the chance constraint in which δ is the unit penalty of violation of the constraint with uncertain parameters.

As it is expected to create a robust model, all of the objective functions and equation 4 need to be modified.

A robust counterpart of the first objective function, minimizing of the total cost, is presented by equation 48.

$$
\begin{aligned}
& Min\ Z_1 = E(TCost) + \gamma_1\left(TCost^{\max} - TCost^{\min}\right) + \delta_1 \sum_p \left(1 - \alpha^p\right) \sum_r \left(d3_r^p - d2_r^p\right) \\
& E(TCost) = FixedCost + E(VariableCost) + E(InventoryCost)
\end{aligned} \tag{48}
$$

$$TCost^{\max} = FixedCost + VariableCost^{\max} + InventoryCost^{\max}$$

$$TCost^{\min} = FixedCost + VariableCost^{\min} + InventoryCost^{\min}$$

$$FixedCost = \sum_{s}(fcs_s)xs_s + \sum_{m}(fcm_m)xm_m + \sum_{d}(fcd_d)xd_d + \sum_{r}(fcr_r)xr_r$$

$$+\sum_{c}(fcc_c)xc_c + \sum_{k}(fck_k)xk_k + \sum_{e}(fce_e)xe_e$$

$$InventoryCost^{\max} = \sum_{p}\sum_{m}\sum_{d}\left(vcd3_d^p\right)qd_{md}^p + \sum_{p}\sum_{d}\sum_{r}\left(vcr3_r^p\right)qr_{dr}^p$$

$$+\sum_{p}\sum_{r}\sum_{c}\left(vcc3_c^p\right)qc_{rc}^p + \sum_{p}\sum_{c}\sum_{k}\left(vck3_k^p\right)qk_{ck}^p$$

$$InventoryCost^{\min} = \sum_{p}\sum_{m}\sum_{d}\left(vcd1_d^p\right)qd_{md}^p + \sum_{p}\sum_{d}\sum_{r}\left(vcr1_r^p\right)qr_{dr}^p$$

$$+\sum_{p}\sum_{r}\sum_{c}\left(vcc1_c^p\right)qc_{rc}^p + \sum_{p}\sum_{c}\sum_{k}\left(vck1_k^p\right)qk_{ck}^p$$

$$E\left(InventoryCost\right) = \sum_{p}\sum_{m}\sum_{d}\left(\frac{vcd1_d^p + 2vcd2_d^p + vcd3_d^p}{4}\right)qd_{md}^p$$

$$+\sum_{p}\sum_{d}\sum_{r}\left(\frac{vcr1_r^p + 2vcr2_r^p + vcr3_r^p}{4}\right)qr_{dr}^p + \sum_{p}\sum_{r}\sum_{c}\left(\frac{vcc1_c^p + 2vcc2_c^p + vcc3_c^p}{4}\right)qc_{rc}^p$$

$$+\sum_{p}\sum_{c}\sum_{k}\left(\frac{vck1_k^p + 2vck2_k^p + vck3_k^p}{4}\right)qk_{ck}^p$$

$$VariableCost^{\max} = \sum_{p}\sum_{s}\sum_{m}\left(vcs3_s^p\right)qsm_{sm}^p + \sum_{p}\sum_{m}\sum_{d}\left(vcm3_m^p\right)qd_{md}^p$$

$$+\sum_{p}\sum_{s}\sum_{m}\left(vsm3_{sm}^p\right)qsm_{sm}^p + \sum_{p}\sum_{m}\sum_{d}\left(vmd3_{md}^p\right)qd_{md}^p + \sum_{p}\sum_{d}\sum_{r}\left(vdr3_{dr}^p\right)qr_{dr}^p$$

$$+\sum_{p}\sum_{r}\sum_{c}\left(vrc3_{rc}^p\right)qc_{rc}^p + \sum_{p}\sum_{c}\sum_{k}\left(vck3_{ck}^p\right)qk_{ck}^p + \sum_{p}\sum_{k}\sum_{m}\left(vkm3_{km}^p\right)qkm_{km}^p$$

$$+\sum_{p}\sum_{k}\sum_{sm}\left(vksm3_{ksm}^p\right)qksm_{ksm}^p + \sum_{p}\sum_{k}\sum_{e}\left(vke3_{ke}^p\right)qke_{ke}^p$$

$$VariableCost^{\min} = \sum_{p}\sum_{s}\sum_{m}\left(vcs1_s^p\right)qsm_{sm}^p + \sum_{p}\sum_{m}\sum_{d}\left(vcm1_m^p\right)qd_{md}^p$$

$$+\sum_{p}\sum_{s}\sum_{m}\left(vsm1_{sm}^p\right)qsm_{sm}^p + \sum_{p}\sum_{m}\sum_{d}\left(vmd1_{md}^p\right)qd_{md}^p + \sum_{p}\sum_{d}\sum_{r}\left(vdr1_{dr}^p\right)qr_{dr}^p$$

$$+\sum_{p}\sum_{r}\sum_{c}\left(vrc1_{rc}^p\right)qc_{rc}^p + \sum_{p}\sum_{c}\sum_{k}\left(vck1_{ck}^p\right)qk_{ck}^p + \sum_{p}\sum_{k}\sum_{m}\left(vkm1_{km}^p\right)qkm_{km}^p$$

$$+\sum_{p}\sum_{k}\sum_{sm}\left(vksm1_{ksm}^p\right)qksm_{ksm}^p + \sum_{p}\sum_{k}\sum_{e}\left(vke1_{ke}^p\right)qke_{ke}^p$$

$$E\left(VariableCost\right) = \sum_{p}\sum_{s}\sum_{m}\left(\frac{vcs1_s^p + 2vcs2_s^p + vcs3_s^p}{4}\right)qsm_{sm}^p$$

$$+\sum_{p}\sum_{m}\sum_{d}\left(\frac{vcm1_{m}^{p}+2vcm2_{m}^{p}+vcm3_{m}^{p}}{4}\right)qd_{md}^{p}+\sum_{p}\sum_{s}\sum_{m}\left(\frac{vsm1_{sm}^{p}+2vsm2_{sm}^{p}+vsm3_{sm}^{p}}{4}\right)qsm_{sm}^{p}$$

$$+\sum_{p}\sum_{m}\sum_{d}\left(\frac{vmd1_{md}^{p}+2vmd2_{md}^{p}+vmd3_{md}^{p}}{4}\right)qd_{md}^{p}+\sum_{p}\sum_{d}\sum_{r}\left(\frac{vdr1_{dr}^{p}+2vdr2_{dr}^{p}+vdr3_{dr}^{p}}{4}\right)qr_{dr}^{p}$$

$$+\sum_{p}\sum_{r}\sum_{c}\left(\frac{vrc1_{rc}^{p}+2vrc2_{rc}^{p}+vrc3_{rc}^{p}}{4}\right)qc_{rc}^{p}+\sum_{p}\sum_{c}\sum_{k}\left(\frac{vck1_{ck}^{p}+2vck2_{ck}^{p}+vck3_{ck}^{p}}{4}\right)qk_{ck}^{p}$$

$$+\sum_{p}\sum_{k}\sum_{m}\left(\frac{vkm1_{km}^{p}+2vkm2_{km}^{p}+vkm3_{km}^{p}}{4}\right)qkm_{km}^{p}+\sum_{p}\sum_{k}\sum_{e}\left(\frac{vke1_{ke}^{p}+2vke2_{ke}^{p}+vke3_{ke}^{p}}{4}\right)qke_{ke}^{p}$$

$$+\sum_{p}\sum_{k}\sum_{sm}\left(\frac{vksm1_{ksm}^{p}+2vksm2_{ksm}^{p}+vksm3_{ksm}^{p}}{4}\right)qksm_{ksm}^{p}$$

Also, a robust counterpart of the second objective function is given by equation 49.

$$
\begin{aligned}
& Min\, Z_2 = E(TEnv) + \gamma_2\left(TEnv^{\max} - TEnv^{\min}\right) + \delta_2 \sum_p \left(1-\alpha^p\right) \sum_r \left(d3_r^p - d2_r^p\right) \\
& E(TEnv) = E(Eng) + \pi_1\left(E(Ems)\right) + \pi_2\left(E(Wtr)\right) \\
& TEnv^{\max} = Eng^{\max} + \pi_1\left(Ems^{\max}\right) + \pi_2\left(Wtr^{\max}\right) \\
& TEnv^{\min} = Eng^{\min} + \pi_1\left(Ems^{\min}\right) + \pi_2\left(Wtr^{\min}\right) \\
& E(Eng) = \sum_p \sum_s \sum_m \left(\frac{ns1_s^p + 2ns2_s^p + ns3_s^p + nsm1_{sm}^p + 2nsm2_{sm}^p + nsm3_{sm}^p}{4} \right) qsm_{sm}^p \\
& + \sum_p \sum_m \sum_d \left(\frac{nm1_m^p + 2nm2_m^p + nm3_m^p + nmd1_{md}^p + 2nmd2_{md}^p + nmd3_{md}^p}{4} \right) qd_{md}^p \\
& + \sum_p \sum_d \sum_r \left(\frac{nd1_d^p + 2nd2_d^p + nd3_d^p + ndr1_{dr}^p + 2ndr2_{dr}^p + ndr3_{dr}^p}{4} \right) qr_{dr}^p \\
& + \sum_p \sum_r \sum_c \left(\frac{nrc1_{rc}^p + 2nrc2_{rc}^p + nrc3_{rc}^p}{4} \right) qc_{rc}^p \\
& + \sum_p \sum_c \sum_k \left(\frac{nc1_c^p + 2nc2_c^p + nc3_c^p + nck1_{ck}^p + 2nck2_{ck}^p + nck3_{ck}^p}{4} \right) qk_{ck}^p \\
& + \sum_p \sum_m \sum_k \left(\frac{nm1_m^p + 2nm2_m^p + nm3_m^p + nkm1_{km}^p + 2nkm2_{km}^p + nkm3_{km}^p}{4} \right) qkm_{km}^p \\
& + \sum_p \sum_k \sum_{sm} \left(\frac{nk1_k^p + 2nk2_k^p + nk3_k^p + nksm1_{ksm}^p + 2nksm2_{ksm}^p + nksm3_{ksm}^p}{4} \right) qksm_{ksm}^p \\
& + \sum_p \sum_e \sum_k \left(\frac{ne1_e^p + 2ne2_e^p + ne3_e^p + nke1_{ke}^p + 2nke2_{ke}^p + nke3_{ke}^p}{4} \right) qke_{ke}^p \\
& E(Ems) = \sum_p \sum_s \sum_m \left(\frac{es1_s^p + 2es2_s^p + es3_s^p + esm1_{sm}^p + 2esm2_{sm}^p + esm3_{sm}^p}{4} \right) qsm_{sm}^p \\
& + \sum_p \sum_m \sum_d \left(\frac{em1_m^p + 2em2_m^p + em3_m^p + emd1_{md}^p + 2emd2_{md}^p + emd3_{md}^p}{4} \right) qd_{md}^p \\
& + \sum_p \sum_d \sum_r \left(\frac{ed1_d^p + 2ed2_d^p + ed3_d^p + edr1_{dr}^p + 2edr2_{dr}^p + edr3_{dr}^p}{4} \right) qr_{dr}^p \\
& + \sum_p \sum_r \sum_c \left(\frac{erc1_{rc}^p + 2erc2_{rc}^p + erc3_{rc}^p}{4} \right) qc_{rc}^p \\
& + \sum_p \sum_c \sum_k \left(\frac{ec1_c^p + 2ec2_c^p + ec3_c^p + eck1_{ck}^p + 2eck2_{ck}^p + eck3_{ck}^p}{4} \right) qk_{ck}^p \\
& + \sum_p \sum_m \sum_k \left(\frac{em1_m^p + 2em2_m^p + em3_m^p + ekm1_{km}^p + 2ekm2_{km}^p + ekm3_{km}^p}{4} \right) qkm_{km}^p \\
& + \sum_p \sum_k \sum_{sm} \left(\frac{ek1_k^p + 2ek2_k^p + ek3_k^p + eksm1_{ksm}^p + 2eksm2_{ksm}^p + eksm3_{ksm}^p}{4} \right) qksm_{ksm}^p \\
& + \sum_p \sum_k \sum_e \left(\frac{ee1_e^p + 2ee2_e^p + ee3_e^p + eke1_{ke}^p + 2eke2_{ke}^p + eke3_{ke}^p}{4} \right) qke_{ke}^p
\end{aligned} \tag{49}
$$

$$E\left(Wtr\right)=\sum_{p}\sum_{s}\sum_{m}\left(\frac{ws1_{s}^{p}+2ws2_{s}^{p}+ws3_{s}^{p}}{4}\right)qsm_{sm}^{p}$$
$$+\sum_{p}\sum_{m}\sum_{d}\left(\frac{wm1_{m}^{p}+2wm2_{m}^{p}+wm3_{m}^{p}}{4}\right)qd_{md}^{p}+\sum_{p}\sum_{d}\sum_{r}\left(\frac{wd1_{d}^{p}+2wd2_{d}^{p}+wd3_{d}^{p}}{4}\right)qr_{dr}^{p}$$
$$+\sum_{p}\sum_{r}\sum_{c}\left(\frac{wr1_{r}^{p}+2wr2_{r}^{p}+wr3_{r}^{p}}{4}\right)qc_{rc}^{p}+\sum_{p}\sum_{c}\sum_{k}\left(\frac{wc1_{c}^{p}+2wc2_{c}^{p}+wc3_{c}^{p}}{4}\right)qk_{ck}^{p}$$
$$+\sum_{p}\sum_{k}\sum_{c}\left(\frac{wk1_{k}^{p}+2wk2_{k}^{p}+wk3_{k}^{p}}{4}\right)qk_{ck}^{p}+\sum_{p}\sum_{e}\sum_{k}\left(\frac{we1_{e}^{p}+2we2_{e}^{p}+we3_{e}^{p}}{4}\right)qke_{ke}^{p}$$
$$Eng^{\max}=\sum_{p}\sum_{s}\sum_{m}\left(ns3_{s}^{p}+nsm3_{sm}^{p}\right)qsm_{sm}^{p}+\sum_{p}\sum_{m}\sum_{d}\left(nm3_{m}^{p}+nmd3_{md}^{p}\right)qd_{md}^{p}$$
$$+\sum_{p}\sum_{d}\sum_{r}\left(nd3_{d}^{p}+ndr3_{dr}^{p}\right)qr_{dr}^{p}+\sum_{p}\sum_{r}\sum_{c}\left(nrc3_{rc}^{p}\right)qc_{rc}^{p}+\sum_{p}\sum_{c}\sum_{k}\left(nc3_{c}^{p}+nck3_{ck}^{p}\right)qk_{ck}^{p}$$
$$+\sum_{p}\sum_{m}\sum_{k}\left(nm3_{m}^{p}+nkm3_{km}^{p}\right)qkm_{km}^{p}+\sum_{p}\sum_{k}\sum_{sm}\left(nk3_{k}^{p}+nksm3_{ksm}^{p}\right)qksm_{ksm}^{p}$$
$$+\sum_{p}\sum_{e}\sum_{k}\left(ne3_{e}^{p}+nke3_{ke}^{p}\right)qke_{ke}^{p}$$

$$Ems^{\max}=\sum_{p}\sum_{s}\sum_{m}\left(es3_{s}^{p}+esm3_{sm}^{p}\right)qsm_{sm}^{p}+\sum_{p}\sum_{m}\sum_{d}\left(em3_{m}^{p}+emd3_{md}^{p}\right)qd_{md}^{p}$$
$$+\sum_{p}\sum_{d}\sum_{r}\left(ed3_{d}^{p}+edr3_{dr}^{p}\right)qr_{dr}^{p}+\sum_{p}\sum_{r}\sum_{c}\left(erc3_{rc}^{p}\right)qc_{rc}^{p}+\sum_{p}\sum_{c}\sum_{k}\left(ec3_{c}^{p}+eck3_{ck}^{p}\right)qk_{ck}^{p}$$
$$+\sum_{p}\sum_{m}\sum_{k}\left(em3_{m}^{p}+ekm3_{km}^{p}\right)qkm_{km}^{p}+\sum_{p}\sum_{k}\sum_{sm}\left(ek3_{k}^{p}+eksm3_{ksm}^{p}\right)qksm_{ksm}^{p}$$
$$+\sum_{p}\sum_{k}\sum_{e}\left(ee3_{e}^{p}+eke3_{ke}^{p}\right)qke_{ke}^{p}$$

$$Wtr^{\max}=\sum_{p}\sum_{s}\sum_{m}\left(ws3_{s}^{p}\right)qsm_{sm}^{p}+\sum_{p}\sum_{m}\sum_{d}\left(wm3_{m}^{p}\right)qd_{md}^{p}+\sum_{p}\sum_{d}\sum_{r}\left(wd3_{d}^{p}\right)qr_{dr}^{p}$$
$$+\sum_{p}\sum_{r}\sum_{c}\left(wr3_{r}^{p}\right)qc_{rc}^{p}+\sum_{p}\sum_{c}\sum_{k}\left(wc3_{c}^{p}\right)qk_{ck}^{p}+\sum_{p}\sum_{k}\sum_{c}\left(wk3_{k}^{p}\right)qk_{ck}^{p}$$
$$+\sum_{p}\sum_{e}\sum_{k}\left(we3_{e}^{p}\right)qke_{ke}^{p}$$

$$
\begin{aligned}
Eng^{\min} = & \sum_p \sum_s \sum_m \left(ns1_s^p + nsm1_{sm}^p \right) qsm_{sm}^p + \sum_p \sum_m \sum_d \left(nm1_m^p + nmd1_{md}^p \right) qd_{md}^p \\
& + \sum_p \sum_d \sum_r \left(nd1_d^p + ndr1_{dr}^p \right) qr_{dr}^p + \sum_p \sum_r \sum_c \left(nrc1_{rc}^p \right) qc_{rc}^p + \sum_p \sum_c \sum_k \left(nc1_c^p + nck1_{ck}^p \right) qk_{ck}^p \\
& + \sum_p \sum_m \sum_k \left(nm1_m^p + nkm1_{km}^p \right) qkm_{km}^p + \sum_p \sum_k \sum_{sm} \left(nk1_k^p + nksm1_{ksm}^p \right) qksm_{ksm}^p \\
& + \sum_p \sum_e \sum_k \left(ne1_e^p + nke1_{ke}^p \right) qke_{ke}^p
\end{aligned}
$$

$$
\begin{aligned}
Ems^{\min} = & \sum_p \sum_s \sum_m \left(es1_s^p + esm1_{sm}^p \right) qsm_{sm}^p + \sum_p \sum_m \sum_d \left(em1_m^p + emd1_{md}^p \right) qd_{md}^p \\
& + \sum_p \sum_d \sum_r \left(ed1_d^p + edr1_{dr}^p \right) qr_{dr}^p + \sum_p \sum_r \sum_c \left(erc1_{rc}^p \right) qc_{rc}^p + \sum_p \sum_c \sum_k \left(ec1_c^p + eck1_{ck}^p \right) qk_{ck}^p \\
& + \sum_p \sum_m \sum_k \left(em1_m^p + ekm1_{km}^p \right) qkm_{km}^p + \sum_p \sum_k \sum_{sm} \left(ek1_k^p + eksm1_{ksm}^p \right) qksm_{ksm}^p \\
& + \sum_p \sum_k \sum_e \left(ee1_e^p + eke1_{ke}^p \right) qke_{ke}^p
\end{aligned}
$$

$$
\begin{aligned}
Wtr^{\min} = & \sum_p \sum_s \sum_m \left(ws1_s^p \right) qsm_{sm}^p + \sum_p \sum_m \sum_d \left(wm1_m^p \right) qd_{md}^p + \sum_p \sum_d \sum_r \left(wd1_d^p \right) qr_{dr}^p \\
& + \sum_p \sum_r \sum_c \left(wr1_r^p \right) qc_{rc}^p + \sum_p \sum_c \sum_k \left(wc1_c^p \right) qk_{ck}^p + \sum_p \sum_k \sum_c \left(wk1_k^p \right) qk_{ck}^p \\
& + \sum_p \sum_e \sum_k \left(we1_e^p \right) qke_{ke}^p
\end{aligned}
$$

Similarly, a robust counterpart of the third objective function will be as equation 50.

$$
\begin{aligned}
& Min\, Z_3 = E\left(S\,\mathrm{Re}\,s\right) + \gamma_3\left(S\,\mathrm{Re}\,s^{\max} - S\,\mathrm{Re}\,s^{\min}\right) + \delta_3 \sum_p \left(1-\alpha^p\right) \sum_r \left(d3_r^p - d2_r^p\right) \\
& E\left(S\,\mathrm{Re}\,s\right) = \sum_s \sum_p \left(\pi_3 \left(\frac{ms1_s^p + 2ms2_s^p + ms3_s^p}{4} \right) - \left(\frac{os1_s^p + 2os2_s^p + os3_s^p}{4} \right) \right) xs_s \\
& + \sum_m \sum_p \left(\pi_3 \left(\frac{mm1_m^p + 2mm2_m^p + mm3_m^p}{4} \right) - \left(\frac{om1_m^p + 2om2_m^p + om3_m^p}{4} \right) \right) xm_m \\
& + \sum_d \sum_p \left(\pi_3 \left(\frac{md1_d^p + 2md2_d^p + md3_d^p}{4} \right) - \left(\frac{od1_d^p + 2od2_d^p + od3_d^p}{4} \right) \right) xd_d \\
& + \sum_c \sum_p \left(\pi_3 \left(\frac{mc1_c^p + 2mc2_c^p + mc3_c^p}{4} \right) - \left(\frac{oc1_c^p + 2oc2_c^p + oc3_c^p}{4} \right) \right) xc_c \\
& + \sum_k \sum_p \left(\pi_3 \left(\frac{mk1_k^p + 2mk2_k^p + mk3_k^p}{4} \right) - \left(\frac{ok1_k^p + 2ok2_k^p + ok3_k^p}{4} \right) \right) xk_k \\
& + \sum_k \sum_p \left(\pi_3 \left(\frac{me1_e^p + 2me2_e^p + me3_e^p}{4} \right) - \left(\frac{oe1_e^p + 2oe2_e^p + oe3_e^p}{4} \right) \right) xe_e \\
& S\,\mathrm{Re}\,s^{\max} = \sum_s \sum_p \left(\pi_3 \left(ms3_s^p \right) - os1_s^p \right) xs_s + \sum_m \sum_p \left(\pi_3 \left(mm3_m^p \right) - om1_m^p \right) xm_m \\
& + \sum_d \sum_p \left(\pi_3 \left(md3_d^p \right) - od1_d^p \right) xd_d + \sum_c \sum_p \left(\pi_3 \left(mc3_c^p \right) - oc1_c^p \right) xc_c \\
& + \sum_k \sum_p \left(\pi_3 \left(mk3_k^p \right) - ok1_k^p \right) xk_k + \sum_k \sum_p \left(\pi_3 \left(me3_e^p \right) - oe1_e^p \right) xe_e \\
& S\,\mathrm{Re}\,s^{\min} = \sum_s \sum_p \left(\pi_3 \left(ms1_s^p \right) - os3_s^p \right) xs_s + \sum_m \sum_p \left(\pi_3 \left(mm1_m^p \right) - om3_m^p \right) xm_m \\
& + \sum_d \sum_p \left(\pi_3 \left(md1_d^p \right) - od3_d^p \right) xd_d + \sum_c \sum_p \left(\pi_3 \left(mc1_c^p \right) - oc3_c^p \right) xc_c \\
& + \sum_k \sum_p \left(\pi_3 \left(mk1_k^p \right) - ok3_k^p \right) xk_k + \sum_k \sum_p \left(\pi_3 \left(me1_e^p \right) - oe3_e^p \right) xe_e
\end{aligned} \tag{50}
$$

Finally, the robust counterpart of equation 4 is represented by equations 51. Equation 52 determines the demand satisfaction level of the retailers.

$$
\sum_d qr_{dr}^p \geq \left(1-\alpha^p\right) d2_r^p + \alpha^p d3_r^p \quad ;\forall r, p \tag{51}
$$

$$
\alpha^p \in \left\{0.5, 0.6, 0.7, 0.8, 0.9, 1\right\} \quad ;\forall p \tag{52}
$$

Thus, the robust possibilistic counterpart model will be as Equations 5-45 and Equations 48-52.

4. The solution procedure

As mentioned before, the proposed model has three conflict objectives. The optimal solution of such problems instead of one unique solution consists of a set of different solutions that are interpreted as Pareto optimal solutions. In fact, this set consists of non-dominated solutions. For the better understanding, consider solutions A and B. If all objectives of solution A are not worse than B equivalently and there exist at least one of A that is better than B in this case, it is said that solution A dominates B (Hajiaghaei-Keshteli & Fard, 2019).

Non-dominated Sorting Genetic Algorithm (NSGA) is one of the first methods of multi-objective evolutionary optimization which was developed by (Srinivas & Deb, 1994). One new version of NSGA algorithm, entitled NSGA-II, was developed by Deb in 2002. The algorithm is better than NSGA in sorting, uses an elitism mechanism in solution selection process and also there is no need to specify the participation parameter (Deb et al., 2002).

NSGA-II compared to usual Genetic Algorithm (GA) has two additional parts, named non-dominated sorting and crowding distance. The function of different parts of the algorithm is as follows. Also, relationships among these parts are depicted in figure 2.

Initial population generation: In the beginning, *k* solution strings (chromosomes) are generated that follow the problem constraints, as much as possible. Each string has *n* decision variables (gene) that are the same as the problem decision variables, in number and type.

Fitness assignment: in this step, based on the values of objective functions, the fitness of the chromosome is calculated.

Non-dominated sorting: in this step, the non-dominated sorting mechanism is applied to the population members. Subsequently, non-dominated fronts of the members are specified. Finally, based on the front number a rank is assigned to each member.

Crowding distance calculation: the crowding distance control parameter determines the degree of proximity of each member to the other members that belong to the same front. The parameter shows the degree of divergence and expansion of the members of each front. In other words, if the solution is located in less crowded areas its parameter is bigger, and vice versa.

It is worth noting that the outputs of the two previous steps are used to determine the front number for the population members.

Solution selection: the aim of this step is selection of solutions for crossover and mutation operators. One of the most efficient methods for this purpose is the roulette wheel selection (Deb, 2000).

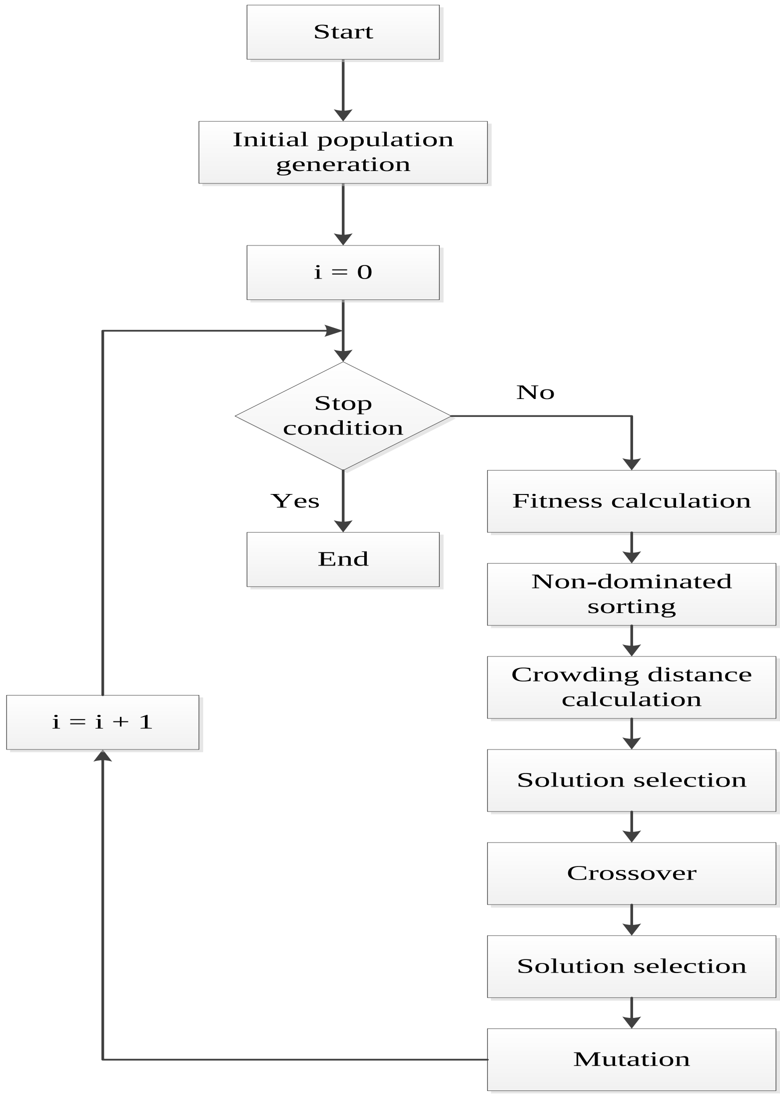

Figure 2. NSGA-II flowchart

Crossover operator: in this step two different offspring are generated from two parents.

Mutation operator: creation of new solution from one unique solution is done by this operator.

4.1. Solution representation

Consider one problem with $P=2$ product types, $S=2$ suppliers, $M=2$ manufacturers, $D=3$ distribution centers, $R=3$ retailers, $C=2$ collection centers, $K=3$ repair centers, $E=3$ disposal centers and $SM=3$ second market zones. One chromosome for this problem is shown in fiqure.3. In this structure each row demonstrates supply chain structure for one product. The number of columns is $M+D+R+R+C+K+K+K+1$ that are placed side by side from left to right. The first M columns determine supplier of each manufacturer. Each cell of this category has one number from 1 to S. The next D columns have numbers from set $\{1,2,...,M\}$ that assign one manufacturer to each DC. The first set of columns with R members determines a distribution center that supports each retailer. It is obvious that each cell of this category gets a number from set $\{1,2,..,D\}$. The second set of columns with R cells shows collection centers that collect returned products from retailers. Each cell of this set is filled by a number from 1 to C. The next C columns assign repair centers to collection centers. It is obvious, that each cell gets a number from set $\{1,2,..,K\}$. The first set of columns with K members shows the second market zones that are buyers of repaired products of repair centers. Each cell of this category is filled by a number from 1 to SM. The next K columns assign manufacturers to repair centers and each cell gets a number from set $\{1,2,..,M\}$. The third K columns show assignment of disposal centers to repair centers. Each cell of this set gets a number from 1 to E. Finally, the last column shows the confidence level of satisfaction of each product demand.

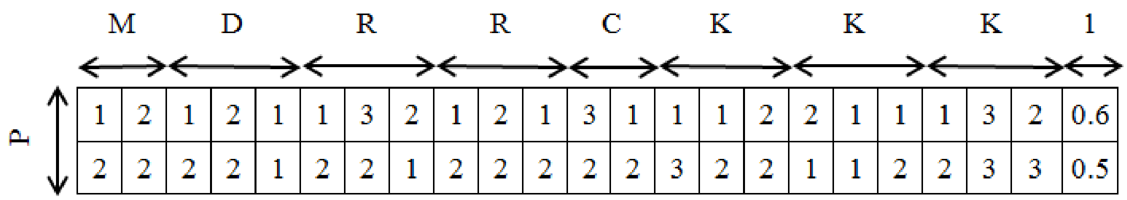

Figure 3. Chromosome structure

4.2. Crossover operator

As previously mentioned the aim of this operator is generating two offspring from two parents. In this paper we use two-point crossover operator (Balaji et al., 2019). In this method, two columns are randomly selected, and all cells between them are exchanged between the two parents. For a better understanding consider the example of the previous section. Two selected parents among the population are depicted in figure 4. Assume columns 3 and 20 are selected during the crossover mechanism.

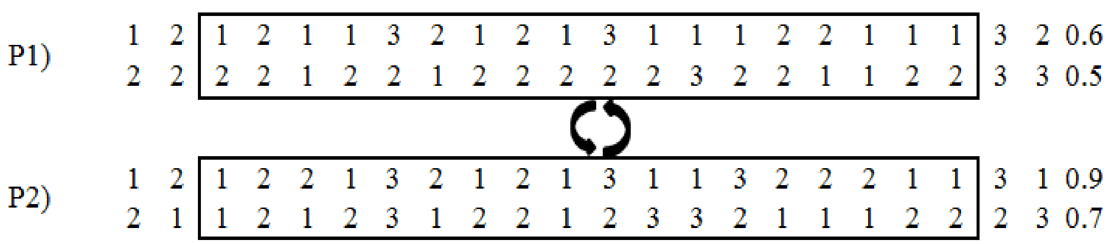

Figure 4. The selected parents

The outputs of this operator are shown in figure.5.

C1)	1	2	1	2	2	1	3	2	1	2	1	3	1	1	3	2	2	2	1	1	3	2	0.6
	2	1	1	2	1	2	3	1	2	2	1	2	3	3	2	1	1	1	2	2	3	3	0.5
C2)	1	2	1	2	1	1	3	2	1	2	1	3	1	1	1	2	2	1	1	1	3	1	0.9
	2	2	2	2	1	2	2	1	2	2	2	2	2	3	2	2	1	1	2	2	2	3	0.7

Figure 5. The generated offspring

4.3. Mutation operator

We use a simple operator for the mutation. In this way, two products are selected randomly and after selecting some parts of their strings they will be exchanged with each other. Figure 6 illustrates the mechanism of this operator. In this figure, S1 and S2 show the solution before and after mutation, respectively.

S1)	1	2	1	2	1	1	3	2	1	2	1	3	1	2	1	2	2	1	1	2	3	2	0.5
	2	2	1	1	1	2	2	3	2	2	2	2	2	1	2	2	1	2	2	2	3	3	0.8
S2)	1	2	1	2	1	2	2	3	2	2	2	3	1	2	1	2	2	1	1	2	3	3	0.8
	2	2	1	1	1	1	3	2	1	2	1	2	2	1	2	2	1	2	2	2	3	2	0.5

Figure 6. The mutation operator

5. Case study

The case study of this research is the automotive industry, which has high rates of both consumption and wastage in Iran. This case is based on the information from an automotive trading company that is currently an importer of automobiles. The company has decided to launch a manufacturing line recently by considering suppliers, a manufacturing plant, distribution centers, retailers and collection, repair, and disposal centers.

5.1. Parameters' values

The value of parameters is estimated based on information from feasibility and market studies. After studying related documents, different meetings were held with managers and experts. In these meetings opinions of participations were acquired and finally approximate values of the parameters were achieved (Lotfi et al., 2019). The authors of this reference have considered the parameters in the form of stochastic values with specific intervals. As previously mentioned in cases where the uncertainty level is high, the possibilistic theory is more effective than the stochastic approach. Therefore, in this study we consider parameters as symmetric triangular fuzzy numbers on related intervals. Table 2 presents the parameter values.

Table 2. The range of parameters

Category	Parameter	Value
Fixed costs (*1000) ($)	$fcs_s,\ fce_e$	$(1,1.5,2)$
	fcm_m	$(40,45,50)$
	fcd_d	$(3,3.5,4)$
	$fcc_c,\ fck_k$	$(2,2.5,3)$
Variable costs ($)	$vcs_s^p, vcm_m^p, vcd_d^p, vcc_c^p, vck_k^p, vce_e^p, vsm_{sm}^p, vmd_{md}^p, vdr_{dr}^p, vrc_{rc}^p, vck_{ck}^p, vkm_{km}^p, vksm_{ksm}^p, vke_{ke}^p$	$(3,3.5,4)$
GHG emission inside the facilities (Kg/Unit)	$es_s^p, ed_d^p, ec_c^p, ek_k^p, ee_e^p$	$(1,1.5,2)$
	em_m^p	$(10,15,20)$
GHG emission in transportation (Kg/Unit)	$esm_{sm}^p, emd_{md}^p, edr_{dr}^p, erc_{rc}^p, eck_{ck}^p, ekm_{km}^p, eksm_{ksm}^p, eke_{ke}^p$	$(4,4.5,5)$
Energy consumption (Mega-Jules/Unit)	$ns_s^p, nm_m^p, nd_d^p, nc_c^p, nk_k^p, ne_e^p, nsm_{sm}^p, nmd_{md}^p, ndr_{dr}^p, nrc_{rc}^p, nck_{ck}^p, nkm_{km}^p, nksm_{ksm}^p, nke_{ke}^p$	$(4,4.5,5)$
Local employment (Unit)	os_s^p	$(40,45,50)$
	om_m^p	$(300,350,400)$
	od_d^p	$(40,45,50)$
	oc_c^p	$(20,25,30)$
	ok_k^p	$(10,12.5,15)$
	oe_e^p	$(5,7.5,10)$
Facilities capacity (*1000) (Unit)	$caps_s^p$	$(5,5.5,6)$
	$capm_m^p$	$(12,13.5,15)$
	$capd_d^p$	$(3,3.5,4)$
	$capc_c^p, capk_k^p$	$(2,2.5,3)$
	$cape_e^p$	$(1,1.5,2)$

Number of missed days (Person-day)	ms_s^p mm_m^p md_d^p mc_c^p, mk_k^p me_e^p	$(10,15,20)$ $(50,75,100)$ $(15,17.5,20)$ $(5,7.5,10)$ $(2,4,6)$
Water consumption (Kg/Unit)	ws_s^p, wk_k^p wm_m^p wd_d^p wc_c^p we_e^p	$(5,7.5,10)$ $(10,15,20)$ $(1,3,5)$ $(1,5.5,10)$ $(1,2,3)$
Retailers demands (*1000) (Unit)	d_r^p	$(1,15,20)$
Flows rates	βr^p αk^p αe^p	$un(0,1)$ $un(0.2,0.21)$ $un(0.1,0.11)$
Sets size	M P S,R,SM,E C,K D	1 2 3 4 5

5.2. Numerical results

In this section, three solutions of the Pareto front are provided. The results are presented in Table 3. In this table, the symbols Z_1^*, Z_2^*, and Z_3^* represent the lowest values of the first, second, and third objective functions, respectively, among the solutions located in the front. For all objectives, $\delta_1 = \delta_2 = \delta_3 = 0.6$ were considered. The algorithm is developed and executed using MATLAB R2015b software on a Core i5 CPU, 3GB RAM PC.

Table 3. Solutions of the optimum Pareto front

The first solution			The second solution			The third solution		
Z_1^*	Z_2	Z_3	Z_1	Z_2^*	Z_3	Z_1	Z_2	Z_3^*
5517370	13129425	9919	5523900	12938880	9186.5	5532100	13115000	9019

6. Sensitivity analysis

Sensitivity analysis is vital for finding the impacts of the critical parameters. Due to the high level of competition among companies in the market, satisfaction of retailers' demands in such supply chains is crucial. This implies that the parameters $\delta_1, \delta_2, \delta_3$ play a decisive role in the supply chain configuration. Thus, to demonstrate the impact of these parameters on the objective functions, a sensitivity analysis is conducted. The results of the experiments are presented in Table 4, while Figure 8 illustrates the impacts of these parameters through diagrams.

Table 4. δ_i variations versus objectives

δ_1	Z_1^*	δ_2	Z_2^*	δ_3	Z_3^*
0	5361700	0	13279000	0	-1601.5
0.3	5444180	0.3	13284000	0.3	4549
0.6	5517370	0.6	12938880	0.6	9019
0.9	5519700	0.9	12943830	0.9	13012
1	5528370	1	13298000	1	17837

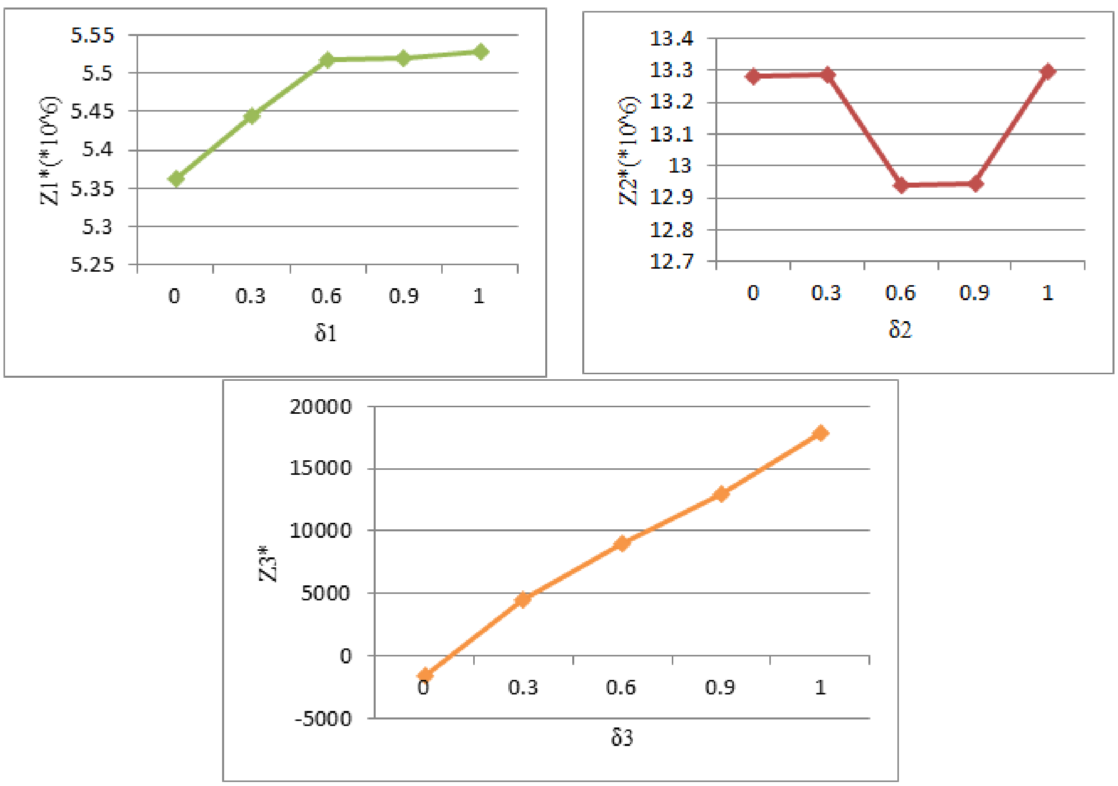

Figure 7. The relationship between δ_i parameter and the objective functions

As Figure 8 shows, unsatisfied demands have the greatest impact on the social objective. The environmental objective experiences moderate effects, while the economic objective is the least affected by unfulfilled demands. These findings are consistent with reality because high competition among competitors in the market leads to the sensitivity of customers to their unsatisfied demands.

The results of the variation of γ_i (robustness coefficient) are presented in Table 5 and Figure 9. It can be inferred that the most robust objective is Z_1^* (with $R_1 = 0.21$), followed by Z_2^* (with $R_2 = 0.33$), while Z_3^* is the least robust (with $R_3 = 0.57$). This order was achieved by using Equation 53. In this Equation Z_i^{*Worst} and Z_i^{*Best} are the worst and the best values of objective function *i*, respectively. It is obvious that a smaller R_i indicates a more robust objective.

$$R_i = \frac{\left(Z_i^{*Worst} - Z_i^{*Best}\right)}{Z_i^{*Worst}} \tag{53}$$

Table 5. γ_i variation versus objective functions

γ_1	Z_1^*	γ_2	Z_2^*	γ_3	Z_3^*
0	4348110	0	8870300	0	7604.5
0.3	4704748	0.3	10563000	0.3	10292
0.6	5037100	0.6	11417000	0.6	11884
0.9	5405624	0.9	13030116	0.9	12058
1	5528370	1	13298000	1	17837

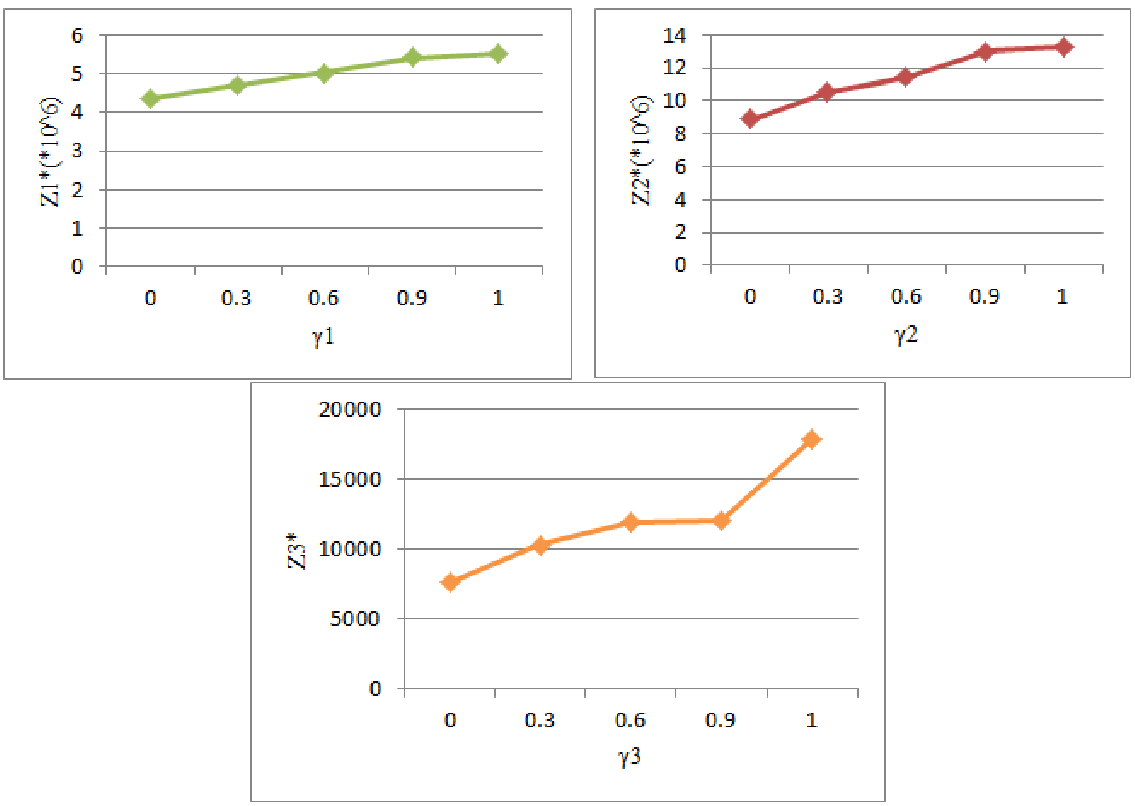

Figure 8. The relationship between γ_i parameter and the objective functions

The result of variation in π_i (objectives coefficients) are presented in Table 6 and Figure 10.

Table 1. π_i variation versus objective functions

π_1	Z_2^*	π_2	Z_2^*	π_3	Z_3^*
0	6603375	0	11648000	0	6895
0.3	10404678	0.3	13067178	0.3	9069.9
0.6	14205981	0.6	14685453	0.6	9162.6
0.9	19009000	0.9	15905139	0.9	10340
1	19753857	1	16847622	1	11272

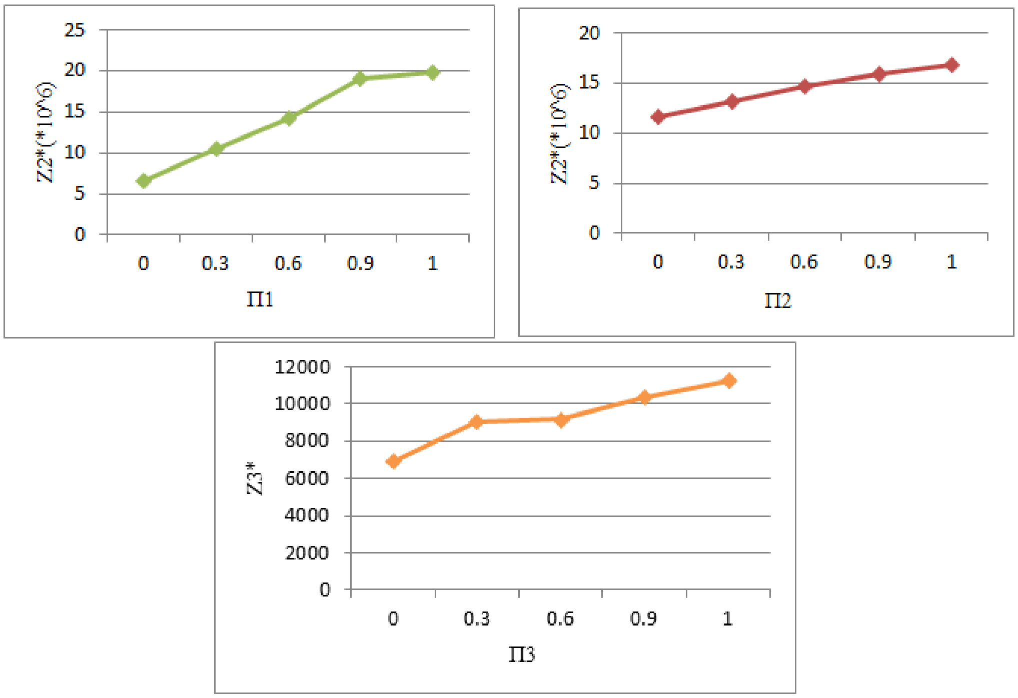

Figure 9. The relationship between π_i parameter and the objective functions

As it was expected, with increasing π_i the optimum value of the related objective will increase. Also, π_1 has a more intensive effect on Z_2^* than the other weight (π_2). It demonstrates that among the amounts of GHG emission and water consumption, the former has more intensive impact on environmental effects of the supply chain. This inference may be based on the fact that public concern about GHG emissions is more widely recognized than water consumption among the Iranian people. In other words, participants of the case study were more fastidious in determining the amount of emitted GHG than that of consumed water. Finally, the ambiguous business environment in Iran led to low accuracy in determining the number of created job opportunities compared to that of missed days caused by occupational accidents by experts.

7. Managerial insights

This paper is the first research which studies all aspects of an uncertain closed loop supply chain in an automotive industry. The highly competitive market compels each new rival seeking success to consider the economic, environmental, and social impacts of its supply chain. This paper considered not only the total cost as the economic aspect, but also the amount of generated GHG emission, energy consumed, and water used as the environmental dimension. Additionally, the social dimension included the number of created job opportunities, and the number of missed workdays. An automotive supply chain was studied to validate the proposed model. This paper provides insights for managers on identifying and controlling the most effective economic, environmental, and social factors to develop their market share. In such supply chains, the role of uncertainty should not be ignored. In cases where a new manufacturer wants to enter the market, the lack of historical data is not a deniable fact. In this uncertain environment, applying fuzzy theory can be helpful. Incorporating this theory and robust possibilistic programming can overcome the uncertain nature of the supply chain and generate a robust network. The importance of demand satisfaction level and the weight of objectives is another key point. The sensitivity analysis of these parameters determines the most effective ones. Through this analysis, the most sensitive objective or parts of the objectives will be specified. Also, the method distinguishes the most effective parameters. Finally, implementing sustainable results helps organizations to be assured about their long-term activities, as these activities not only are harmless to the environment and society but also follow additional benefits.

8. Conclusion and future directions

This paper presented a comprehensive design of a closed loop supply chain. This research tried to consider all aspects of a supply chain consisting of economic, environmental, and social responsibilities. It is not negligible that a real world decision making problem always is exposed to uncertainties in the parameters. Hence, in this study all of the parameters are considered as triangular fuzzy numbers. Furthermore, this study developed a novel mathematical model for the problem. Subsequently, a robust counterpart model was developed using the robust possibilistic programming method. Since the proposed model includes three conflict objectives, a NSGA-II algorithm was developed as a solution method. Finally, a real case from the automotive industry in Iran was provided. The results of the study demonstrated the significant impact of satisfaction of retailers' needs on the objective of social responsibilities compared to economic or environmental aspects of the supply chain.

For future extension of the study considering new concepts like resiliency and block-chain will be useful. Also, for solving developed models, valid inequalities, decomposition techniques, hybrid of meta-heuristic algorithms, augmented epsilon constraint, and so on can be utilized.

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