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Research Paper

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Development of scenario-based mathematical model for sustainable closed loop supply chain considering reliability of direct logistics elements

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***Abstract** – In this study a scenario-based multi-objective fuzzy model was provided in the SCLSC , which in addition to three aspects of sustainability including, social impact such as the creation of job opportunities, customer satisfaction, and so on, environmental impact such as reducing air pollution, and so on, economic impact such as reducing cost, increasing the reliability of the SC and product routing have been modeled. Two algorithms, including MOPSO and NSGA-II Algorithms, were applied to solve the proposed model. After tuning their parameters by the Taguchi method, their performance in problems with different dimensions were tested followed by evaluating them by powerful criteria. The proposed model was implemented on Chipboard Pooya Company in Iran in two scenarios of economic recession and prosperity aimed at evaluating its accuracy. A sensitivity analysis was eventually performed on the proposed model followed by making some suggestions to develop the model.*

***Keywords**– Sustainability, CLSC Network, Reliability, Mixed-Integer Nonlinear Programming, Metaheuristic Algorithms*

I. INTRODUCTION

Globalization, increasing number of rules of official and non- official organizations, and customer pressure and needs regarding environmental problems have led organizations to investigate the required measures to apply SCLSC management in order to improve environmental and economic performance (Rabbani et al., 2020). The problem of vehicle routing in the SC distribution network is recognized as one of the sub-problems of SC management, which involves selecting and allocating possible routes to available vehicles for distribution and delivery of goods to distribution stations or customers designated to minimize the relevant costs. The optimal solving of this problem will lead to timely delivery of goods, reduce the need for warehousing and maintenance of goods, and increase customer satisfaction meanwhile reducing the distribution costs (Biuki et al., 2020). One may also claim that vehicle routing is one of the most challenging issues in the context of transportation and support of the SC (Mamaghani et al., 2020). A variety of products have to be made available to the customers at their request in today's global competitions. The customers' demand for high quality and fast service-providing has led to enhanced pressures that have not been faced before (Peng et al., 2020). In today's

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economic and industrial environment and given the growing trend of industries followed by the rise in the environmental pollution in contrast, and most importantly, the use of limited resources, the need to recycle resources from manufactured products as well as informing the consumers about the need for a change in attitude seem to be a priority not only in the production of goods but in all stages of production (Alzoubi et al., 2020).). Many measures have been taken in this direction, including recycling waste in the production cycle, the reuse of consumer goods, returning the quality control returned goods to the production line, recycling, etc. The set of these activities accompanied by applying environmental and social considerations form the concept of the SCLSC (Dündar et al., 2020). On the other hand, aimed at accurate management and preventing the waste of resources, the management units currently have no choice other than to adopt and employ new scientific approaches, models, processes, and techniques tailored to the current conditions to provide proper performance regarding the resources used (Abdel et al., 2020). It is usually assumed in SC network design studies that active utilities (facilities) are able to provide service continuously for a long period of time without any breakdown and will continue to operate without interruption (Jabbarzadeh et al., 2018). In the real world, utilities may suffer from disruptions and failures with possible causes of human error, natural disasters, etc. (Gaur et al., 2020). Thus, the failure of one component of the SC network may disrupt the functioning of the entire SC, or in the best case, reduce the efficiency of the chain. Hence, it seems essential to consider the factor of reliability in the design of the closed-loop SC, especially in its direct components (Forward logistic stage). However, this issue has been less addressed in recent studies. Therefore, it was decided to provide a new multi-objective, multi-period, multi-product, and scenario-based fuzzy mathematical model in this research for locating, routing, and distributing goods for a sustainable CLSC. In addition to sustainability components, this model considers the SC reliability, quality of returned products, and the routing of the flow of goods as well.

II. LITERATURE REVIEW

The relevant literature that contributes to identifying the general framework of this article is reviewed in this section. D.G. Mogale (2022) provided a CLSCs network, in which, the demand was considered sensitive to the price, consumer motivation, and the quality level. The core goal of the proposed model is to reduce the total cost and carbon emissions produced by the activities resulting from production, distribution, transportation, and disposal. They employed an NSGAII algorithm and a Co-Kriging approach to solving the model. The study results revealed the positive effects of motivational pricing on the returned goods. Y. Kazancoglu (2022) presented an MILP model for designing the green D-C and CLSCs. In this presentation purpose is optimally select echelons and and obtaining alternative modes of transportation according to the conditions. The proposed model is supported by a case study in the home appliance industry in this study. Keshmiry Zadeh et al. (2021) presented a multi-objective mathematical model for the GCLS with the possibility of disruption. The results of the model showed that the proposed model has a good performance.. H. Gitinavar et al. (2021) proposed a possibilistic programming to estimate the hesitant fuzzy membership function. They also provided a mathematical model for a biomass. The results obtained from the computational experiment indicated the validity. Agahgolnezhad Gerdrodbari et al. (2021) designed a two-objective model for the CLSC of perishable products by considering economic and environmental dimensions. The results of sensitivity analysis showed that the economic dimension is more sensitive to the change in demand. Nasr et al. (2021) presented a new approach based on the MOMLIP method to design a CLSC with LIR problem. To solve the proposed model, they used a fuzzy multi-objective solution, which showed the high efficiency of the model solution. Sadeghi Ahangar et al. (2021) presented a mathematical model for the design of SCLSC for urban waste management based on the fuzzy mathematical programming approach. In this model, they minimized work cost and the level of CO2 emissions. Gitinavard et al. (2020) presented an adaptive framework based on the weighting method and preferential demand adaptation under the DHFS method. Kalantari Khali et al. (2020) designed a CLSC , which was considered in its reverse flow to increase the efficiency of the chain of regeneration and recycling stations. Transportation methods between stations are considered according to their cost and the amount of greenhouse gas emissions in the target functions. Vakili et al. (2020) presented location-routing model considering the dimensions of stability. Due to the uncertain nature of the presented model, a robust stochastic planning approach was used.

Gitinavard et al. (2019) presented a mathematical model for a SCLSC for perishable products under the condition of demand uncertainty. The proposed model was implemented on a real case and its efficiency was confirmed148 .Goli et al. (2020) examined a multi-objective, multi-period, and multi-product CLSC (CLSC) model with uncertain parameters aimed at combining the financial cash flow as cash flow and debt constraints and employment. The objectives of the proposed mathematical model in their study included increasing the cash flow, maximizing the jobs created and maximizing the reliability of raw materials consumed. They developed and used MOSA, MOIW, and MOGW meta-heuristic algorithms to solve the model at a large scale. Ali et al. (2020) provided a novel mathematical model for reverse SC management of air conditioning products. Their considered SC was sustainable with fuzzy demand uncertainty. Locating hubs and recycling stations were among the most important goals of their research. The case study covered the industries of Saudi Arabia and India. In their research, identified places were prioritized with a hierarchical process analysis approach after solving the mathematical model. Reyhani et al. (2020) provided a multi-objective and multi-period mathematical model for inventory management for the SCLSC. The most important decisions made in their model included determining the amount of flow at each level and locating the hubs. The main objectives of the study contained minimizing transportation costs and the costs of CO2 emissions and maximizing social responsibility. The case study was focused on agricultural products. Rabbani et al. (2020) presented a sustainable multi-objective and multi-level mathematical model to locate distribution hubs and allocate warehouses to distribution stations. The proposed innovation included a variety of technologies for cars, which causes the release of different amounts of CO2 from different vehicles. They used the Epsilon constraint approach to solve the model in small and medium dimensions. Wang et al. (2020) provided a mathematical model for the green inverse SC. One of their innovations was to consider the pricing of goods using the game theory. They considered three different prices for different types of goods in this article to price goods. Minimizing costs in the SC, including manufacturers, distributors, customers, and collection stations were some of the objectives of this study. According to their results, the chain costs were minimized to the desired level. Mohtashami et al. (2020) proposed a green SCs to environmental effects. They used the GA to solve the proposed model in large dimensions. Rad et al. (2018) provided a mathematical model, which included four layers in the forward and three layers in (backward). The production and inspection stations were integrated into the proposed model to reduce transportation costs. Besides economic goals, environmental aspects such as green production, technology, and transportation modes were also considered in this model. Also, the amount of raw materials purchased and the volume of greenhouse gases produced in the production process were considered dependent on the level of technology. Haji Aghaei et al. (2019) provided a nonlinear mixed-integer mathematical program model to formulate a SCLSC with consideration of discounts on shipping costs. They suggested three hybrid RDSA, KAGA, and ICTS algorithms to solve the model, which were compared by four evaluation criteria by Pareto analysis. The comparison result indicated that the proposed new hybrid KAGA algorithm brings better solutions compared to other algorithms but needs more time for solving. They finally introduced a real example in the glass industry to confirm the proposed model and the algorithms provided. Ghomi et al. (2018) presented a multi-objective model in the green CLSC by considering the failure of downtime of stations. Pricing of products with a collaborative approach to game theory was one of the innovations of this research. The problem was fuzzily modeled due to the fuzzy nature of the data, which most important goal was set to minimize the amount of pollutant gases released in the proposed chain. Rahimi and Ghezavati (2018) presented a mathematical model for managing inventory and the flow of goods in a SCLSC. Considering discounts for customers associated with uncertainty in demand were among the innovations in their research. The main purpose of the model was to minimize transportation costs and environmental costs. The results revealed an 11% reduction in costs after implementing the model. Wang et al. (2017) provided a CLSC where three competitive scenarios implemented by the manufacturer were studied. They used Stackelberg's game theory for studying this model. According to their conclusion, a producer is more inclined to perform the recycling and reproduction processes by himself and refrains from outsourcing

A. Research gap

The research gap can be summarized as follows according to the subject literature:

1- Insufficient attention to the inherent uncertainty of SC issues together with their elements

2- Lack of attention to statistical reliability and various errors in the proposed mathematical models

3- Insufficient attention to a real study and limiting the solution of the model just with numerical examples

B. Research innovations

1- In this model, increasing the SC reliability, the quality of the products returned by the customers and the routing of the goods are also considered besides the three aspects of sustainability, namely, the social effect such as job creation, customer satisfaction, and distributors, the environmental effect such as reducing air pollution, and the economic effect such as reducing the SC costs.

2- In the real world, all the components of a CLSC like production stations, etc. may not fully operate and are likely to stop working due to events such as human errors, weather conditions, terrorist attacks, etc. in period t. Thus, this limitation has been considered in the form of using statistical reliability to approach the real situation.

3- Considering a real case study for customizing the proposed model .

III. PROBLEM STATEMENT

The SC network provided in this study is a closed-loop, multi-objective and multi-period scenario-based network, which encompasses suppliers, manufacturers, distributors, customers, hubs, repair, recycling, landfill, and demolition stations. It should be noted that the hubs, distribution stations, recycling stations, and repair and burial stations are equipped with the capability to be reopened. In the reopening process, some places are selected as candidate points and the model chooses the optimal place from them. In the SC functioning process, suppliers provide raw materials to manufacturers. The manufacturers and the warehouses under their supervision send the products to distributors. The breakdown and failure of raw materials supply stations, warehouses, and production stations are some of the issues and problems addressed in this study. This focus makes the issue closer and more similar to the real world. Distributors send products to customers. There are hubs, recycling, landfill, and repair stations in the backward direction. The important point is how to determine the flow of returned products is their quality. The hubs send the returned products to repair, landfill, or production stations depending on their quality. After repairing, the repair stations send the products to distributors. The recycling stations also send products to manufacturers. It should be noted that some of the returned goods from customers can be sent directly to the reproduction stations located in the production station and do not need recycling in the recycling stations. Figure 1 shows the proposed SC structure.

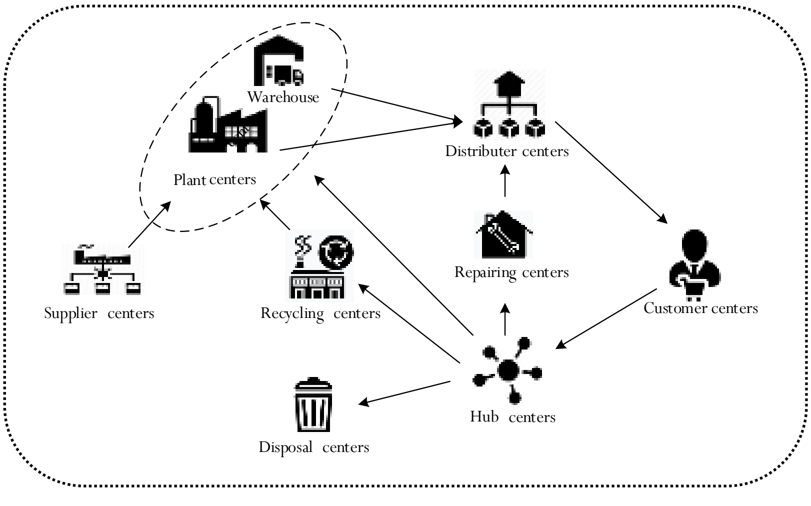


Fig 1. The structure of the proposed model

Maximizing the social responsibility dimension is one of the goals of the proposed model, in which, the employment rate, customer satisfaction, and distribution stations are maximized by sending maximum products from raw materials supply and production stations to them. Minimizing the economic and environmental costs of the SC is set to be another goal of this model. This parameter is considered to be fuzzy due to the inherent uncertainty of demand. Locating, examining the flow rate between components, and the routing of goods are other decisions that are supposed to be made in this research.

IV. FORMULATING THE MODEL

A. Model assumptions

1. The capacity of the stations is limited.
2. The distances between stations are assumed to be fixed and definite.
3. Every producer has a warehouse to store the produced goods.
4. There is a reproduction station in each production station.
5. The produced goods are sent both from production stations and from their warehouses to the distribution stations.
6. The locations of supplier stations, producers, and their warehouses are fixed and predetermined and already known.
7. Any production station and its warehouse and supply stations cannot be rehabilitated and reconstructed in the case of being destroyed by an accident.

B. Indices

R: Routes $r \in R$

L: Customers $l \in L$

J: Manufacturers $j \in J$

Q : The set of quality levels $Q_1, Q_2, Q_3 Q_4$, $Q = Q_1 \cup Q_2 \cup Q_3 \cup Q_4$

Q_1: Quality level of products that are sent from hub stations to repair stations.

Q_2 : Quality level of products that are sent directly from the hub stations to the production stations.

Q_3: Quality level of products that are sent from hub stations to recycling stations.

Q_4: Quality level of products that are sent from hub stations to disposal stations,

(where $Q_1 \succ Q_2 \succ Q_3 \succ Q_4$ $\succ$ is the quality level of the comparison operator).

I: Suppliers $i \in I$

O: The set of raw materials $o \in O$

P: Candidate points for recycling stations $p \in P$

M: Candidate points for hubs $m \in M$

W: Candidate points for repair stations $w \in W$

V: The set of means of transportation $v \in V$

C: Products set index $c \in C$

N: Candidate points for landfill and disposal stations $n \in N$

K: Candidate points of distribution stations $k \in K$

S : Set of scenarios $s \in S$

T: Period index $t \in T$

C. Parameters

$aq_{jj,s}$: Distance of the production station j from its own warehouse in scenario s

$a_{lm,s}$: Distance from the customer station l to the hub m in scenario s

$a_{mj,s}$: Distance of the hub station m from the production station j in scenario s

$a_{kl,s}$: Distance of the distribution station k from the customer station l in scenario s

$a_{ij,s}$: Distance of the supplier i from the production station of j in scenario s

$a_{jk,s}$: Distance of the production station j from the distribution station k in scenario s

$a_{mn,s}$: Distance of the hub m from the landfill canter n in scenario s

$a_{pj,s}$: Distance of the recycling station p from the production station j in scenario s

$a_{mp,s}$: Distance of the hub m from the recycling station p in scenario s

$a_{mw,s}$: Distance of the hub m from the repair station w in scenario s

$a_{wk,s}$: Distance of the repair station w from the distribution station k in scenario s

$dq_{jk,s}$: Distance of the producer warehouse j from the distribution station k in scenario s

EM_p: CO2 emitted during the construction of the recycling station p

EM_k: CO2 emitted during the construction of the distribution station k

EM_m: CO2 emitted during the construction of the hub m

EM_n: The CO2 emitted during the construction of the landfill and disposal station n

EM_W: CO2 emitted during the construction of the repair station w

EMS_v: CO2 emitted from the shipment of a product unit by a type v vehicle over one kilometer

γ: CO2 emitted from transporting a unit of product from the production station j to its own warehouse

u_p^t: Valency of the recycling station p in the period t

u_n^t: Valency of the landfill and disposal station n in the period t

u_k^t: Valency of the distribution station k in the period t

u_i^t: Valency of the supply station i in the period t

u_w^t: Valency of the repair station w in the period t

u_{jj}^t: Valency of the producer's j warehouse in the period t

u_j^t: Valency of the production station j in the period t

u_m^t: Valency of the hub m in the period t

cr_j^t: Valency to remanufacturing products in the production station j in the period t

E_n^t: Fixed cost of constructing the landfill and disposal (demolition) station n in the period t

E_m^t: Fixed cost of constructing the hub station m in the period t

E_k^t: Fixed cost of constructing the distribution station k in the period t

E_p^t: Fixed cost of constructing the recycling station p in the period t

E_w^t: Fixed cost of constructing the repair station w in the period t

$\widetilde{d_{l,s}^{ct}}$: Amount of demand for the product c by the customer l in the period t in scenario s

$r_{lq,s}^{ct}$: Return rate of the product c with the quality q from the customer station l in the period t in scenario s

rb_{mj}^{ct}: Return rate of the product c from the hub station m to the production station j in the period t

rb_{mn}^{ct}: Return rate of the product c from the hub station m to the landfill and disposal station n in the period t

rb_{mp}^{ct}: Return rate of the product c from the hub station m to the recycling station p in the period t

rb_{mw}^{ct}: Return rate of the product c from the hub station m to the repair station w in the period t

$fp_{lmq,s}^{ct}$: Return cost of each unit of the returned product c with quality q from the customer station l to the hub station m in the period t in scenario s

$f_{j,s}^{ct}$: Maintenance cost of each unit of the product c in the producer's warehouse at location j in the period t in scenarios

$\square_{mnq,s}^{c}$: Transfer fee per unit of the returned product c with quality q from the hub station m to the landfill station n in scenario s

$\square^{c}_{kl,s}$: Transfer fee per unit of the product c from the distribution station k to the customer station l in scenario s

$\square^{o}_{ij,s}$: Transfer fee per unit of the raw materials o from the supply station i to the production station j in scenario s

$\square^{c}_{jk,s}$: Transfer fee per unit of the product c from the production station j to the distribution station k in scenario s

$\square^{c}_{mjq,s}$: Transfer fee per unit of the comebacked product c with quality q from the hub station m to the production station j in scenario s

$\square^{c}_{mpq,s}$: Transfer fee per unit of the comebacked product c with quality q from the hub station m to the recycling station p in scenario s

$\square^{c}_{pj,s}$: Transfer fee per unit of the comebacked product c from the recycling station p to the production station j in scenario s

$\square^{c}_{mwq,s}$: Transfer fee per unit of the comebacked product c with quality q from the hub station m to the repair station w in scenario s

$\square^{c}_{wk,s}$: Transfer fee per unit of the product c from the repair station w to the distribution station k in scenario s

$cq^{c}_{jk,s}$: Transfer fee per unit of the product c from the warehouse of the producer j to the distribution station k in scenario s

$cq^{c}_{jj,s}$: Transfer fee per unit of the product c from the production station j to its own warehouse in scenario s

$\square^{c}_{lmq,s}$: Transfer fee per unit of the returned product c from the customer l to the hub station m in scenario s

$cj_{ct,s}$: Transfer fee per unit of the product c in the production station j in the period t in scenario s

$rcj_{ct,s}$: Transfer fee per unit of the product c in the reproduction station j in the period t in scenario s

$cn_{ct,s}$: Transfer fee per unit of the product c at the demolition station n in the period t in scenario s

$cm_{ct,s}$: Cost of collecting and sending a unit of the product c to the hub station m in the period t in scenario s

$cp_{ct,s}$: Cost of recycling a unit of the product c at the recycling station p in the period t in scenario s

$cw_{ct,s}$: Cost of repairing a unit of the product c in the repair station w in the period t in scenario s

$ck_{ct,s}$: Cost of distributing a unit of the product c in the distribution station k in the period t in scenario s

$\alpha j_{m,s}$: Fixed number of permanent job founded if established the hub station m in scenario s

$\alpha j_{p,s}$: Fixed number of permanent job founded if established the recycling station p in scenario s

$\alpha j_{w,s}$: Fixed number of permanent job founded if established the repair station w in scenario s

$\alpha j_{n,s}$: Fixed number of permanent job founded if established the demolition station n in scenario s

$\alpha j_{k,s}$: Fixed number of permanent job founded if established the distribution station k in scenario s

$\beta j_{m,s}$: Variable number of permanent job founded if established the hub station m in scenario s

$\beta j_{p,s}$: Variable number of permanent job founded if established the recycling station p in scenario s

$\beta j_{w,s}$: Variable number of permanent job founded if established the repair station w in scenario s

$\beta j_{n,s}$: Variable number of permanent job founded the demolition station n in scenario s

$\beta j_{k,s}$: Variable number of permanent job founded if established the distribution station k in scenario s

the distribution station k in scenario s

dl_j^t: Missed working days due to work injury in the production station j in the period t

D. Variables

$ro_{vij,s}^{rt}$: Equivalent to 1 if the vehicle of type v goes from the supplier i to the manufacturer j from the route r in the period t in scenario s, otherwise 0

$ro_{vjk,s}^{rt}$: Equivalent to 1 if the vehicle of type v goes from the manufacturer j to the distributor k from the route r in the period t in scenario s, otherwise 0

$Ro_{vjk,s}^{rt}$: Equivalent to 1 if the vehicle of type v goes from the warehouse of the manufacturer j to the distributor k of the route r in the period t in scenario s, otherwise 0

$ro_{vkl,s}^{rt}$: Equivalent to 1 if the vehicle of type v goes from the distributor k to the customer l from the route r in the period t in scenario s, otherwise 0

$ro_{vlm,s}^{rt}$: Equivalent to 1 if the vehicle of type v goes from the customer l to the hub m from the route r in the period t in scenario s, otherwise 0

$ro_{vmp,s}^{rt}$: Equivalent to 1 if the vehicle of type v goes from the hub m to the recycling station p from the route r in the period t in scenario s, otherwise 0

$ro_{vpj,s}^{rt}$: Equivalent to 1 if the vehicle of type v goes from the recycling station p to the manufacturer j from the route r in the period t in scenario s, otherwise 0

$ro_{vmj,s}^{rt}$: Equivalent to 1 if the vehicle of type v goes from the hub m to the manufacturer j from the route r in the period t in scenario s, otherwise 0

$ro_{vmn,s}^{rt}$: Equivalent to 1 if the vehicle of type v goes from the hub m to the demolition station n from the route r in the period t in scenario s, otherwise 0

$ro_{vmw,s}^{rt}$: Equivalent to 1 if the vehicle type v goes from the hub m to the repair station w from the route r in the period t in scenario s, otherwise 0

$ro_{vwk,s}^{rt}$: Equivalent to 1 if the vehicle type v goes from the repair station w to the distributor k from the route r in the period t in scenario s, otherwise 0

$z_{lmq,s}^{ct}$: Flow amount of the returned product c with the quality of the type q from the customer l to the hub m in the period t in scenario s

$z_{mpq,s}^{ct}$: Flow amount of the returned product c with the quality of the type q from the hub m to the recycling station p in the period t in scenario s

$z_{ij,s}^{ot}$: Flow amount of the raw materials o from the supply station i to the production station j in the period t in scenarios

$z_{pj,s}^{ct}$: Flow amount of the reused product c from the recycling station p to the production station j in the period t in scenario s

$z_{mnq,s}^{ct}$: Flow amount of the returned product c with the quality of the type q from the hub m to the demolition station n in the period t in scenario s

$z_{mjq,s}^{ct}$: Flow amount of the returned product c with the quality of the type q from the hub m to the production station j in the period t in scenario s

$z_{mwq,s}^{ct}$: Flow amount of the returned product c with the quality of the type q from the hub m to the repair station w in the period t in scenario s

$z_{wk,s}^{ct}$: Flow amount of the product c from the repair station w to the distribution station k in the period t in scenario s

$z_{jk,s}^{ct}$: Flow amount of the product c from the production station j to the distribution station k in the period t in scenarios

$z_{kl,s}^{ct}$: Flow amount of the product c from the distribution station k to the customer l in the period t in scenario s

$Q_{jk,s}^{ct}$: Flow amount of the product c from the warehouse of the producer j to the distribution station k in the period t in scenario s

$Q_{jj,s}^{ct}$: Flow amount of the product c from the production station j to its own warehouse in the period t in scenario s

x_k^t: If the distribution station is established at the location k in the period t, its value would be equal to 1, and otherwise0.

x_p^t: If the recycling station is established at the location p in the period t, its value would be equal to 1, and otherwise0.

x_m^t: If the hub is established at the location m in the period t, its value would be equal to 1, and otherwise 0.

x_n^t: If the landfill and demolition station is established at the location n in the period t, its value would be equal to 1, and otherwise 0.

x_w^t: If the repair station is established at the location w in the period t, its value would be equal to 1, and otherwise 0.

$Inv_{j,s}^{ct}$: The residual inventory of the product c in the warehouse of the producer j in the period t in scenario s

E. Objective functions

We know that the time it takes for the warehouse of the production station j to break down over the period T_j follows an exponential distribution with a mean value of $\lambda_{jt}^{'}$. Thus, the reliability of the warehouse of the production station j in sending products to the distribution station k in the period t is equal to:

$$R_j = p\left(T_j > \tau_j^{'}\right) = \int_{\tau_j^{'}}^{\infty} \lambda_{jt}^{'}\, e^{-\lambda_{jt}^{'}\tau_j^{'}} dt = e^{-\lambda_{jt}^{'}\tau_j^{'}} \tag{1}$$

Therefore, the mean value of the products sent from the warehouse of the production stations to distribution stations is equal to:

$$\sum_{t\in T}\sum_{c\in C}\sum_{s\in S}\sum_{j\in J}\sum_{k\in K} Q_{jks}^{ct} e^{-\lambda'_{jt}\tau'_j} \tag{2}$$

Therefore, the mean value of the products sent from production stations and their warehouses to distribution stations is equal to:

$$\sum_{t\in T}\sum_{c\in C}\sum_{s\in S}\left(\sum_{j\in J}\sum_{k\in K} Q_{jks}^{ct} e^{-\lambda'_{jt}\tau'_j} + \sum_{j\in J}\sum_{k\in K} Z_{jks}^{ct} e^{-\lambda_{jt}\tau_j}\right) \tag{3}$$

Similarly, the average of raw materials sent from supplier stations to production stations is equal to:

$$\sum_{t\in T}\sum_{o\in O}\sum_{s\in S}\sum_{i\in I}\sum_{j\in J} Z_{ijs}^{ot} e^{-\lambda_{it}\tau''_i} \tag{4}$$

$$max\, z_1 = J_1 + J_2 + R - In \tag{5}$$

$$J_1 = \sum_{t\in T}\sum_{s\in S}\left(\sum_{m\in M}\alpha j_{m,s}\ \mathrm{x}_m^t + \sum_{p\in P}\alpha j_{p,s}\ \mathrm{x}_p^t + \sum_{w\in W}\alpha j_{w,s}\ \mathrm{x}_w^t + \sum_{n\in N}\alpha j_{n,s}\ \mathrm{x}_n^t + \sum_{k\in N}\alpha j_{k,s}\ \mathrm{x}_k^t\ \right) \tag{6}$$

$$\begin{aligned} J_2 = {} & \sum_{t\in T}\sum_{c\in C}\sum_{s\in S}\Bigg(\sum_{k\in K}\sum_{l\in L}\frac{\beta j_k}{u_k^t} z_{kl,s}^{ct} + \sum_{l\in L}\sum_{m\in M}\sum_{q\in Q}\frac{\beta j_m}{u_m^t} z_{lmq,s}^{ct} + \sum_{m\in M}\sum_{n\in N}\sum_{q\in Q_4}\frac{\beta j_n}{u_n^t} z_{mnq,s}^{ct} + \\ & \sum_{m\in M}\sum_{w\in W}\sum_{q\in Q_1}\frac{\beta j_w}{u_w^t} z_{mwq,s}^{ct} + \sum_{m\in M}\sum_{p\in P}\sum_{q\in Q_3}\frac{\beta j_p}{u_p^t} z_{mpq,s}^{ct}\Bigg) \end{aligned} \tag{7}$$

$$\boldsymbol{R} = \sum_{\boldsymbol{t\in T}}\sum_{\boldsymbol{c\in C}}\sum_{\boldsymbol{s\in S}}\left(\sum_{\boldsymbol{j\in J}}\sum_{\boldsymbol{k\in K}} \boldsymbol{Q_{jks}^{ct} e^{-\lambda'_{jt}\tau'_j}} + \sum_{\boldsymbol{j\in J}}\sum_{\boldsymbol{k\in K}} \boldsymbol{Z_{jks}^{ct} e^{-\lambda_{jt}}}\right) + \sum_{\boldsymbol{t\in T}}\sum_{\boldsymbol{o\in O}}\sum_{\boldsymbol{s\in S}}\sum_{\boldsymbol{i\in I}}\sum_{\boldsymbol{j\in J}} \boldsymbol{Z_{ijs}^{ot} e^{-\lambda_{it}}} \tag{8}$$

$$\boldsymbol{In} = \sum_{\boldsymbol{t\in T}}\sum_{\boldsymbol{s\in S}}\sum_{\boldsymbol{j\in J}}\sum_{\boldsymbol{c\in C}} \boldsymbol{dl_j^t}(\boldsymbol{Q_{jj,s}^{ct}} + \sum_{\boldsymbol{k\in K}}(\boldsymbol{z_{jk,s}^{ct}})\ \ () \tag{9}$$

The first objective function represents the social responsibility dimension of the SC network, where:

J_1: The number of fixed jobs created

J_2: The number of variable jobs created

R: The average amount of product flow sent from suppliers, production stations, and their warehouses (as the R value increases, the satisfaction level of distribution stations and customers will increase.)

In: The work injury rate due to jobs created in the production stations and their warehouses

$$Min\ z_2 = C_1 + C_2 + C_3 \tag{10}$$

$$\boldsymbol{C_1} = \sum_{\boldsymbol{t\in T}}\left(\sum_{\boldsymbol{m\in M}} \boldsymbol{E_m^t x_m^t} + \sum_{\boldsymbol{n\in N}} \boldsymbol{E_n^t x_n^t} + \sum_{\boldsymbol{p\in P}} \boldsymbol{E_p^t x_p^t} + \sum_{\boldsymbol{w\in W}} \boldsymbol{E_w^t x_w^t} + \sum_{\boldsymbol{k\in K}} \boldsymbol{E_k^t x_k^t}\right) \tag{11}$$

$$\begin{aligned} & \sum_{\boldsymbol{l\in L}}\sum_{\boldsymbol{m\in M}}\sum_{\boldsymbol{v\in V}}\sum_{\boldsymbol{q\in Q}} \boldsymbol{h_{lmq,s}^{c} z_{lmq,s}^{ct} ro_{vlm,s}^{rt}} + \sum_{\boldsymbol{m\in M}}\sum_{\boldsymbol{p\in P}}\sum_{\boldsymbol{v\in V}}\sum_{\boldsymbol{q\in Q_3}} \boldsymbol{h_{mpq,s}^{c} z_{mpq,s}^{ct} ro_{vmp,s}^{rt}} + \\ & \sum_{\boldsymbol{k\in K}}\sum_{\boldsymbol{l\in L}}\sum_{\boldsymbol{v\in V}} \boldsymbol{h_{kl,s}^{c} z_{kl,s}^{ct} ro_{vkl,s}^{rt}} + \sum_{\boldsymbol{p\in P}}\sum_{\boldsymbol{j\in J}}\sum_{\boldsymbol{v\in V}} \boldsymbol{h_{pj,s}^{c} z_{pj,s}^{ct} ro_{vpj,s}^{rt}} + \sum_{\boldsymbol{m\in M}}\sum_{\boldsymbol{n\in N}}\sum_{\boldsymbol{v\in V}}\sum_{\boldsymbol{q\in Q_4}} \boldsymbol{h_{mnq,s}^{c} z_{mnq,s}^{ct} ro_{vmn,s}^{rt}} + \\ & \sum_{\boldsymbol{m\in M}}\sum_{\boldsymbol{j\in J}}\sum_{\boldsymbol{v\in V}}\sum_{\boldsymbol{q\in Q_2}} \boldsymbol{h_{mjq,s}^{c} z_{mjq,s}^{ct} ro_{vmj,s}^{rt}} + \sum_{\boldsymbol{m\in M}}\sum_{\boldsymbol{w\in W}}\sum_{\boldsymbol{v\in V}}\sum_{\boldsymbol{q\in Q_1}} \boldsymbol{h_{mwq,s}^{c} z_{mwq,s}^{ct} ro_{vmw,s}^{rt}} + \\ & \sum_{\boldsymbol{w\in W}}\sum_{\boldsymbol{k\in K}}\sum_{\boldsymbol{v\in V}} \boldsymbol{h_{wk,s}^{c} z_{wk,s}^{ct} ro_{vwk,s}^{rt}} + \sum_{\boldsymbol{c\in C}}\sum_{\boldsymbol{j\in J}} \boldsymbol{f_{j,s}^{ct} Inv_{j,s}^{ct}}) \end{aligned} \tag{12}$$

$$\begin{aligned} \boldsymbol{C_3} = {} & \sum_{\boldsymbol{t\in T}}\sum_{\boldsymbol{s\in S}}\sum_{\boldsymbol{c\in C}}\Big(\sum_{\boldsymbol{l\in L}}\sum_{\boldsymbol{m\in M}}\sum_{\boldsymbol{q\in Q}} \boldsymbol{z_{lmq,s}^{ct} fp_{lmq,s}^{ct}} + \sum_{\boldsymbol{m\in M}}\sum_{\boldsymbol{p\in P}}\sum_{\boldsymbol{q\in Q_3}} \boldsymbol{z_{mpq,s}^{ct} cp_{ct,s}} + \\ & \sum_{\boldsymbol{l\in L}}\sum_{\boldsymbol{m\in M}}\sum_{\boldsymbol{q\in Q}} \boldsymbol{x_{lmq,s}^{ct}\, c\, m_{ct,s}} + \sum_{\boldsymbol{k\in K}}\sum_{\boldsymbol{l\in L}} \boldsymbol{z_{kl,s}^{ct} ck_{ct,s}} + \sum_{\boldsymbol{m\in M}}\sum_{\boldsymbol{n\in N}}\sum_{\boldsymbol{q\in Q_4}} \boldsymbol{z_{mnq,s}^{ct} cn_{ct,s}} + \\ & \sum_{\boldsymbol{m\in M}}\sum_{\boldsymbol{w\in W}}\sum_{\boldsymbol{q\in Q_1}} \boldsymbol{z_{mwq,s}^{ct} cw_{ct,s}} + \sum_{\boldsymbol{m\in M}}\sum_{\boldsymbol{j\in J}}\sum_{\boldsymbol{q\in Q_2}} \boldsymbol{z_{mjq,s}^{ct} rcj_{ct,s}} + \sum_{\boldsymbol{j\in J}}(\boldsymbol{c\, j_{ct,s}}\,(\boldsymbol{Q_{jj,s}^{ct}} + \sum_{\boldsymbol{k\in K}} \boldsymbol{z_{jk,s}^{ct}})\ \Big) \end{aligned} \tag{13}$$

The second objective function encompasses the SC costs as follows:

C_1: The costs of establishing hub, repair, distribution, demolition, landfill, and recycling stations

C_2: The costs of production and maintenance of products in the production sector

C_3: The costs of recycling, demolition, etc.

$$\boldsymbol{Min\ z_3 = F_1 + F_2} \tag{14}$$

$$\boldsymbol{F_1 = \sum_{t\in T}\left(\sum_{n\in N} EM_n x_n^t + \sum_{m\in M} EM_m x_m^t + \sum_{p\in P} EM_p x_p^t + \sum_{w\in W} EM_w x_w^t + \sum_{k\in K} EM_M x_k^t\right)} \tag{15}$$

$$\boldsymbol{F_2 = \sum_{s\in S}\sum_{r\in R}\sum_{t\in T}\sum_{v\in V} EMS_v\Big(\sum_{j\in J}\sum_{k\in K} a_{jk,s} z_{jk,s}^{ct} ro_{vjk,s}^{rt} + \sum_{j\in J}\sum_{k\in K} dq_{jk,s}\, Q_{jk,s}^{ct} Ro_{vjk,s}^{rt} +} \\ \boldsymbol{\sum_{k\in K}\sum_{l\in L} a_{kl,s}\, z_{kl,s}^{ct} ro_{vkl,s}^{rt} + \sum_{q\in Q}\sum_{l\in L}\sum_{m\in M} a_{lm,s}^{c} z_{lmq,s}^{ct}\, ro_{vlm,s}^{rt} + \sum_{q\in Q_3}\sum_{m\in M}\sum_{p\in P} a_{mp,s} z_{mpq,s}^{ct}\, ro_{vmp,s}^{rt} +} \\ \boldsymbol{\sum_{q\in Q_4}\sum_{m\in M}\sum_{n\in N} a_{mn,s} z_{mnq,s}^{ct}\, ro_{vmn,s}^{rt}} + \sum_{q\in Q_2}\sum_{m\in M}\sum_{j\in J} a_{mj,s}\, z_{mjq,s}^{ct} ro_{vmj,s}^{rt} + \\ \sum_{q\in Q_1}\sum_{m\in M}\sum_{w\in W} a_{mw,s}\, z_{mwq,s}^{ct}\, ro_{vmw,s}^{rt} + \sum_{w\in W}\sum_{k\in K} a_{wk,s} z_{wk,s}^{ct}\, ro_{vwk,s}^{rt}\Big) + \sum_{p\in P}\sum_{j\in J} a_{pj,s} z_{pj,s}^{ct} r\, o_{vpj,s}^{rt} + \\ \sum_{s\in S}\sum_{o\in O}\sum_{r\in R}\sum_{t\in T}\sum_{v\in V}\sum_i\sum_j EMS_v\, a_{ij,s} z_{ij,s}^{ot} ro_{vij,s}^{rt} + \sum_{t\in T}\sum_{s\in S}\sum_{c\in C}\sum_{j\in J}\gamma\, aq_{jj,s} Q_{jj,s}^{ct} \tag{16}$$

The third objective function includes environmental effects and the amount of CO2 emitted due to the establishment of potential stations (F_1) and transportation in the SC (F_2).

F. Constraints

$$\sum_{k\in K} x_k^t \geq 1 \qquad \forall t \in T \tag{17}$$

$$\sum_{w\in W} x_w^t \geq 1 \qquad \forall t \in T \tag{18}$$

$$\sum_{m\in M} x_m^t \geq 1 \qquad \forall t \in T \tag{19}$$

$$\sum_{p\in P} x_p^t \geq 1 \qquad \forall t \in T \tag{20}$$

$$\sum_{n\in N} x_n^t \geq 1 \qquad \forall t \in T \tag{21}$$

$$\sum_{k\in K} ro_{vjk,s}^{rt} + \sum_{k\in K} Ro_{vjk,s}^{rt} \leq \sum_{k\in K} x_k^t \qquad \forall j \in J, r \in R, v \in V, t \in T, s \in S \tag{22}$$

$$\sum_{m\in M} ro_{vlm,s}^{rt} \leq \sum_{m\in M} x_m^t \qquad \forall l \in L, r \in R, v \in V, t \in T, s \in S \tag{23}$$

$$\sum_{p\in P} ro_{vmp,s}^{rt} \leq \sum_{p\in P} x_p^t \qquad \forall m \in M, r \in R, v \in V, t \in T, s \in S \tag{24}$$

$$\sum_{n\in N} ro_{vmn,s}^{rt} \leq \sum_{n\in N} x_n^t \qquad \forall m \in M, r \in R, v \in V, t \in T, s \in S \tag{25}$$

$$\sum_{w\in W} ro^{rt}_{vmw,s} \le \sum_{w\in W} x^{t}_{w} \qquad \forall m\in M, r\in R, v\in V, t\in T, s\in S \tag{26}$$

$$\sum_{k\in K} z^{ct}_{kl,s} = d^{ct}_{l,s} \qquad \forall l\in L, c\in C, t\in T, s\in S \tag{27}$$

$$\sum_{q\in Q_2}\sum_{j\in J} z^{ct}_{mj,q,s} = \sum_{j\in J} rb^{ct}_{mj} \sum_{q\in Q}\Big(\sum_{l\in L} z^{ct}_{lm,q,s}\Big) \qquad \forall m\in M, c\in C, t\in T, s\in S \tag{29}$$

$$\sum_{q\in Q_3}\sum_{p\in P} z^{ct}_{mpq,s} = \sum_{p\in P} rb^{ct}_{mp} \sum_{q\in Q}\Big(\sum_{l\in L} z^{ct}_{lm,q,s}\Big) \qquad \forall m\in M, c\in C, t\in T, s\in S \tag{30}$$

$$\sum_{q\in Q_4}\sum_{n\in N} z^{ct}_{mnq,s} = \sum_{n\in N} rb^{ct}_{mn} \sum_{q\in Q}\Big(\sum_{l\in L} z^{ct}_{lmq,s}\Big) \qquad \forall m\in M, c\in C, t\in T, s\in S \tag{31}$$

$$\sum_{q\in Q_1}\sum_{w\in W} z^{ct}_{mwq,s} = \sum_{w\in W} rb^{ct}_{mw} \sum_{q\in Q}\Big(\sum_{l\in L} z^{ct}_{lmq,s}\Big) \qquad \forall m\in M, c\in C, t\in T, s\in S \tag{32}$$

$$\sum_{q\in Q_3}\sum_{m\in M} z^{ct}_{mpq,s} = \sum_{j\in J} z^{ct}_{pj,s} \qquad \forall p\in P, c\in C, t\in T, s\in S \tag{34}$$

$$\sum_{q\in Q_1}\sum_{m\in M} z^{ct}_{mwq,s} = \sum_{k\in K} z^{ct}_{wk,s} \qquad \forall w\in W, c\in C, t\in T, s\in S \tag{35}$$

$$\sum_{i\in I} z^{ot}_{ij,s} + \sum_{q\in Q_2}\sum_{m\in M} z^{ct}_{mjq,s} + \sum_{p\in P} z^{ct}_{pj,s} = \sum_{k\in K} z^{ct}_{jk,s} + Inv^{ct}_{j,s} \qquad \forall j\in J, c\in C, o\in O, t\in T, s\in S \tag{36}$$

$$\sum_{q\in Q_2}\sum_{j\in J} z^{ct}_{mjq,s} + \sum_{q\in Q_3}\sum_{p\in P} z^{ct}_{mpq,s} + \sum_{q\in Q_4}\sum_{n\in N} z^{ct}_{mnq,s} + \sum_{q\in Q_1}\sum_{w\in W} z^{ct}_{mwq,s} = \sum_{q\in Q}\sum_{l\in L} z^{ct}_{lmq,s} \qquad \forall m\in M, c\in C, t\in T, s\in S \tag{37}$$

$$\sum_{r\in R} ro^{rt}_{vjk,s} + \sum_{r\in R} Ro^{rt}_{vjk,s} \ge 1 \qquad \forall j\in J, k\in K, v\in V, t\in T, s\in S \tag{38}$$

$$\sum_{r\in R} ro^{rt}_{vlm,s} \ge 1 \qquad \forall m\in M, l\in L, v\in V, t\in T, s\in S \tag{39}$$

$$\sum_{r\in R} ro^{rt}_{vmp,s} \ge 1 \qquad \forall m\in M, p\in P, v\in V, t\in T, s\in S \tag{40}$$

$$\sum_{r\in R} ro^{rt}_{vmn,s} \ge 1 \qquad \forall m\in M, n\in N, v\in V, t\in T, s\in S \tag{41}$$

$$\sum_{r\in R} ro^{rt}_{vij,s} \ge 1 \qquad \forall i\in I, j\in J, v\in V, t\in T, s\in S \tag{42}$$

$$\sum_{r\in R} ro^{rt}_{vkl,s} \ge 1 \qquad \forall k\in K, l\in L, v\in V, t\in T, s\in S \tag{43}$$

$$\sum_{r\in R} ro_{vpj,s}^{rt} \geq 1 \qquad \forall p \in P, j \in J, v \in V, t \in T, s \in S \qquad (44)$$

$$\sum_{r\in R} ro_{vmj,s}^{rt} \geq 1 \qquad \forall m \in M, j \in J, v \in V, t \in T, s \in S \qquad (45)$$

$$\sum_{r\in R} ro_{vwk,s}^{rt} \geq 1 \qquad \forall w \in W, k \in K, v \in V, t \in T, s \in S \qquad (46)$$

$$\sum_{r\in R} ro_{vmw,s}^{rt} \geq 1 \qquad \forall m \in M, w \in W, v \in V, t \in T, s \in S \qquad (47)$$

$$Inv_{j,s}^{ct} = Q_{jj,s}^{ct} - \sum_{k\in K} Q_{jk,s}^{ct} \qquad \forall j \in J, \forall c \in C, t \in T, \forall s \in S \qquad (48)$$

$$\sum_{c\in C} Inv_{j,s}^{ct} \leq u_{jj}^{t} \qquad \forall j \in J, t \in T, \forall s \in S \qquad (49)$$

$$\sum_{k\in K} Q_{jk,s}^{ct} \leq Q_{jj,s}^{ct} \qquad \forall j \in J, c \in C, t \in T, s \in S \qquad (50)$$

$$\sum_{o\in O}\sum_{j\in J} z_{ij,s}^{ot} \leq u_{i}^{t} \qquad \forall t \in T, i \in I, s \in S \qquad (51)$$

$$\sum_{c\in C}\sum_{k\in K} z_{jk,s}^{ct} + \sum_{c\in C} Q_{jj,s}^{ct} \leq u_{j}^{t} \qquad \forall j \in J, t \in T, s \in S \qquad (52)$$

$$\sum_{c\in C}\sum_{l\in L} z_{kl,s}^{ct} \leq u_{k}^{t} x_{k}^{t} \qquad \forall k \in K, t \in T, \forall s \in S \qquad \mathbf{(53)}$$

$$\sum_{q\in Q_2}\sum_{c\in C}\sum_{j\in J} z_{mjq,s}^{ct} + \sum_{q\in Q_3}\sum_{c\in C}\sum_{p\in P} z_{mpq,s}^{ct} + \sum_{q\in Q_4}\sum_{c\in C}\sum_{n\in N} z_{mnq,s}^{ct} + \sum_{q\in Q_1}\sum_{c\in C}\sum_{w\in W} z_{mwq,s}^{ct} \leq u_{m}^{t} x_{m}^{t} \qquad \forall m \in M, t \in T, s \in S$$
(54)

$$\sum_{c\in C}\Big(\sum_{q\in Q_2}\sum_{m\in M} z_{mjq,s}^{ct} + \sum_{p\in P} z_{pj,s}^{ct}\Big) + \sum_{i\in I}\sum_{o\in O} z_{ij,s}^{ot} \leq cr_{j}^{t} \qquad \forall j \in J, t \in T, s \in S \qquad (55)$$

$$\sum_{q\in Q_4}\sum_{c\in C}\sum_{m\in M} z_{mnq,s}^{ct} \leq u_{n}^{t} x_{n}^{t} \qquad \forall n \in N, t \in T, \forall s \in S \qquad (56)$$

$$\sum_{q\in Q_3}\sum_{c\in C}\sum_{m\in M} z_{mpq,s}^{ct} \leq u_{p}^{t} x_{p}^{t} \qquad \forall p \in P, t \in T, s \in S \qquad (57)$$

$$\sum_{q\in Q_1}\sum_{c\in C}\sum_{m\in M} z_{mwq,s}^{ct} \leq u_{w}^{t} x_{w}^{t} \qquad \forall w \in W, t \in T, s \in S \qquad (58)$$

$$\sum_{r\in R} ro_{vjk,s}^{rt} + \sum_{r\in R} Ro_{vjk,s}^{rt} \leq \sum_{r\in R} ro_{vij,s}^{rt} \qquad \forall j \in J, i \in I, k \in K, v \in V, t \in T, s \in S \qquad (59)$$

$$\sum_{r\in R} ro^{rt}_{vkl,s} \le \sum_{r\in R} ro^{rt}_{vjk,s} \qquad \forall j\in J, l\in L, k\in K, v\in V, t\in T, s\in S \tag{60}$$

$$\sum_{r\in R} ro^{rt}_{vlm,s} \le \sum_{r\in R} ro^{rt}_{vkl,s} \qquad \forall m\in M, l\in L, k\in K, v\in V, t\in T, s\in S \tag{61}$$

$$\sum_{r\in R} ro^{rt}_{vpj,s} \le \sum_{r\in R} ro^{rt}_{vmp,s} \qquad \forall j\in J, p\in P, m\in M, v\in V, t\in T, s\in S \tag{62}$$

$$\sum_{r\in R} ro^{rt}_{vmw,s} \le \sum_{r\in R} ro^{rt}_{vwk,s} \qquad \forall w\in W, k\in K, m\in M, v\in V, t\in T, s\in S \tag{63}$$

$$\sum_{r\in R} (ro^{rt}_{vmp,s} + ro^{rt}_{vmn,s} + ro^{rt}_{vmj,s} + ro^{rt}_{vmw,s}) \le \sum_{r\in R} ro^{rt}_{vlm,s} \qquad \forall m\in M, j\in J, w\in W, n\in N, l\in L, p\in P, v\in V, t\in T, s\in S \tag{64}$$

$$z^{ct}_{lmq,s}, z^{ct}_{mpq,s}, z^{ot}_{ij,s}, z^{ct}_{pj,s}, z^{ct}_{mnq,s}, z^{ct}_{mjq,s}, z^{ct}_{mwq,s}, z^{ct}_{wk,s}, z^{ct}_{jk,s}, z^{ct}_{kl,s}, Q^{ct}_{jk,s}, Q^{ct}_{jj,s}, Inv^{ct}_{j,s} \ge 0$$

$$x^{t}_{k}, x^{t}_{p}, x^{t}_{m}, x^{t}_{n}, x^{t}_{w}, Ro^{rt}_{vjk,s}, ro^{rt}_{vij,s}, ro^{rt}_{vjk,s}, ro^{rt}_{vkl,s}, ro^{rt}_{vlm,s}, ro^{rt}_{vmp,s}, ro^{rt}_{vpj,s}, ro^{rt}_{vmj,s}, ro^{rt}_{vmn,s}, ro^{rt}_{vmw,s}, ro^{rt}_{vwk,s} \in \{0,1\} \tag{65}$$

The constraints (17-21) suggest that at least one of the potential distribution, repair, hub, recycling, and disposal stations in the SC is established. The constraints (22-26) suggest that a potential station should first be established to subsequently create a route (path) to this potential station. The constraint (27) indicates the satisfaction of customers' demands. The constraint (28) shows the balance between distributing, customer, and hub stations. The constraint (29) indicates the balance between customer, hub, and production stations. The constraint (30) shows the balance between customer, hub, and recycling stations. The constraint (31) indicates the balance between customer, hub, and landfill and disposal stations. The constraint (32) shows the balance between customer, hub, and repair stations. The constraint (33) indicates the balance between manufacturer, distributor, customer, and repair stations. The constraint (34) shows the balance between hub, recycling, and manufacturing stations. The constraint (35) shows the balance between hub, repair, and distributor stations. The constraints (36-37) determine the product flows in terms of its quality. The constraints (38-47) suggest that there is at least one path between the SC elements. The constraints (48-49) indicate the amount of inventory and the final capacity of the manufacturer. The constraint (50) determines the amount of the producer's inventory in its warehouse. The constraints (51-58) indicate the capacity of the fixed and potential stations. The constraints (59-64) explain the limitations of vehicle routing. Finally, the constraint (65) represents the decision variables of the proposed model.

G. Converting the indefinite demand constraint to its equivalent definite constraint

A fuzzy number is a certain type of the normalized convex real line fuzzy set (Hanss et al., 2005). There are several patterns such as triangular, trapezoidal, bell-shaped patterns, etc. to describe fuzzy numbers. This paper used the TFN in this article to represent the fuzzy demand parameter. TFN can accurately represent the uncertainty of the parameter and is close to the actual situation. Thus, the demand fuzzy parameter was defined as$((d^{ct}_{ls})^{p}, (d^{ct}_{ls})^{m}, (d^{ct}_{ls})^{o})$, in which, the upper indices o, m, and p represent the most pessimistic, most possible, and the most optimistic values for the parameter, respectively. Therefore, the demand membership function would be as follows:

$$\mu_{\widetilde{d^{ct}_{ls}}}(x) = \begin{cases} \dfrac{x-(d^{ct}_{ls})^{p}}{(d^{ct}_{ls})^{m}-(d^{ct}_{ls})^{p}} & (d^{ct}_{ls})^{p} \le x \le (d^{ct}_{ls})^{m} \\ \dfrac{(d^{ct}_{ls})^{o}-x}{(d^{ct}_{ls})^{o}-(d^{ct}_{ls})^{m}} & (d^{ct}_{ls})^{m} \le x \le (d^{ct}_{ls})^{o} \end{cases} \tag{66}$$

This paper utilized the weighted-average method in this paper to convert the fuzzy demand parameter to the equivalent definite parameter. Therefore, the fuzzy constraint (27) is determined based on Equation (67).

$$\sum_{k\in K} z_{kl,s}^{ct} = w_1\left(d_{ls,\beta}^{ct}\right)^p + w_2\left(d_{ls,\beta}^{ct}\right)^m + w_3\left(d_{ls,\beta}^{ct}\right)^o \qquad \forall l \in L, c \in C, t \in T, s \in S \tag{67}$$

In Equation (67), $w_1 + w_2 + w_3 = 1$ and β are the minimum acceptable likelihood in converting the fuzzy parameter to an equivalent real number. The symbols $w_3,\ w_2\ ,w_1$ show the most pessimistic, most possible, and the most optimistic weight of fuzzy demand values, respectively. In this study, these weights were considered based on the proposed values of Lai and Hwang and other conducted studies (Liang et al., 2006; Wang et al., 2005) as $\beta = 0.5\ ,\ w_1 = w_3 = \frac{1}{6}\ w_2 = \frac{4}{6}$.

V. SOLVING APPROACHES

A. Epsilon constraint

This method is based on turning a multi-objective optimization problem into a single-objective optimization problem. Thus, one of the objectives of the problem is optimized as the main objective regarding other objectives as a constraint in this method (Laumanns et al., 2006). It is assumed that the decision to minimize the objective functions (68) is associated with the constraints (69).

$$Min \quad F(x) = \{f_1(x)\ ,\dots,\ f_n(x)\} \tag{68}$$

$$st\colon \begin{array}{l} g(x) \le 0 \\ \square(x) = 0 \end{array} \tag{69}$$

One of the objective functions is selected as the main objective function according to Equation (70) based on this approach. Other objective functions are considered as the constraint (71), and each time, the problem is solved according to one of the objective functions and optimal and corresponding values of each objective function are calculated (Fakhrzad et al., 2013).

$$Min \quad F(x) \tag{70}$$

$$st\colon \begin{array}{ll} & f_j(x) \le \varepsilon_j \\ & f \\ & j \\ min_{j_j}{}^{max\,\square(x)=0}_{\quad g(x)\le 0} & j = 1,\dots,n\ ,j \ne 1 \end{array} \tag{71}$$

B. MOPSO algorithm

MOPSO is a metaheuristic algorithm based on the intelligence group introduced by Coello (Coello et al., 2004) for the first time. In this algorithm, each solution is considered as a particle that tries to update its velocity v_p and its position x_p at iteration t based on two categories of information, namely its previous best experience x_{pb} and the best global experience throughout the whole swarm x_g. Equations (71) and (72) show the mathematical formulation of the updating procedure (Rabbani et al, 2022).

$$v_p(t) = w\ v_p(t-1) + c_1 r_1(x_{pb}(t) - x_p(t)) + c_2 r_2\,(x_g(t) - x_p(t)) \tag{71}$$

$$x_p(t) = x_p(t-1) + v_p(t) \tag{72}$$

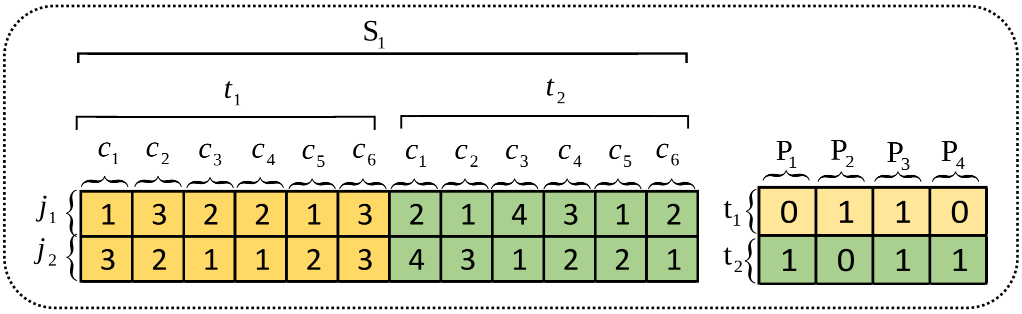
w denotes the inertia factor that affects the global and local ability of the particle. c_1 is the cognitive coefficient that influences the impact of x_{pb}, whereas c_1 is the social learning coefficient that is responsible for controlling influences the effect of x_g.

C. NSGA II algorithm

NSGA-II was introduced by Deb et al. (2002) for the first time. This algorithm can be considered as an extension of the Genetic Algorithm (GA) with the same operators (crossover and mutation) that can handle mathematical models with multiple contradicting objective functions. Based on the flowchart (Rabbani et al, 2022), the algorithm starts with the N_{pop} number of individuals as the initial population that is randomly generated. Next, non-dominated sorting is used to divide the initial population into several Pareto fronts. Each front consists of non-dominated individuals that need to be sorted according to the crowding distance operator. This operator is responsible for measuring the density of possible solutions along with a particular solution approximately. Then, roulette wheel selection is employed to choose a number of parents that undertake crossover and mutation for forming an offspring population. In this type of selection, individuals with a better rank and more crowding distance have a higher chance of being chosen. The next generation consists of the best population members among the previous generation members and offspring, considering the non-dominated sorting and crowding distance in each front. The algorithm stops when the maximum number of iterations is met. First-ranked individuals among the last generation form the Pareto optimal solution of the proposed algorithm.

D. Chromosome structure

Figure 2 shows the multi-segment chromosome presented in this study. For example, the figure on the right shows the chromosome related to the $Inv_{j,s}^{ct}$variable. The value within each gene represents the amount of residual inventory of product c in the warehouse of the production station j in the period t in scenario s. The figure on the left also shows the chromosome corresponding to the variable x_p^t. If the value within each gene is equal to 1, the recycling station at location p is established in period t.

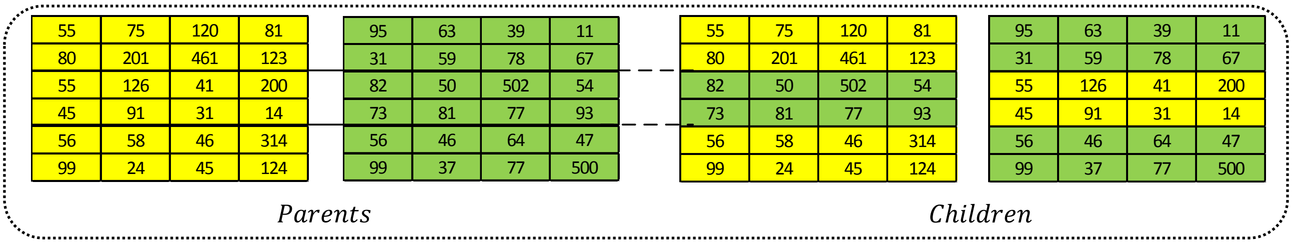


	c_1	c_2	c_3	c_4	c_5	c_6	c_1	c_2	c_3	c_4	c_5	c_6
j_1	1	3	2	2	1	3	2	1	4	3	1	2
j_2	3	2	1	1	2	3	4	3	1	2	2	1

	P1	P2	P3	P4
t1	0	1	1	0
t2	1	0	1	1

Fig 2. The proposed chromosome structure

Figure 3 illustrates the intersection operator. As seen in the figure, the single-point intersection has been used in this research. In this type of intersection, the two sides of the chromosome will be displaced together.



55	75	120	81
80	201	461	123
55	126	41	200
45	91	31	14
56	58	46	314
99	24	45	124

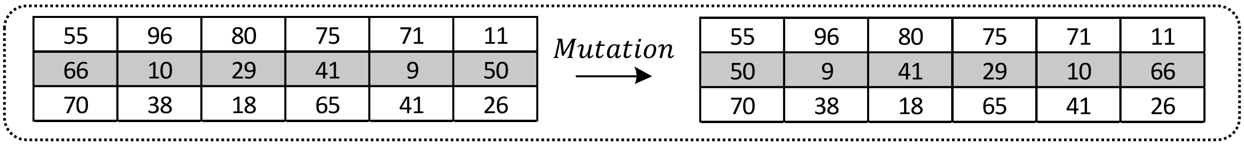
95	63	39	11
31	59	78	67
82	50	502	54
73	81	77	93
56	46	64	47
99	37	77	500

55	75	120	81
80	201	461	123
82	50	502	54
73	81	77	93
56	58	46	314
99	24	45	124

95	63	39	11
31	59	78	67
55	126	41	200
45	91	31	14
56	46	64	47
99	37	77	500

Fig 3. The intersection operator

As shown in Figure 4, the mutation operator considered in this study is a reverse mutation type. In this type of mutation, a row of chromosomes is selected and will be then reversed.



55	96	80	75	71	11
66	10	29	41	9	50
70	38	18	65	41	26

$\xrightarrow{Mutation}$

55	96	80	75	71	11
50	9	41	29	10	66
70	38	18	65	41	26

Fig 4. The mutation operator

E. Tuning the parameters

Since the output of the problems strongly depends on the parameters of the proposed algorithms, thus, the Taguchi method was used to tune their parameters. The advantage of the Taguchi method over other test design methods in addition to cost is to obtain the optimal levels of parameters in less time (Fraley et al., 2006). Choosing an orthogonal array appears to be one of the most important steps, which estimates the effects of factors on the mean values of the solution and variations. The most appropriate test design in this research was found to be the three-level experiments at three low, moderate, and high levels. Then, the arrays L_9 and L_{27} were chosen as the suitable test design to tune the parameter of the proposed algorithms due to the Taguchi standard orthogonal arrays. The levels of the parameters of NSGA II and MOPSO algorithms are given in Table I for their tuning.

Table I . The algorithm parameters

MOPSO algorithm parameters				*NSGA II algorithm parameters*			
Parameter	***Level 1***	***Level 2***	***Level 3***	***Parameter***	***Level 1***	***Level 2***	***Level 3***
Number of iterations (Maxit)	100	150	200	Number of iterations (Maxit)	100	130	150
Population size (npop)	50	80	100	Population size (npop)	50	100	150
Repository size (nRep)	60	85	100	Mutation rate (pm)	0.8	0.85	0.9
Inertia coefficient (w)	0.3	0.5	0.8	Crossover rate (pc)	0.1	0.15	0.2
inertia weight damping ratio (wdamp)	0.8	0.9	0.99	-	-	-	-
Number of grids per dimension (nGride)	3	5	7	-	-	-	-
Grid increase rate (alpha)	0.1	0.2	0.3	-	-	-	-
Leader selection pressure (beta)	2	4	5	-	-	-	-
Leader removal pressure (gama)	2	4	5	-	-	-	-
Mutation rate (mu)	0.1	0.15	0.2	-	-	-	-
Individual learning coefficient (c1)	1	2	4	-	-	-	-
Collective learning coefficient (c2)	2	3	5	-	-	-	-

A statistical index of efficiency, known as the signal to noise ratio (S/N) is considered in the Taguchi method to tune the optimal parameters. This ratio encompasses mean values and variations, and it would be more desirable at higher levels. The solution variable considered in this study is the ratio of the two indices of the Mean Ideal Distance (MID, Equation 74) and the Diversification Metric (DM, Equation 75) .

$$\frac{S}{N} = -10\, log\left(\frac{1}{n}\sum_{i=1}^{n} y_i^2\right) \tag{73}$$

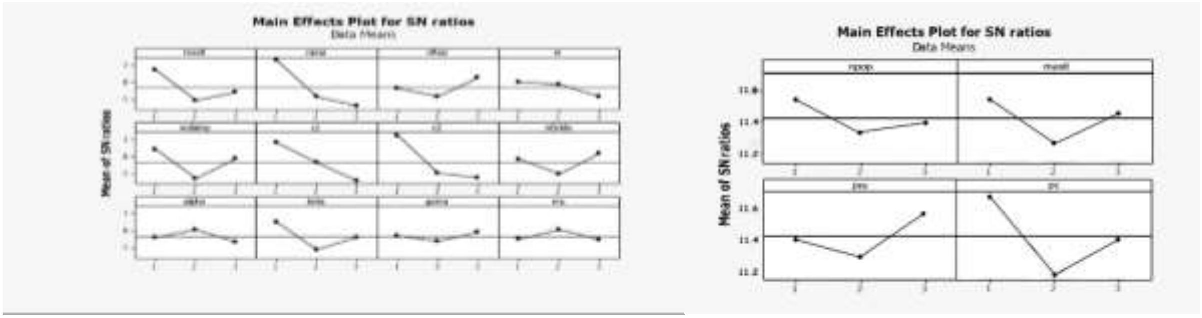


Fig 5. The S/N ratios of the parameters of the proposed algorithms

VI. COMPUTATIONAL RESULTS

A. Validation and comparison of employed algorithms

In this section, the model is first solved in small and medium dimensions aimed at evaluating the accuracy and precision of the proposed model. Table II shows the problems with small dimensions (samples 1 to 5) and medium dimensions (samples 6 to 10). For example, there is a customer, a manufacturer, a supplier, a recycling station, a hub, a repair station, a distributor, and a landfill station in sample number 1.

Table II. The dimensions of the problem

Number of the problem	*Customers*	*Manufacturers*	*Suppliers*	*Recycling stations*	*Hub*	*Repair stations*	*Distribution stations*	*Burial stations*
1	1	1	1	1	1	1	1	1
2	1	2	1	2	1	2	1	2
3	2	2	2	3	2	2	2	1
4	3	2	1	3	2	3	3	2
5	3	3	3	3	3	3	3	3
6	3	2	3	4	3	3	4	3
7	4	3	4	3	4	4	4	4
8	5	4	5	4	4	5	5	4
9	5	5	5	5	5	5	5	5
10	6	5	6	5	6	5	5	5

Figure 6 shows the model solution time for NSGA II, MOPSO algorithms, and the Epsilon constraint method. As can be seen, the solution time by the Epsilon constraint method is increasing exponentially as the dimension of the problem increases. Thus, MOPSO and NSGA II meta-heuristic algorithms had to be used to solve the problem on larger scales. It should be noted that the computations were performed by an Intel Core i3, 3.3 GH, 4GB RAM computer.

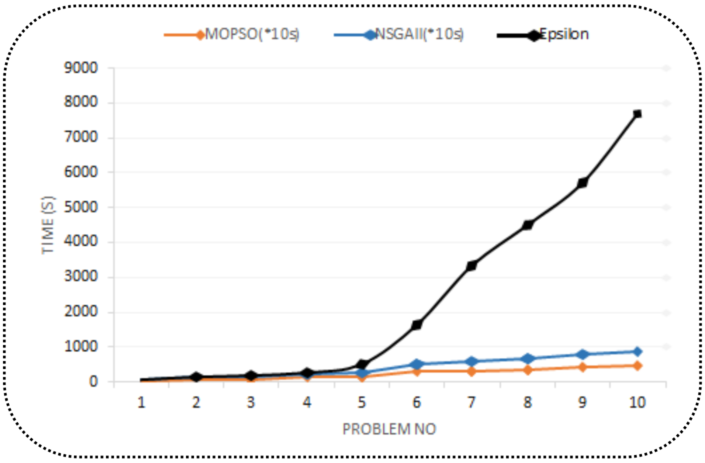


Fig 6. The model solution time in terms of increasing the problem dimension

The efficiency of the algorithm used to solve the proposed model was evaluated by the following criteria, which are described below.

- MID

This criterion measures the degree of closeness between the solutions found on the Pareto front and the ideal points $(f_1^{best}, f_2^{best}, f_3^{best})$, which is calculated by Equation 74. The lower the value of this criterion for an algorithm, the better the performance of that algorithm would be.

$$MID = \frac{\sqrt{\left(\frac{f_{1i}-f_1^{best}}{f_1^{nadir}-f_1^{best}}\right)^2+\left(\frac{f_{2i}-f_2^{best}}{f_2^{nadir}-f_2^{best}}\right)^2+\left(\frac{f_{3i}-f_3^{best}}{f_3^{nadir}-f_3^{best}}\right)^2}}{n} \quad (74)$$

In Equation 74, $n$is the number of non-dominated answers, while $f_i^{best}$and $f_i^{nadir}$are the best and worst values of the i-th objective function, respectively (Habibi et al., 2017).

- DM

This criterion measures the scattering of the Pareto solutions, which is calculated by Equation 75.

$$DM = \sqrt{\left(\frac{max\{f_{1i}\}-min\{f_{1i}\}}{f_1^{nadir}-f_1^{best}}\right)^2 + \left(\frac{max\{f_{2i}\}-min\{f_{2i}\}}{f_2^{nadir}-f_2^{best}}\right)^2 + \left(\frac{max\{f_{3i}\}-min\{f_{3i}\}}{f_3^{nadir}-f_3^{best}}\right)^2} \quad (75)$$

According to Equation 75, a higher value of DM indicates a better performance of the algorithm (Habibi et al., 2017).

- SM

This criterion measures the scattering pattern of the non-dominated solutions, which is calculated by Equation 77.

$$SM = \frac{\sum_{i=1}^{n-1}|d_i-\bar{d}|}{(n-1)\bar{d}} \quad (76)$$

In Equation 76, the $d_i$determines the Euclidean distance between successive solutions in the set of the non-dominated solutions obtained by the algorithm. According to the definition of SM, the lower the value of this index, the better the algorithm would be (Habibi et al., 2017).

For compare the results of the used algorithms, two meta-heuristics are applied to solve 10 problems in various dimensions and the obtained results are reported in Table III. The NSGA-II algorithm offered higher-diversity solutions than the MOPSO algorithm. Based on the two final columns of this table can be found that NSGA-II is the finest in terms of DM, SM, and MID. For more results analysis, the expected value chart along with an interval plot has been presented for the two proposed algorithms in Fig 7 according to the DM, SM, and MID criteria. For a closer look at the results of the two algorithms, the following hypothesis was tested according to DM, SM, and MID. T-test was used by spss. Three hypotheses are considered as follows:

Hypothesis 1. $\mu_{DM}^{MOPSO} \neq \mu_{DM}^{NSGA\ II}$ (77)

Hypothesis 2. $\mu_{MID}^{MOPSO} \neq \mu_{MID}^{NSGA\ II}$ (78)

Hypothesis 3. $\mu_{SM}^{MOPSO} \neq \mu_{SM}^{NSGA\ II}$ (79)

The results of three hypotheses are shown in Table IV. This table showed the p-value of 0.13, 0.48, and 0.36 for the metrics of diversity, ideal distance, and spacing (higher than 0.05); The research hypotheses were not confirmed statistically That is, there is no significant difference between the efficiency indices of the two proposed algorithms.

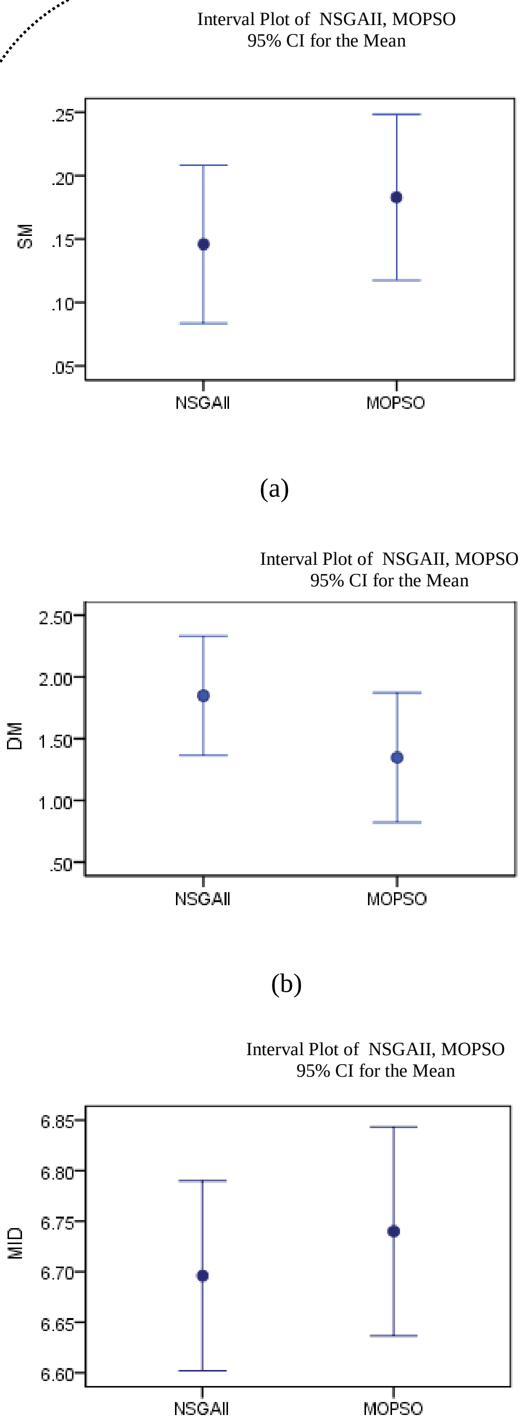
Table III. The computational results of comparison measurement criteria of MOPSO and NSGAII algorithms

Problem No		١	٢	٣	٤	٥	٦	٧	٨	٩	١٠	*Sum*	*Ave*
NSGAII	SM	٠	٠	٠,١١	٠,١٣	٠,١٩	٠,١٧	٠,٢٥	٠,١٨	٠,٢٢	٠,٢١	1.46	0.146
	MID	٦,٤٦	٦,٤٩	٦,٦٩	٦,٦٨	٦,٧٢	٦,٦٩	٦,٧٨	٦,٧٦	٦,٨٥	٦,٨٤	66.96	6.696
	DM	1.29	1.06	1.28	1.8	1.51	1.38	2.43	2.24	2.29	3.2	18.48	1.848
MOPSO	SM	٠	٠,٠٩	٠,١٢	٠,١٦	٠,٢٢	٠,١٩	٠,٣	٠,٢٤	٠,٢٦	٠,٢٥	1.83	0.183
	MID	٦,٤٩	٦,٤٩	٦,٧٣	٦,٧٥	٦,٧٦	٦,٧٥	٦,٨٢	٦,٨٢	٦,٨٧	٦,٩٢	67.4	6.74
	DM	0.47	0.68	0.74	0.93	1.12	1.27	1.45	1.82	2.2	2.79	13.47	1.347

Table IV.The results of the Student's T-Test

	Average differences	*SD.*	*Sig.*	*DoF.*	*t-statistics*	*95% confidence level*	
						Lower level	*higher level*
DM	0.5	0.31	0.13	18	1.58	-0.16	1.61
MID	-0.04	0.06	0.48	18	-0.17	-0.17	0.08
SM	-0.03	0.03	0.36	18	-0.92	-0.12	0.04

In general, according to Figure 8, the NSGAII algorithm shows superior performance compared to the MOPSO algorithm in solving the proposed model.



Interval Plot of NSGAII, MOPSO
95% CI for the Mean

(a)

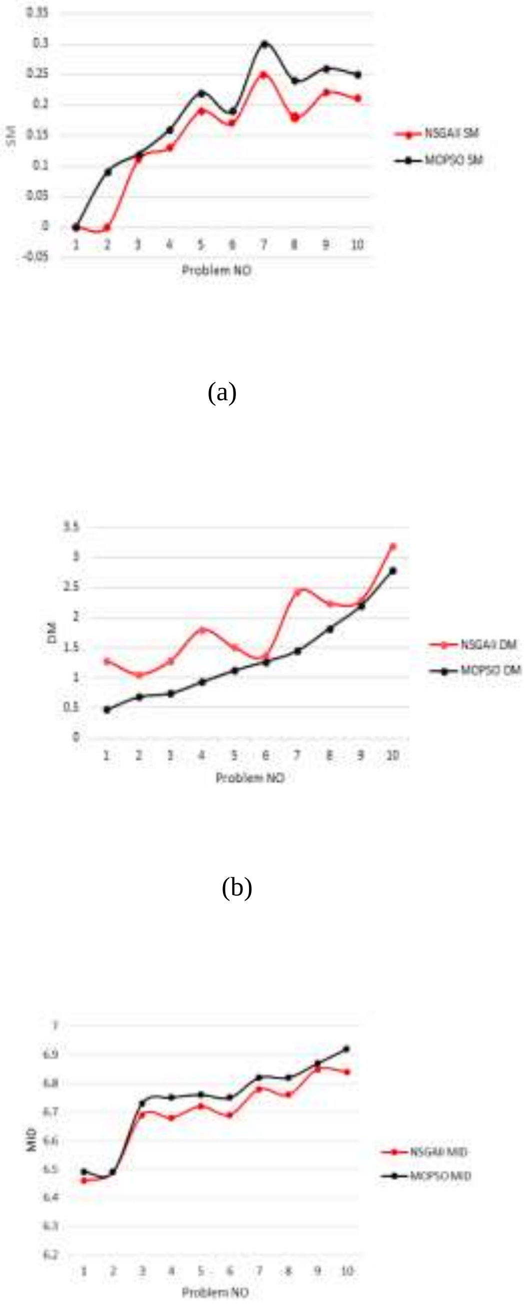
Interval Plot of NSGAII, MOPSO
95% CI for the Mean

(b)

Interval Plot of NSGAII, MOPSO
95% CI for the Mean

(c)

Fig 7. Interval plots for proposed algorithms according to the SM (a), DM (b), and MID (c) criterions



(a)

(b)

(c)

Fig 8. The result of comparing proposed algorithms according to the SM (a), DM (b), and MID (c)

B. Case study

In this section, an Iranian company is investigated as a real case study to validate the performance of the proposed MINLP model. Pooya Industrial Group is one of the largest chipboard manufacturing and distribution companies in Iran with different branches in the cities of Tehran, Isfahan, Mazandaran, Gilan, etc. At present, more than 40% of the Iranian market share is held by this industrial group. With a daily production capacity of 1400 m^2 of chipboard in accordance with international standards, this factory has the largest production capacity of chipboard in the Middle East and has the capability to produce all types of raw chipboard with the amount of formaldehyde released at the standard level of developed European countries. Two types of chipboard products with different dimensions and 6 wholesale customers were considered in this research. Also, 5 landfill stations, 8 recycling stations, 7 repair stations, 8 distribution stations, and hubs were considered for Pooya Industrial Group. Table V shows the amount of customers' demand in each period:

Table V. The fuzzy product demand amount in terms of tons

Customer/product		***Recession scenario***		***Customer/product***		***Prosperity scenario***	
		Demand of period 1	***Demand of period 2***			***Demand of period 1***	***Demand of period 2***
Customer 1	Product 1	(2920,3420,3920)	(2150,2650,3150)	Customer 1	Product 1	(7943,8443,8943)	(6306,6806,7306)
	Product 2	(2650,3150,3650)	(2250,2750,3250)		Product 2	(8087,8587,9087)	(6135,6635,7135)
Customer 2	Product 1	(3000,3500,4000)	(2650,3150,3650)	Customer 2	Product 1	(5430,5930,6430)	(7987,8487,8987)
	Product 2	(2605,3105,3605)	(2350,2850,3350)		Product 2	(7607,8107,8607)	(5514,6014,6514)
Customer 3	Product 1	(2450,3105,3605)	(2140,2640,3140)	Customer 3	Product 1	(8495,8995,9495)	(6371,6871,7371)
	Product 2	(1500,2000,2500)	(2400,2900,3400)		Product 2	(8157,8657,9157)	(6855,7355,7855)
Customer 4	Product 1	(3750,4250,4750)	(1600,2100,2600)	Customer 4	Product 1	(7859,8359,8859)	(4586,5086,5586)
	Product 2	(2180,2680,3180)	(2000,2500,3000)		Product 2	(4669,5169,5669)	(7891,8391,8891)
Customer 5	Product 1	(3600,4100,4600)	(3040,3540,4040)	Customer 5	Product 1	(5975,6475,6975)	(7940,8440,8940)
	Product 2	(3150,3650,4150)	(3140,3640,4140)		Product 2	(7219,7719,8219)	(5695,6195,6695)
Customer 6	Product 1	(2750,3250,3750)	(2500,3000,3500)	Customer 6	Product 1	(4503,5003,5503)	(5921,6421,6921)
	Product 2	(3000,3500,4000)	(2910,3410,3910)		Product 2	(4875,5375,5875)	(5766,6266,6766)

Table VI shows the cost of producing one unit of products in each period.

Table VI. The cost of producing one unit of the product c in the period t

Products	***Recession Scenario***		***Prosperity Scenario***	
	Production cost of period 1	***Production cost of period 2***	***Production cost of period 1***	***Production cost of period 2***
Product 1	٣٥٠٠٠٠٠	٣٨٠٠٠٠٠	٤٥٠٠٠٠٠	٤٢٠٠٠٠٠
Product 2	٥٦٠٠٠٠٠	٥٩٠٠٠٠٠	٦٤٠٠٠٠٠	٦٨٠٠٠٠٠

Table VII shows the cost of constructing the hub stations in the case study.

Table VII. The cost of constructing the hub station on the site m

Collection Station	***Recession Scenario***		***Prosperity Scenario***	
	Cost of Period 1	***Cost of Period 2***	***Cost of Period 1***	***Cost of Period 2***
Station 1	٧٥٠٠٠٠٠٠٠	٧٠٠٠٠٠٠٠٠	٧٥٠٠٠٠٠٠٠	٧٠٠٠٠٠٠٠٠
Station 2	٨٥٠٠٠٠٠٠٠	٨٠٠٠٠٠٠٠٠	٨٥٠٠٠٠٠٠٠	٨٠٠٠٠٠٠٠٠
Station 3	٩٠٠٠٠٠٠٠٠	٨٥٠٠٠٠٠٠٠	٩٠٠٠٠٠٠٠٠	٨٥٠٠٠٠٠٠٠
Station 4	٦٥٠٠٠٠٠٠٠	٧٥٠٠٠٠٠٠٠	٦٥٠٠٠٠٠٠٠	٧٥٠٠٠٠٠٠٠
Station 5	٦٧٠٠٠٠٠٠٠	٧١٠٠٠٠٠٠٠	٥٥٠٠٠٠٠٠٠	٦١٠٠٠٠٠٠٠
Station 6	٦٠٠٠٠٠٠٠٠	٧٠٠٠٠٠٠٠٠	٦٠٠٠٠٠٠٠٠	٧٠٠٠٠٠٠٠٠
Station 7	٨٣٠٠٠٠٠٠٠	٧٤٠٠٠٠٠٠٠	٨٣٠٠٠٠٠٠٠	٧٢٠٠٠٠٠٠٠
Station 8	٧٣٠٠٠٠٠٠٠	٦٩٠٠٠٠٠٠٠	٧٧٠٠٠٠٠٠٠	٧١٠٠٠٠٠٠٠

Table VIII shows the capacity of recycling stations.

Table VIII. The capacity of the recycling station at site p

Recycling Station	***Capacity in Period 1***	***Capacity in Period 2***
Station 1	١٥٠٠٠٠	١٠٠٠٠٠
Station 2	٢٠٠٠٠٠	٢٠٠٠٠٠
Station 3	١٠٠٠٠٠	١٠٠٠٠٠
Station 4	٣٠٠٠٠٠	٢٥٠٠٠٠
Station 5	٢٠٠٠٠٠	١٥٠٠٠٠
Station 6	٢١٠000	١٥٠000
Station 7	١٦٠000	١٢0000
Station 8	٣٢٠000	٢50000

C. The case study results

The results of solving the case study for one of the Pareto points are given in Table IX. It should be noted that according to the priority of the cost objective function for the studied company, the Pareto point with the best cost compared to other Pareto points was chosen. Table IX shows ten Pareto points for the case study. Given that the values of SM and MID indices are close to zero, one can say that the proposed solution approach has shown a suitable and acceptable performance.

Table IX. The results of solving the case study

NSGAII		***NO***
MID	***SM***	
٠,٢٢	٠,٠٥٥	١
٠,٢٤	٠,٠٦٠	٢
٠,٢٥	٠,٠٥٨	٣
٠,٢٣	٠,٥٦	٤
٠,٢٠	٠,٠٥٩	٥
٠,٢٦	٠,٠٦٣	٦
٠,٢٨	٠,٠٦٤	٧
٠,٢٢	٠,٠٥٥	٨
٠,٢٤	٠,٠٥٩	٩
٠,٢٥	٠,٠٥٨	١٠

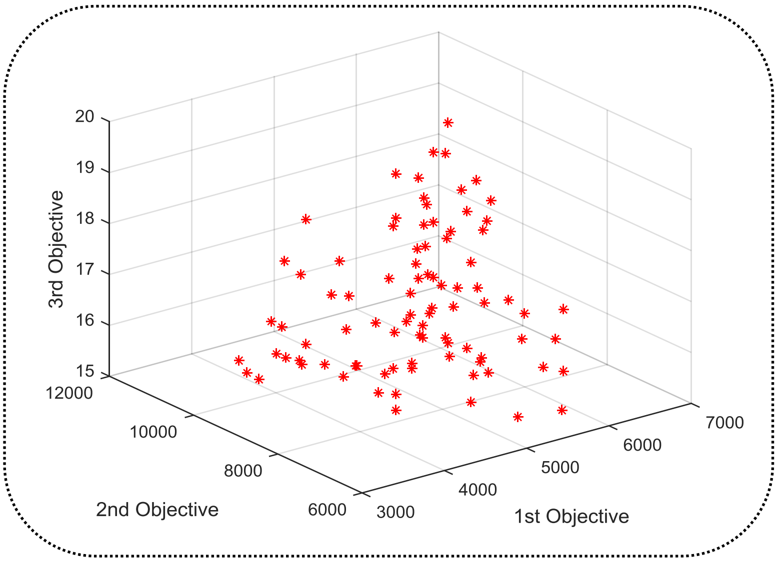


Fig 9. The Pareto points derived from the proposed mathematical model. Each dimension of the graph represents an objective function.

Table X shows the number of established stations in each scenario. As seen, the number of established stations in the prosperity scenario has been far greater than in the recession scenario. For example, in the recession scenario, 4 landfill stations, and 3 distribution stations have been established, while 5 landfill stations and 7 distribution stations have been established in the prosperity scenario. Figure 11 indicates that the number of established stations is greater in the prosperity scenario than in the recession scenario. According to this figure, the minimum difference is related to landfill stations; i.e., the number of active landfills is not much different in both recession and prosperity scenarios, which can be due to the lack of quality raw materials or the dispersion of these stations. The highest difference belongs to recycling stations; i.e., much more recycling stations are active in the prosperity scenario, which can be caused by inefficiency or aging of the production system.

Table X. The location values of stations

Recession Scenario						*Prosperity Scenario*					
Station No.	*Landfill station*	*Recycling station*	*Repair station*	*Distribution station*	*Hub*	*Station No.*	*Landfill station*	*Recycling station*	*Repair station*	*Distribution station*	*Hub*
١	١	١	٠	٠	١	١	١	٠	١	١	٠
٢	١	٠	١	١	٠	٢	١	١	١	١	١
٣	١	٠	٠	٠	١	٣	١	١	٠	١	١
٤	٠	٠	٠	٠	٠	٤	١	١	١	٠	١
٥	١	٠	٠	١	١	٥	١	١	١	١	١
٦	-	١	١	١	٠	٦	-	١	١	١	١
٧	-	٠	٠	٠	٠	٧	-	١	١	١	١
٨	-	٠	-	٠	١	٨	-	١	-	١	١

Table XI shows the amount of product flow from supply stations to production stations in kilograms. For example, supplier No. 1 respectively sends 85 kg and 110 kg of types 1 and 2 raw materials to manufacturer No. 1 in the recession scenario.

According to Figure 10, the amount of raw material flow to the production stations has been higher in the prosperity scenario than in the recession scenario, which seems a normal condition. The figure suggests the flow of raw materials to the stations is higher in the second period than in the first period in both prosperity and recession scenarios. This may be the result of factors such as eliminating some bureaucracies over time and establishing relative trust between the buyer and the seller of raw materials.

Table XI. The product flow values from supply stations to production stations in kilograms

(I,J)/(scenario, t)	*Recession scenario*				*Prosperity scenario*			
	Period 1		*Period 2*		*Period 1*		*Period 2*	
	Raw material 1	*Raw material 2*	*Raw material 1*	*Raw material 2*	*Raw material 1*	*Raw material 2*	*Raw material 1*	*Raw material 2*
(i1,j1)	٨٥	١١٠	٦٥٠	٤٨٥	١٦٢	٢٦٠	٩٣١	٥٦٤
(i1,j2)	-	-	٦٣٠	٥٠٠	٢٥١	٣٦١	٨٩٠	٧١٠
(i1,j4)	١٠٠	٩٠	٦٥٠	٦٥٠	٢٦٤	٣٦٤	٩٠١	٨٤٥
(i2,j2)	١٠٥	١٢٠	-	-	١٦٥	١٨٥	٢٠٩	٣٠٢
(i2,j3)	-	-	٤٣٠	٤٢٠	٣٦٢	٤١٠	٥٩٤	٦٧٤
(i3,j4)	٤٣٥	٤٤٠	٤٥٠	٦٤٠	٤٩٠	٥١٩	٨١٧	٧١٨
(i3,j5)	-	-	-	-	٢٦٨	٢٧٥	٣٥٦	٤٥٠
(i4,j1)	٢٤٠	٢٦٤	٦٥٠	٧٠٥	٢٩٨	٣١٠	٨٤١	٨٦٠
(i4,j4)	٤٠٨	٤١٠	٥١٠	٥٠٠	٥٣٠	٦٩٠	٧٩٠	٨١١
(i5,j1)	٣٩٥	٣٦٥	٤٦٠	٤١٠	٤١١	٥١٣	٦٩٠	٥٥٣
(i5,j3)	-	-	٦٠٠	٧٣٠	٤١٠	٤٦٥	٩٨٢	٨٤٠
(i5,j4)	٢٧٥	٢٢٠	٥٦٠	٥٠٠	٤٢٥	٣٨٩	٦٩١	٧٤١

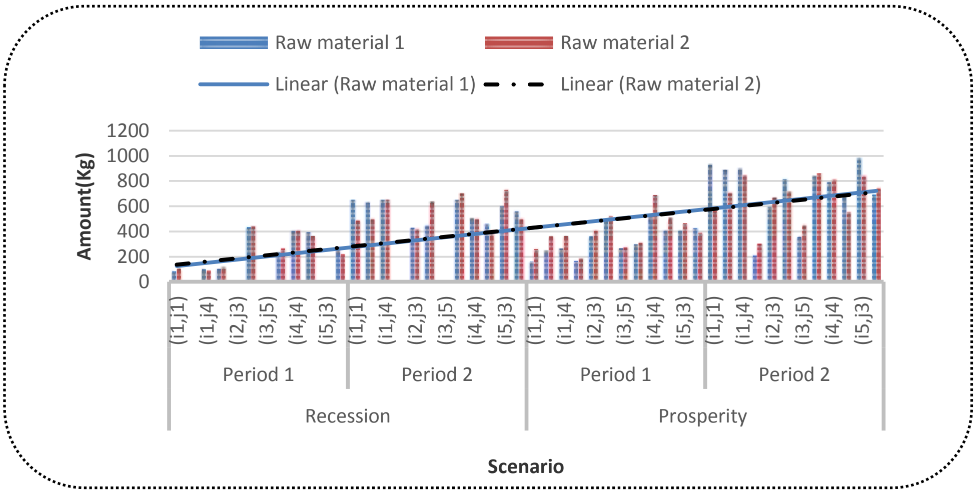


Fig 10. The product flow values from supply stations to production stations in each scenario

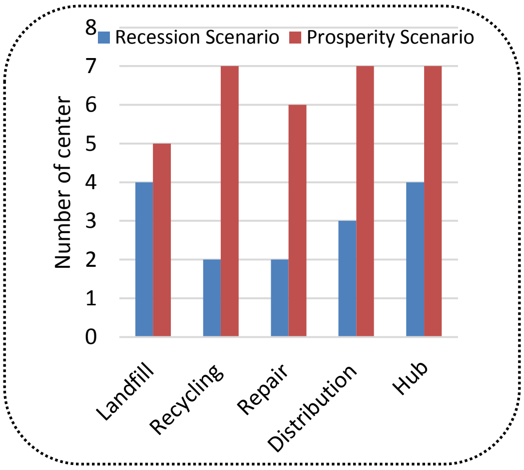


Fig 11. The number of established stations in each scenario

Table XII shows the flow amount of the returned products with different qualities. For example, hub number 1, in recession conditions, sends 368 kg of product 1 with quality 3 to the recycling station 1 and 141 kg to the recycling station 6. Based on the last row of this table, the highest rate of sending products from the hub stations has been to repair station 6 with a grade 1 quality. This may be due to the high sensitivity of quality control processes in hub stations. The lowest amount of products sent from hub stations belongs to production station 3 with a grade 2 quality.

Table XII. The flow amount of the returned product in the recession conditions

Hub-product/recycling, production, repair, and landfill stations	***Quality grade 3***		***Quality grade 2***			***Quality grade 1***			***Quality grade 4***		
	Recycling 1	***Recycling 6***	***Production 1***	***Production 2***	***Production 3***	***Repair 2***	***Repair 6***	***Landfill 1***	***Landfill 2***	***Landfill 3***	***Landfill 5***
Hub 1-Product 1	368	141	319	277	142	224	293	-	206	185	-
Hub 1-Product 2	437	-	232	388	439	-	370	130	155	433	109
Hub 2-Product 1	249	360	319	206	-	398	187	94	-	332	327
Hub 2-Product 2	-	153	213	378	-	310	402	291	-	108	171
Hub 3-Product 1	187	-	252	340	160	172	415	253	110	179	-
Hub 3-Product 2	96	438	140	348	-	355	341	372	384	225	371
Hub 4-Product 1	393	235	352	96	-	168	316	-	94	443	383
Hub 4-Product 2	-	261	411	365	160	323	177	251	143	295	367
Hub 5-Product 1	200	198	232	120	251	191	156	121	374	361	327
Hub 5-Product 2	188	396	125	236	-	121	333	310	230	204	387
Hub 6-Product 1	136	147	390	316	409	-	175	419	162	-	205
Hub 6-Product 2	418	368	-	226	110	340	401	-	405	97	406
Hub 7-Product 1	443	149	299	391	-	445	325	381	340	411	276
Hub 7-Product 2	146	163	343	306	443	301	343	347	182	94	377
Hub 8-Product 1	98	-	174	211	92	167	93	-	189	202	250
Hub 8-Product 2	317	-	169	277	-	352	374	98	450	122	-
sum	3676	3009	3970	4481	2206	3867	4701	3067	3424	3691	3956

Table XIII shows the results of the vehicle routing variable. As can be seen, there are 8 distributors and 6 customers associated with 20 vehicles in the case study. The numbers listed in Table XIII indicate the number of vehicles used. For example, vehicle No. 11 delivers the considered goods from distributor 1 to customer 1. According to Figure 12 and Table XIII, the number of vehicles allocated from distribution stations to customer stations is higher in the prosperity scenario. Also, according to the same figure, the number of vehicles allocated to distribution stations is more uniform in the prosperity scenario, which may result from employing more manpower in these stations in the prosperity scenario. According to Figure 13, the distribution of equipment brought into the customer stations is more uniform during the recession period, probably due to the cultural context of customer stations.

Table XIII. The routing of vehicles

	Scenario													
	Prosperity							***Recession***						
Distribution Station/Customer	***١***	***٢***	***٣***	***٤***	***٥***	***٦***	***Count***	***١***	***٢***	***٣***	***٤***	***٥***	***٦***	***Count***
١	11	14	8	12	9	-	5	5	10	-	8	5	-	4
٢	19	2	18	15	5	18	6	-	-	19	9	-	12	3
٣	14	11	3	12	13	1	6	9	8	-	1	11	-	4
٤	10	13	12	20	18	14	6	-	7	4	12	13	9	5
٥	20	4	15	1	15	10	6	15	1	10	-	9	6	5
٦	16	3	10	5	7	5	6	-	-	6	-	2	20	3
٧	6	13	18	10	12	8	6	4	11	16	6	9	4	6
٨	12	-	16	17	-	6	4	6	-	14	12		-	3
Count	8	7	8	8	7	7	Count	5	5	6	6	6	5	

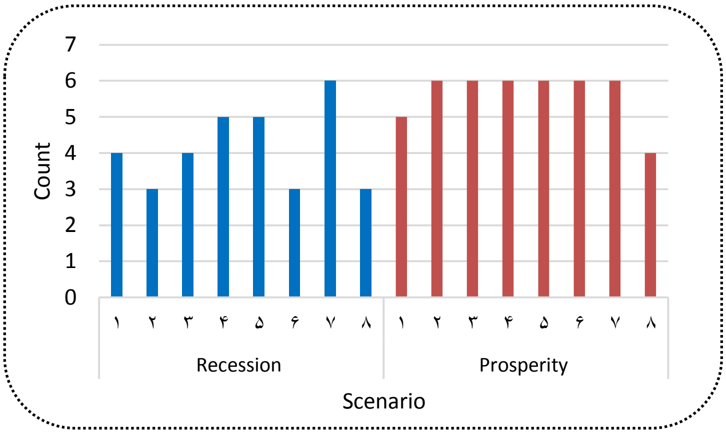


Fig ۱۲.The number of vehicles assigned to each distribution station in each scenario

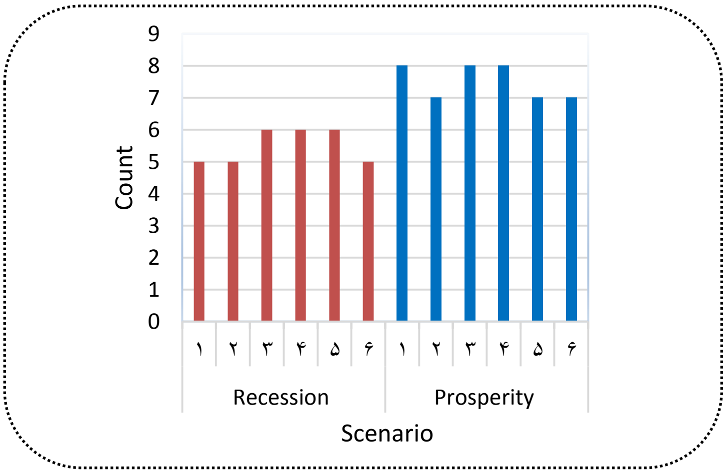


Fig 13. The number of vehicles arrived at each customer station in each scenario

D. The sensitivity analysis of the results of the case study

Impact of sensitive parameters of the model on objective functions is investigated in this section. Figure ۱۴ shows the changes in the demand rate versus the first objective function in the recession and prosperity scenarios. As observed, the job creation rate, customer satisfaction levels, and the number of production stations rise with the increased demand rate. According to this figure, in general, the growth rates of job creation, customer satisfaction, and production stations follow a faster trend in the prosperity conditions than in the recession conditions. This implies that the social dimension is more sensitive to changes in demand in the recession state and the rise in the demand rate leads to the growth and strengthening of this dimension after sustainability. According to Figure ۱۵, the SC costs also increase with increasing the demand rate. The SC costs have been higher in the prosperity scenario than in the recession conditions as well. As the demand rate increases, so does environmental damage. A glance at Figure 15 reveals that the rise in demand rate has a lower effect on the SC costs in the prosperity conditions. However, in general, the economic dimension (SC stability) shows less sensitivity to changes in the demand rate during the recession period. According to Figure 16, the increased demand rate leads to further environmental damages in both scenarios. These damages are more in the prosperity state than in the recession state. Also, according to this figure, with increasing demand, these damages grow with a higher slope in the prosperity conditions, suggesting that the environmental dimension is more sensitive to changes in demand during the prosperity period. Figure ۱۷ displays the effect of increasing and decreasing the capacity rate of all the established stations on the first objective function. As shown by this figure, as the rate of capacity increases, the rate of created jobs, customer satisfaction, and the number of production stations will increase. Accordingly, the control and transportation mostly occur between the established stations. Also, the growth rate of the first objective function is found to be faster in the prosperity mode than in the recession mode. For example, a 30% increase in the capacity of the stations will increase the employment rate to 10982 units in a prosperity state and up to 8910 units in a recession mode. According to Figure ۱۸, as the capacity rate of established stations increases, so do the costs and this increase follows a faster trend in the recession mode. Moreover, as this rate rises, the costs gradually remain constant. This occurs due to the fact that the number of established stations decreases with the increased capacity rate of other stations, which minimizes the costs of establishment. According to Figure ۱۹, the environmental pollution level increases with the increased capacity rate of the established stations. This pollution is more in the prosperity mode than in the recession mode.

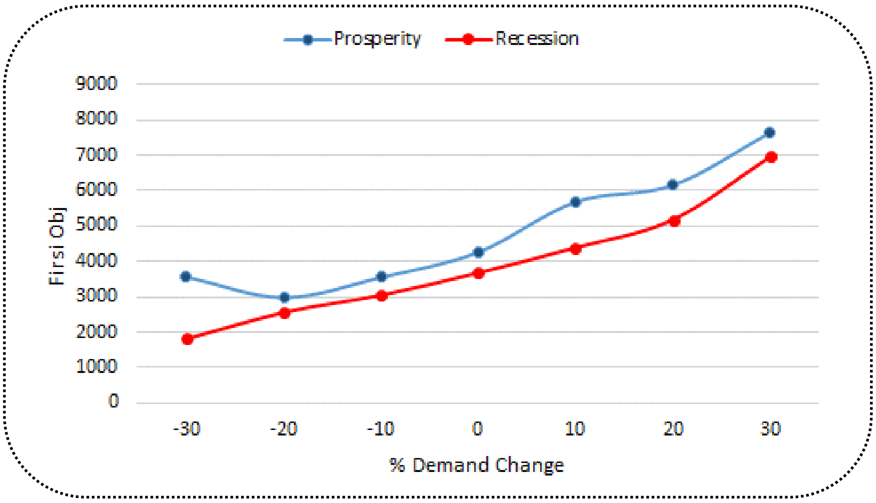


Fig ۱٤. The effect of changes in demand rates on the first objective function

Fig 15. The effect of changes in demand rates on the second objective function

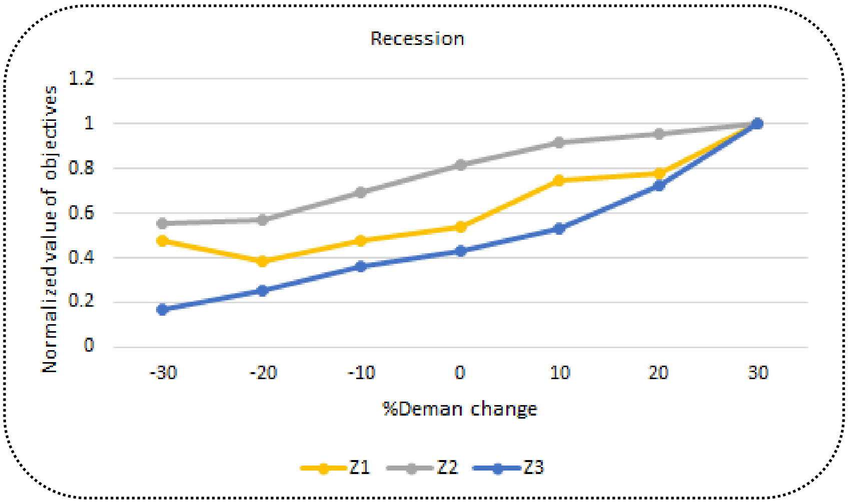


Fig 16. The effect of changes in demand rates on the third objective function

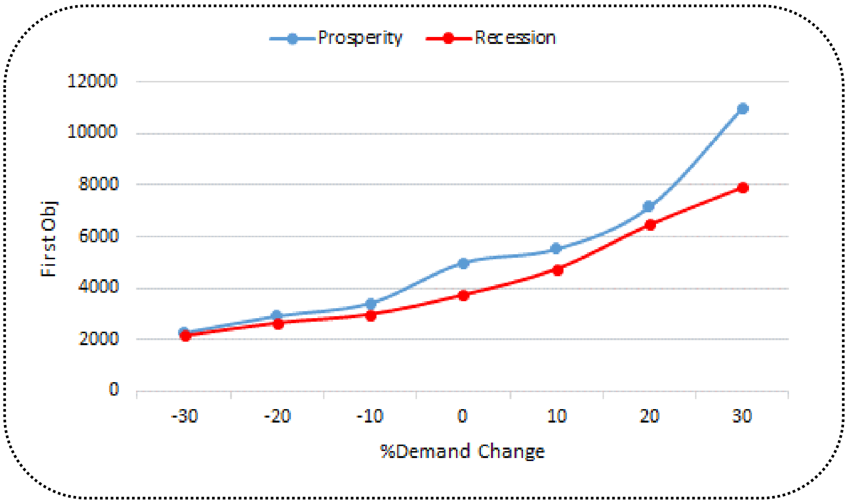


Fig 17. The effect of changes in the capacity rate of all potential stations on the first objective function

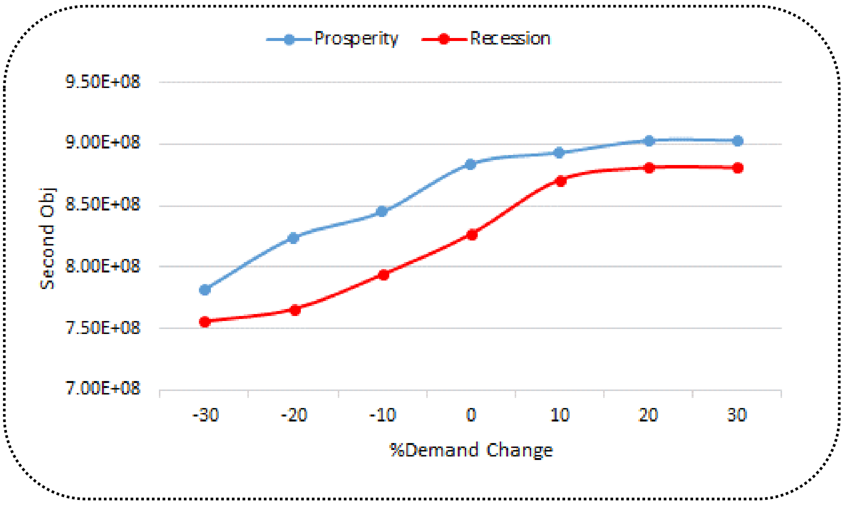


Fig 18. The effect of changes in the capacity rate of all potential stations on the second objective function

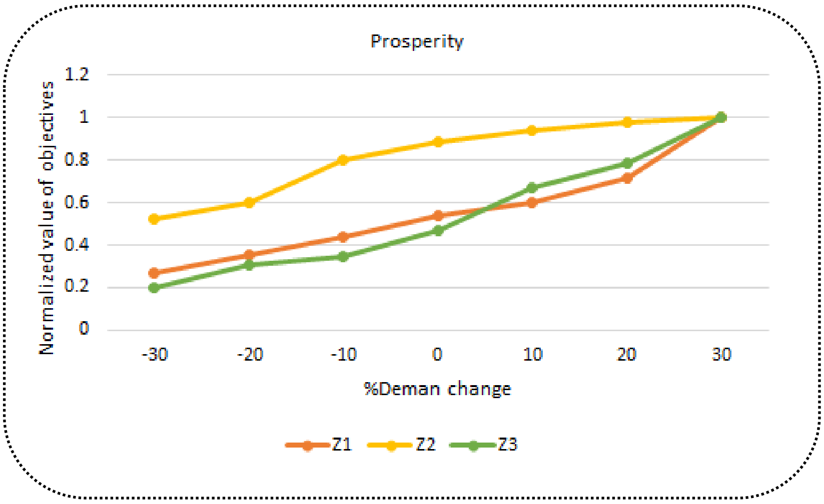


Fig 19. The effect of changes in the capacity rate of all potential stations on the third objective function

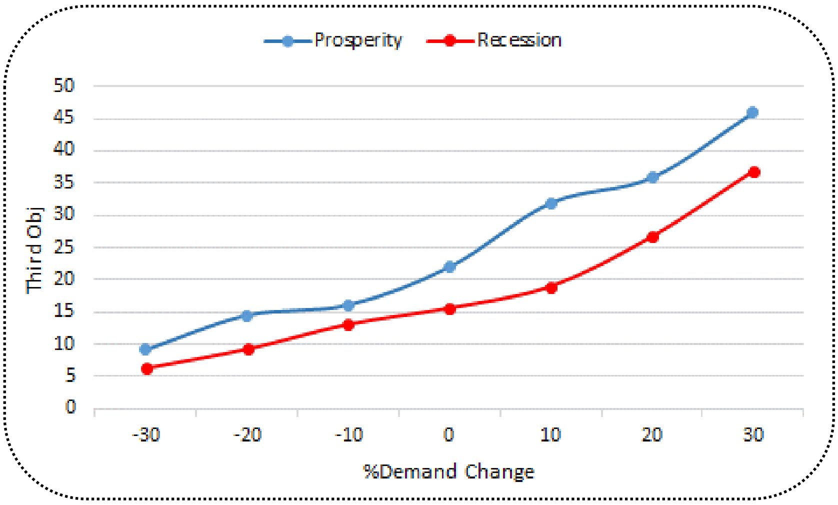


Fig 20. The effect of changes in demand rates on the all objective functions in recession mode

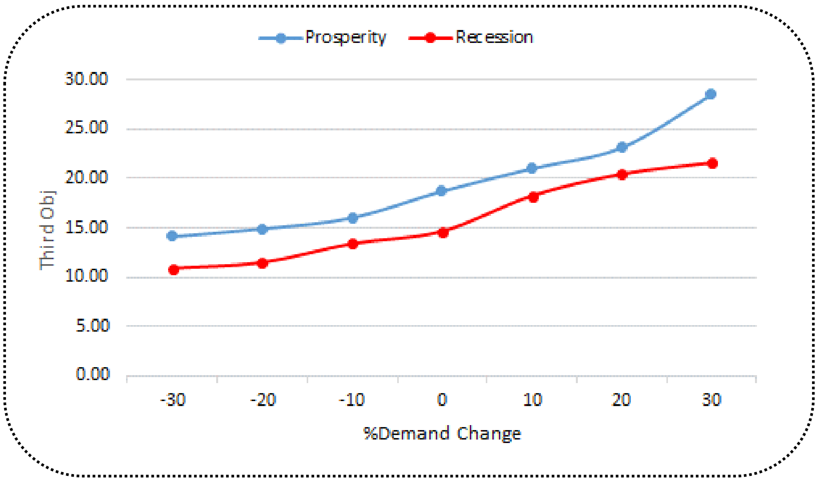


Fig 21.The effect of changes in demand rates on the all objective functions in prosperity mode

The normalized values have been used for the sensitivity analysis of the objective functions. According to Table XIV and Figure 20, in general, the dimension of social responsibility (Z1) shows the highest rate of sensitivity to changes in demand rate in the recession conditions. According to this figure, the cost dimension (Z2) follows a decreasing trend the environmental dimension (Z3) is on the rise. In the Prosperity conditions, according to Table XIV and Figure 21, the cost dimension (Z2) has the lowest sensitivity to changes in demand, and social responsibility (Z1) and environmental responsibility dimensions (Z3) are on the rise.

Table XIV. The values of normalized objective functions based on the percentage of changes in demand

Objective	***Scenario***	***Demand change***						
		-30	***-20***	***-10***	***0***	***10***	***20***	***30***
Z1	Recession	0.48	0.38	0.48	0.54	0.75	0.78	1.00
	Prosperity	0.27	0.36	0.44	0.54	0.60	0.72	1.00
Z2	Recession	0.56	0.57	0.69	0.82	0.92	0.95	1.00
	Prosperity	0.52	0.60	0.80	0.89	0.94	0.98	1.00
Z3	Recession	0.17	0.25	0.36	0.43	0.53	0.72	1.00
	Prosperity	0.20	0.30	0.35	0.47	0.67	0.78	1.00

VII. MANAGERIAL IMPLICATIONS

The Outputs provide multiple and different insights to managers to make the right decisions and help them make future decisions. The most important influential parameter is the market situation. Whether the market is in a state of stagnation or boom would dramatically affect the type of strategy and decision-making by decision-makers. For example, the figure and table indicate that, in general, the cost and environmental effects dimensions are less sensitive to changes in demand than the responsibility dimension in the recession scenario.

VIII. CONCLUSION AND FUTURE DIRECTIONS

A. Conclusion

In this paper, a novel multi-objective, multi-period, multi-product scenario-based fuzzy mathematical model was first developed for the CLSC, in which direct logistics elements were subject to random failures. These failures were assumed to occur due to natural disasters, terrorist attacks, ownership change, labor mistakes, weather conditions, and so on. The quality of the products returned by the customers and routing of the flow of goods in the SC were considered in the proposed model in addition to the three aspects of sustainability, namely the social, economic, and environmental impacts. The social responsibility dimension includes job creation rate, customer satisfaction, and distribution stations. The economic dimension encompasses the cost of the SC, and the environmental dimension includes the amount of CO2 emissions. The demand parameter was considered fuzzy in this network. The proposed model was solved in small and medium scales using the Epsilon constraint approach and NSGAII and MOPSO algorithms. Since the problem was NP-Hard, the duration of solving the problem by the Epsilon constraint approach increased exponentially by increasing its dimensions. Three criteria of MIS, DM, and SM were used in this study to compare the two proposed metaheuristic algorithms after tuning their parameters by the Taguchi method aimed at evaluating their performance. All three criteria showed the superiority of the NSGAII algorithm. In order to evaluate the performance of the model, the model was implemented on Pooya Chipboard Company in Iran in two recession and prosperity scenarios, which results demonstrated the efficiency and usefulness of the proposed model. The results of the sensitivity analysis of the change in the demand rate on the objective functions revealed that their values will also enhance with increasing the demand rate. By increasing the capacity rate of all the stations that could be established, the rates of jobs created, customer satisfaction, and distributive stations increased with a relatively steep slope, which also increased the environmental pollution.

B. Limitations and future research directions of the study

The model proposed in this paper can be developed in future research by considering several decision-makers in the network and the use of the concept of the game. The robust planning approach can be also used to deal with the SC uncertainty, making the model more powerful and flexible in the face of uncertainty. the financial risk can be added to the model. In order to make the proposed model more reliable, it can be established so that changes in uncertain parameters have less effect on the answers obtained from the model output. Also, instead of the exponential distribution assumed to model the reliability of the direct logistics elements, other probability distributions such as Erlang or Weibull can be considered. Multiple financial, environmental, and social goals combined with dynamic constraints can provide more effective and practical solutions.

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