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Designing a green closed-loop supply chain network for the automotive tire industry under uncertainty

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Abstract

The last decade has seen numerous studies focusing on the closed-loop supply chain. Accordingly, the uncertainty conditions as well as the environmental impacts of facilities are still open issues. This research proposes a new bi-objective mixed-integer linear programming model to design a closed-loop supply chain tire remanufacturing network considering environmental issues that improve performance in conditions of uncertainty associated with the tire industry. This model seeks to maximize the total profits of the network, including customer centers, collection centers, recycling centers, manufacturing/remanufacturing plants, distribution centers, and on the other hand, is looking to minimize environmental impact all over the supply chain network. Another novelty of the proposed model is in the solution methodology. By using an exact approach, the augmented ε-constraint method, and meta-heuristic algorithm, a well-known Grasshopper Optimization Algorithm (GOA), optimal and Pareto solutions have been obtained for medium and large size sample problems. We analyze the effectiveness of these meta-heuristics through numerical experiments. Also, sensitivity analysis has been provided for some parameters of the model. Finally, the results and suggestions for future research are presented.

Keywords: closed-loop supply chain, fuzzy mathematical programming, bi-objective optimization, grasshopper optimization algorithms, augmented epsilon constraint, tire industry

1-Introduction

As a crucial planning problem, the supply chain network design (SCND) determines the physical structure and infrastructure of a supply chain (Melo, Nickel, & Saldanha-Da-Gama, 2009). Recently the reduction of impacts made by humans has attracted more attention because of growing environmental impacts and their significant role in human life. Green supply chains are among the most effective subjects' related to environmental impacts, an increased number of studies in this area verifies this opinion. A green supply chain means a supply chain that considers at least one of its strategic decisions to protect the environment. Due to the increasing competition patterns and public awareness of environmental issues, some industries are using environmental considerations as a competitive advantage (Thierry, Salomon, Van Nunen, & Van Wassenhove, 1995). Hence, many researchers have studied reverse logistics (RL). The logistics activities entirely from used products, which are returned by end-users, to again usable in a market is defined as reverse logistics (Fleischmann et al., 1997). Forward and reverse logistics integration leads to a closed-loop supply chain (CLSC) network.

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Closed loops are durable products that cannot be destroyed in the short term and can be reused in the production of new products, recycled or sold in the secondary market, despite the fact that traditional Forward Logistics (FL), CLSC networks usually are more complex networks (Melo et al., 2009).

The most important strategic decisions in the supply chain are to design the network efficiently (Dai & Zheng, 2015; Khalifehzadeh, Seifbarghy, & Naderi, 2015; Ramezani, Kimiagari, Karimi, & Hejazi, 2014). The decision-maker (DM) can consider several factors to designing a closed-loop supply chain network more efficiently, such as costs, governmental regulations, CO_2 emissions, operational risks and disruption, social dimensions, uncertainty in the parameters, reliability of the network, and etc. The lack of precise and accurate information and the dynamics and complexity of supply chain components can be attributed to uncertainty in the parameters, which is probably posing a major challenge to the SCND (Tehrani & Gupta, 2021). This is so important that the output of the model in both deterministic and non-deterministic conditions, in addition to being different, can also change the CPU solution time (Ghasemzadeh, Sadeghieh, Shishebori, & Sustainability, 2021) **.**

In this study, we tried to design the Green Closed-loop Supply Chain (GCLSC) network for the automotive tire industry under the uncertainty of some parameters. There is an average of 50 to 65 thousand tons of used tire varieties in Iran. Unfortunately, a very small percentage of them are in the recycling and retreading cycle. So, paying attention to the tire retreading industry can make significant savings in the country's resources, and in addition, the environment can be protected from the current pollution in this industry. One of the challenging tasks in a value chain for the tire industry is the management of new tires and the utilization of used tires as well as synchronization of the front and reverse logistics networks. Therefore, a suitable logistics network for this type of industry is necessary. Currently, there are three ways for tire recycling: 1- the manufacturer is responsible for recycling, 2- the manufacturer outsources the recycling to retailers (manufacturer does not play a role), and 3- third-party logistics is responsible for recycling (manufacturer role is insignificant in this way but not zero) (Ran and Yin, 2021). In addition to recycling, tire retreading or remanufacturing is another choice for recovering tires in Iran. Retreaded tires can be used in different vehicles such as cars and trucks. Due to both price and using environmentally responsible aspects, tire remanufacturing is popular. The price of a retreaded tire is 40% to 50% of the brand-new tires. The quality of the remanufactured tire is almost equal to the quality of the new one. In Iran, used tires are of great importance due to the boom in road transport, which accounts for 80% of the country's transportation and also the poor quality of tires produced, and then the tires get out of the consumption cycle very quickly. The purpose of this study is to present a Green Closed-loop Supply Chain Network model for the automobile tires industry under uncertainty. According to the literature review, none of the earlier studies has examined the tire closed-loop supply chain network with considering uncertainty in all parameters such as demand, rate of returned tires, rate of recoverable products, and so on.

This study proposes a bi-objective mathematical model that considers two indispensable dimensions of a green closed-loop supply chain (exhaust gases and supply chain profit) and considers tire manufacturing/remanufacturing CLSC network configuration. To the best of our knowledge, this research is the first investigation that can be considered the effects of uncertainty in all parameters, especially the rate of returned products in the tire CLSC network. This way, questions that should be addressed in this research are as follows:

- Which manufacturing/remanufacturing plants, distribution centers, collection centers, and recycling centers should be opened?
- How many products exist in each part of the network?
- How many raw materials are purchased from each supplier?

To answers the above questions, this study will be developed a mixed-integer linear programming model to design and optimize a tire closed-loop supply chain network. The objective function maximizes the total profit and minimizes exhaust gases.

The remainder of the paper is organized as follows. We present a review of the relevant literature in section 2, and propose a bi-objective mixed-integer linear programming model in section 3. The proposed solution approach to solve the problem is outlined in section 4, and the numerical results obtained from solving medium size and large size problems have been presented along with sensitivity analysis for important model parameters in section 5. Finally, conclusions have been summarized in section 6.

2-Literature review

In recent years, many articles have been published on the closed-loop supply chain (CLSC) and reverse logistics (RL). In fact, the profit of collecting and recycling the products leads to research on them (Devika, Jafarian, & Nourbakhsh, 2014). With regard to environmental concerns, the design of logistics networks in various industries requires the consideration of facilities for the return of End-of-life products and recycling of them in other industries. According to the U.S. Environmental Protection Agency (EPA) report, world demand for tires is increasing 4.1 percent per year and reaches to 3.0 billion units in 2019 (Amin, Zhang, & Akhtar, 2017). Hence, the economic design of the tire supply chain network became an important issue for both academics and practitioners (Stadtler, 2015). Ferrer (1997) explained generic supply chains of tires. Also, he reviewed the tire retreading process and reviewed the value-adding operations. He offered suggestions for selecting the number of times the tire was retread. In 2009, the mathematical model to probe the tire supply chain was introduced by (Kannan, Noorul Haq, & Devika, 2009). They developed a CLSC system for tires and plastic via Mixed Integer Linear Programming (MILP). In addition, an RL system for the tire supply chain was addressed by (Sasikumar, Kannan, & Haq, 2010) for the truck tire remanufacturing process.

This study attempts to design and optimize the Closed-Loop supply chain network in the tire industry. Some papers have been published in the relevant literature, such as (Amin et al., 2017; Fakhrzad & Goodarzian, 2019; Fathollahi-Fard, Hajiaghaei-Keshteli, & Mirjalili, 2018; Mohammadi, Alemtabriz, Pishvaee, & Zandieh, 2020; Subulan, Taşan, & Baykasoğlu, 2015; Yadollahinia, Teimoury, & Paydar, 2018). Subulan et al. (2015) published an article on a case study of tire remanufacturing in Turkey. They used a Fuzzy Mixed Integer Programming (FMIP) by a fuzzy solution approach to address their CLSC optimization model. Amin et al. (2017) designed and optimized the tire closed-loop supply chain network. They formulated the problem as a mixed-integer linear programming model. Their model is employed in the design of a real network in Toronto, Canada. Fathollahi-Fard et al. (2018) developed a tri-level programming model to design the location-allocation of the tire CLSC for the first time. They formulated the model on the static Stackelberg game between tri-level in the framework of CLSC. Yadollahinia et al. (2018) designed tire forward and reverse supply chain. A novel idea of their study was integrating customer relationship management (CRM) concepts into their mathematical modeling framework. Since customer segmentation is the fundamental essence of the CRM, they categorized the customers into three types. In addition, their model is employed in the design of a real network in Mazandaran, Iran. Fakhrzad and Goodarzian (2019) proposed a model for a green closed-loop supply chain (GCLSC). Also, a multi-objective Mixed Integer Linear Programming formulation is developed to minimizing the total costs, and the gas emissions costs due to vehicle movements between centers and maximizing the reliability of delivery demand due to the reliability of the suppliers. As an innovation, they developed their GCLSC model by considering resuscitation and recycle simultaneously. Mohammadi et al. (2020) presented a multi-stage stochastic programming model for sustainable closed-loop supply chain network design with considering financial and risk decisions. The parameters of the rate of return (on investment and debts) and customers' demand have been considered under uncertainty into closer to reality. Also, their model is employed in a case study of a plastic production and recycling supply chain network.

Fazli-Khalaf, Naderi, Mohammadi, Pishvaee, and Sustainability (2021) designed a tire closed-loop supply chain network that is resilient to supply-demand disruptions in addition to being sustainable. To immune network against disruptions, the authors maximize customers' demand by incorporating the new concept of maximum coverage while there are distance-based limitations. This model is based on a real case in Iran, which examines four gaps in the literature in order to optimize four objective functions, including minimizing the total costs and CO_2 emissions, maximizing the operational reliability of facilities, and the social responsibility of the network. Also, in this research, a mixed fuzzy possibilistic-flexible programming method has been used to deal with uncertainties. Like the Fazli-Khalaf et al. (2021) paper, Mehrjerdi and Shafiee (2021) developed the tire CLSC network by incorporating the concepts of sustainability and resilience, But they achieve this goal in entirely different ways. First, the authors asked academic experts to identify the impacts of supply chain's strategies on the resilience criteria in linguistic variables. Then, by using the fuzzy TOPSIS method, considered two criteria of information sharing and multiple sourcing as the main resilience criteria. Then they formulated a mixed-integer programming model by considering two criteria with sustainable goals simultaneously. The real data of the Barez factory located at Kurdistan State in Iran was applied to validate the model and the results indicate that the level of the network's response to customer needs has improved.

In table 1, some CLSCs papers have been categorized based on multi-period, multi-product, multi-objective, uncertainty, sources of uncertainty, financial factors, type of product, and environmental issues. Also, in order to show the difference between this study and other researches, the classification of the related literature is illustrated in table 1.

Some authors have considered CLSC networks under uncertainty. Francas and Minner (2009) studied the network design problem of a firm that manufactures new products and remanufactures returned products in its facilities. They examined the expected performance and capacity decisions of two alternative manufacturing network configurations when both returned flow, and demand are uncertain. Demirel, Özceylan, Paksoy, and Gökçen (2014) developed the model by using a genetic algorithm approach with fuzzy and crisp objectives. Subulan et al. (2015) considered more sources of uncertainty in the model, including demand, return, and disposal rate. We observe that a few authors have considered more than three sources of uncertainty at the same time in CLSCs.

In the CLSC network configuration, a few authors have considered financial factors. Ramezani, Kimiagari, and Karimi (2014) proposed a financial approach to the CLSC network model. They included fixed and current assets and liabilities and a set of budgetary constraints in the model. However, they have not been considered uncertainty in the model. Cardoso, Barbosa-Povoa, and Relvas (2016) developed a mixed-integer linear programming (MILP) model that integrates financial risk measures in a CLSC network. They used the ε-constraint method to solve the optimization problem. Pishvaee, Yousefi, and Engineering (2019) used scenario-based stochastic programming to deal with the uncertainty of demand and rate of return products. They develop a mathematical model that simultaneously focuses on optimizing the financial and physical flows in an integrated manner and uses the financial ratios in the form of a closed loop supply chain. In Mohammadi et al. (2020) paper, financial decision-making involves a sequence of decisions to react to outcomes that evolve overtime periods have been considered. Financial decisions are related to both investment and loan. Also, they considered various investment alternatives for a corporate, which is making decisions on the SCND problem. Mohtashami, Aghsami, and Jolai (2020) design a bi-objective NLP model for green supply chain with forward and reverse logistic consideration to optimize transportation fleets' network's transportation and waiting time. The network includes supplier, production system, distribution center, repair center, recycling center, disposal center, and collection center. Used products are collected from customers at the collection center and transferred to other centers based on their type. The authors employed queuing systems in the proposed supply chain to reduce environmental impacts and energy consumption of transportation fleets by determining loading. Since a sufficient number of servers are available in unloading centers, no queue will exist there. Moghadas Poor, Jabalameli, Bozorgi-Amiri, and Engineering (2020) proposed a multi-period, multiproduct, bi-objective mathematical model to design a closed-loop supply chain network in the tire industry concerning sustainability factors (economic and social) under the third-party logistics management. Their model aims to maximize profits from different processes and maximize the purposes of social sustainability.

Recently Ran and Yin (2021) presented the impact of government subsidies on automobile tire recycling in a dual-channel closed-loop supply chain at the International Conference on Mechanics and Civil, Hydraulic Engineering (CMCHE) which was held on 4th-6th June 2021 in Kunming, China. Because of the problems of recycling waste, especially automobile tires, in China, they see the role of government subsidies as a solution to the process of recycling automobile tire waste to address the severe environmental pollution and resource shortages that China's economy has recently faced. This study is mainly from a two-channel supply chain and has two models, the first model is without government subsidy and the second one with government subsidy. It is assumed that there is a relationship between the manufacturer and the retailer of Stackelberg games, and both of them are decided to maximize the profit. In this game, the manufacturer and the retailer are the leader and the follower, respectively. Both of them are risk-neutral and have exactly the same information. The results of this study show that government subsidies increased total profits and demand for tires as well as reduced the impact of their waste on the environment.

Several articles have been published about CLSC networks configuration (Abbey, Meloy, Guide Jr, & Atalay, 2015; Alimoradi, Yussuf, Ismail, & Zulkifli, 2015; Amin & Zhang, 2013; Bottani, Montanari, Rinaldi, & Vignali, 2015; K. Das & Posinasetti, 2015; Hashemi, Chen, & Fang, 2014; Karimi, Ghezavati, Damghani, & Engineering, 2015; Moghaddam, 2015a, 2015b; Rezaei et al., 2021; Mohajeri & Fallah, 2016; Özceylan, Paksoy, & Bektaş, 2014; Ruimin, Lifei, Maozhu, Peiyu, & Zhihan, 2016; Zohal & Soleimani, 2016), recently (Fakhrzad & Goodarzian, 2019; Fathollahi-Fard et al., 2018; Moghadas Poor et al., 2020; Mohammadi et al., 2020; Pishvaee et al., 2019; Rad & Nahavandi, 2018; Moghadam et al., 2021). Most of the publications in the CLSC field have focused on general networks and locations based on random numbers. Based on the literature review and the associated summarization in table 1, it is evident that modeling the problem of a multi-period, multi-product, and multi-level closed-loop supply chain for the automotive tire industry with considering environmental issue could be an interesting and relevant research topic. This study follows to provide a solution for the proposed model considering the concerns of the environmental impacts of a green supply chain. This model includes some of the customer centers, collection centers, recycling centers, manufacturing/remanufacturing plants, and distribution centers.

We propose a fuzzy multi-objective programming approach to formulate a green closed-loop supply chain network design problem under an uncertain environment. Subsequently, fuzzy multi-objective programming is used to solve the proposed model. This approach would dominate other approaches used in previous studies owing to its use of fuzzy numbers for discrete distributions and stochastic variables for continuous distributions to deal with uncertainties. Also, in the model presented, transportation costs, manufacturing, and remanufacturing operations, distribution coefficientsCO_2, return rates, used product collection and recovery, facility capacity are considered fuzzy due to the nature of the uncertainty in the real world.

Table 1. Summary of the literature review

Authors	Uncertainty	Sources of uncertainty	Financial factors	Multi-period	Multi-product	Multi-Objective	Type of product	environmental issue
(Fleischmann et al., 1997)							Copier, Paper	✓
(Francas & Minner, 2009)	✓	Demand, Return			✓			
(Kannan et al., 2009)				✓			Tire	✓
(Sasikumar et al., 2010)				✓			Tire	
(Shi, Zhang, Sha, & Amin, 2010)	✓	Demand, Return			✓			
(Amin & Zhang, 2012)					✓		Computer	
(Amin & Zhang, 2013)	✓	Demand, Return			✓	✓	Copier	✓
(Ramezani, Bashiri, & Tavakkoli-Moghaddam, 2013)	✓	Return, Cost Price		✓	✓	✓		
(Demirel et al., 2014)			✓	✓	✓	✓		
(Mirakhorli, 2014)	✓	Demand, Return				✓	Bread	
(Ramezani, Kimiagari, & Karimi, 2014)			✓	✓				
(Zeballos, Méndez, Barbosa-Povoa, & Novais, 2014)	✓	Demand, Supply		✓	✓			✓
(Subulan et al., 2015)				✓	✓	✓	Tire	✓
(Accorsi, Manzini, Pini, & Penazzi, 2015)					✓	✓		✓
(Keyvanshokooh, Ryan, & Kabir, 2016)	✓	Demand, Return		✓				
(Cardoso et al., 2016)	✓	Demand	✓	✓	✓	✓		
(Qiu & Wang, 2016)	✓	Demand, Supply	✓				Tea	
(Gaur, Amini, & Rao, 2017)			✓	✓			Battery	
(Amin et al., 2017)	✓	Demand, Return	✓	✓	✓		Tire	✓
(Nakao, Shen, & Chen, 2017)	✓	Demand						
(Rad & Nahavandi, 2018)			✓	✓	✓	✓		✓
(Fathollahi-Fard et al., 2018)	✓	Demand			✓		Tire	
(Yadollahinia et al., 2018)	✓	Demand, Capacity		✓	✓	✓	Tire	
(Fakhrzad & Goodarzian, 2019)	✓	All parameters	✓	✓	✓	✓		✓
(Fattahi, 2020)	✓	Demand		✓	✓			
(R. Das, Shaw, & Irfan, 2020)	✓	Demand, Capacity						✓
(Mohammadi et al., 2020)	✓	Demand, Return	✓	✓	✓	✓	Plastic	
(Mohtashami et al., 2020)	✓					✓		✓
(Fazli-Khalaf et al., 2021)	✓	All parameters	✓			✓	Tire	✓
(Mehrjerdi & Shafiee, 2021)			✓		✓	✓	Tire	✓
(Ghasemzadeh et al., 2021)	✓	Demand, Return & Raw material	✓	✓		✓	Tire	✓
(Ran & Yin, 2021)			✓				Tire	✓
(Tehrani & Gupta, 2021)	✓	Return & Recycle & Retread	✓		✓	✓	Tire	✓
This study	✓	**All parameters**		✓	✓	✓	**Tire**	✓

3-Problem explanation

3-1-Problem definition

According to figure 1, which shows the closed-loop supply chain network in this study, forward and reverse direction have four and three levels, respectively, i.e., suppliers, manufacturing plants, distribution centers, and customer centers in the forward direction, and in the reverse direction, collection centers, recycling centers, and remanufacturing centers are considered.

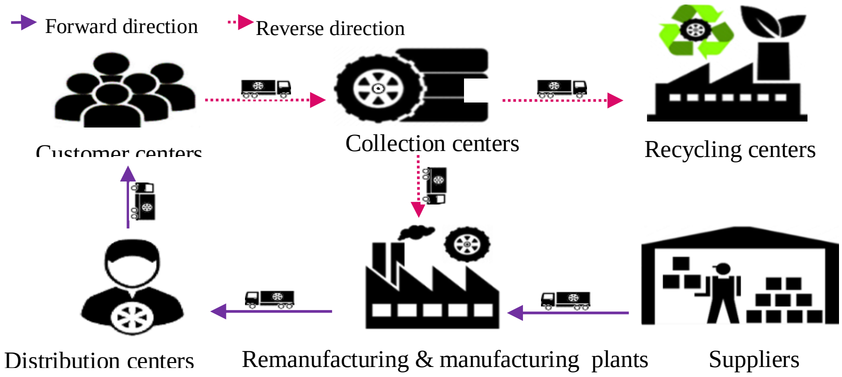


Fig 1. Automotive tire industry closed-loop supply chain network

In the forward direction, it is assumed that suppliers provide the raw material for the manufacturer. The manufacturer can manufacture and remanufacture the tires. The new tires or remanufactured tire are sent to distribution centers by the manufacturer. Then, customers purchase the tires. In the reverse direction, used tires are collected from customer centers. In fact, collection centers have to collect used tires from customer centers; in the collection centers, many inspections are executed for determining that the used tires are recoverable or not. Recoverable used tires are sent to manufacturing plants, and unrecoverable tires are sent to recycling centers to turn into raw materials for use in other industries, this strongly depends on the quality of the returned tires.

We aim to determine the location and number of facilities in each layer, the flow of tires between the facilities of each layer, the quantities of the produced tires by manufacturer, and the amount of purchased raw material from suppliers. The network will be the development of a complex integer linear programming problem. This study proposes a bi-objective mathematical model that takes into account two indispensable dimensions of a green closed-loop supply chain (exhaust gases and supply chain profit). The purpose of this model is to maximize the total profit in the CLSC network and minimize exhaust gases to achieve the best structure for the green closed-loop network by determining the location and number of facilities in each echelon and the amount of flow of tires between the facilities of each echelon.

3-2-Assumptions

The key assumptions of this research are as follows:

- A multi-level, multi-product, and multi-period model has been developed.
- The location of customers is known and fixed.
- The number of facilities that can be opened and their capacity is limited.
- Uncertainty for all parameters of the model is considered.
- The amount of released gas CO_2 due to the transportation system is considered uncertainty.
- All returned products from customers must be collected.
- The manufacturer can manufacture and remanufacture (retread) the tires.
- Purchasing of raw materials is performed at the beginning of the time period t, and suppliers should be sent the raw materials during the period to the manufacturing centers.
- The distributors and customers do not differentiate between new and remanufactured tires; in fact, it is assumed that the quality of new and retreaded tires is the same.
- The purchased raw materials are used to produce new tires, and remanufactured returned tires, e.g., remanufacturing plants use the raw materials for creating tires' casing.
- Manufacturing/remanufacturing plants purchased used tires as raw materials from collection centers.
- The transportation cost depends on the distances between locations and the transportation system provided by the supplier.

3-3-Problem formulation

To describe the aforementioned CLSC network, the following notations are used in the model formulation:

3-3-1-Notations

Indices:

j	Set of products, (j = 1,2,3,…,J)
s	Set of suppliers, (s = 1,2,3,…,S)
k	Set of customers centers locations, (k = 1,2,3,…,K)
r	Index for potential locations for distribution centers, (r = 1,2,3,…,R)
i	Index for potential locations of manufacturing/remanufacturing plants, (i = 1,2,3,…,I)
l	Index for potential locations for collection centers, (l = 1,2,3,…,L)
n	Index for potential locations for recycling centers, (n = 1,2,3,…,N)
t	Index of period time (t = 1,2,3,…,T)
m	Index of transportation system provided by the supplier, (m = 1,2,3,…,M)

Parameters:

$\tilde{S}_{jirt}$	Selling price of product j from manufacturing plant i to distribution center r in period t
$\widetilde{CS}_{jt}$	Cost Saving of product j in period t (because of product recovery)
$\widetilde{cP}_{jit}$	Production Cost of product *j* in manufacturing plant i in period t
$\widetilde{cR}_{st}$	Purchased cost of raw material from supplier s in period t
$\widetilde{RC}_{jnt}$	Recycling Cost of product *j* in recycling center n in period t
$\widetilde{HC}_{jrt}$	Holding cost of the product *j* in distribution center r in period t
$\widetilde{SHC}_{jkt}$	Cost of shortage the unit of product *j* for customer center k in period t
$\widetilde{fcS}_{st}$	Fixed-Cost associated with supplier s in period t
$\widetilde{fcP}_{it}$	Fixed-Cost for opening plant i by the manufacturer in period t
$\widetilde{fcD}_{rt}$	Fixed-Cost for opening distribution center r in period t
$\widetilde{fcC}_{lt}$	Fixed-Cost for opening the collection center l in period t
$\widetilde{fcN}_{nt}$	Fixed-Cost for opening the recycling center n in period t
eS_{si}	The distance between locations of supplier s and plant i
eP_{ir}	The distance between locations of manufacturing plant i and distribution center r
eD_{rk}	The distance between locations of distribution center r and customer centers k
eK_{kl}	The distance between locations of customer centers k and collection center l
eN_{ln}	The distance between locations of collection center l and recycling center n
eC_{li}	The distance between locations of collection center l and remanufacturing plant i
$\widetilde{ftS}_{sit}^{m}$	Fixed-Cost of sending transportation system m from supplier s to manufacturing plant i in period t
$\widetilde{ftP}_{irt}^{m}$	Fixed-Cost of sending transportation system m from manufacturing plant i to distribution center r in period t
$\widetilde{ftD}_{rkt}^{m}$	Fixed-Cost of sending transportation system m from distribution center r to customer centers k in period t
$\widetilde{ftK}_{klt}^{m}$	Fixed-Cost of sending transportation system m from customer centers k to collection center l in period t
$\widetilde{ftN}_{lnt}^{m}$	Fixed-Cost of sending transportation system m from collection center l to recycling center n in period t
$\widetilde{ftC}_{lit}^{m}$	Fixed-Cost of sending transportation system m from collection center l to remanufacturing plant i in period t
$\widetilde{tcS}_{sit}^{m}$	Transportation Cost of raw material per km from supplier s to manufacturing plant i with transportation system m in period t
$\widetilde{tcP}_{jirt}^{m}$	Transportation Cost of product j per km from manufacturing plant i to distribution center r with transportation system m in period t
$\widetilde{tcD}_{jrkt}^{m}$	Transportation Cost of product j per km from distribution center r to customer centers k with transportation system m in period t
$\widetilde{tcK}_{jklt}^{m}$	Transportation Cost of used product j per km from customer centers k to collection center l with transportation system m in period t
$\widetilde{tcN}_{jlnt}^{m}$	Transportation Cost of used product j per km from collection center l to recycling center n with transportation system m in period t

$\widetilde{tcC}_{jlit}^{m}$ Transportation Cost of used product j per km from collection center l to remanufacturing plant i with transportation system m in period t

$\tilde{v}_j$ Volume of each unit product j

$\widetilde{vr}$ Volume of raw material

ur_{jt} The rate of using the raw material for produce product j in period t

uru_{jt} The rate of using the raw material for remanufacturing used product j in period t

$\widetilde{RR}_j$ Rate of Recoverable used product j

$\widetilde{RT}_j$ Rate of Return used product *j*

$\widetilde{capP}_{it}$ End Product Storage Capacity of manufacturing/ remanufacturing plant i in period t

$\widetilde{capPR}_{it}$ Raw material Storage Capacity of manufacturing/ remanufacturing plant i in period t

$\widetilde{capD}_{rt}$ Capacity of distribution center r in period t

$\widetilde{capC}_{lt}$ Capacity of collection center l in period t

$\widetilde{capN}_{nt}$ Capacity of recycling center n in period t

$\widetilde{capS}_{st}$ Capacity of supplier s in period t

$\widetilde{capL}_{mt}$ Potential capacity of each of transportation tools m in period t

$\tilde{d}_{jkt}$ Demand of customer centers k for product j in period t

$\tilde{\theta}^{m}$ Amount of released CO_2 for transportation with transportation system m

$\widetilde{EIS}_{st}$ Environmental impact of raw materials purchased from supplier s in period t

$\widetilde{EIP}_{it}$ Environmental impact of opening manufacturing/remanufacturing plant i in period t

$\widetilde{EID}_{rt}$ Environmental impact of opening distribution center r in period t

$\widetilde{EIC}_{lt}$ Environmental impact of opening collection center l in period t

$\widetilde{EIN}_{nt}$ Environmental impact of opening recycle center n in period t

Decision variables:

QP_{jit} Quantity of product j produced at manufacturing plant i in period t

QR_{st} Quantity of purchased raw material from supplier s in period t

TRS_{sit}^{m} Quantity of raw material shipped with transportation m from supplier s to manufacturing plant i in period t

TPP_{jirt}^{m} Quantity of product j shipped with transportation m from manufacturing plant i to distribution center r in period t

TPD_{jrkt}^{m} Quantity of product j shipped with transportation m from distribution center r to customer centers k in period t

TPK_{jklt}^{m} Quantity of product j shipped with transportation m from customer centers k to collection center l in period t

TPC_{jlit}^{m} Quantity of product j shipped with transportation m from collection center l to remanufacturing plant i in period t

TPN_{jlnt}^{m} Quantity of product j shipped with transportation m from collection center l to recycling center n in period t

ID_{jrt} Inventory of product j at the distribution center r in period t

SH_{jkt} Quantity of product j unsatisfied demand for customer centers k at the end of period t

NS_{sit}^{m} Number of transportation system trips m from supplier s to manufacturing plant i in period t

NP_{irt}^{m} Number of transportation system trips m from manufacturing plant i to distribution center r in period t

ND_{rkt}^{m} Number of transportation system trips m from distribution center r to customer centers k in period t

NK_{klt}^{m} Number of transportation system trips m from customer centers k to collection center l in period t

NC_{lit}^{m} Number of transportation system trips m from collection center l to remanufacturing plant i in period t

NN_{lnt}^{m} Number of transportation system trips m from collection center l recycling center n in period t

X_{it} 1, if the manufacturing/remanufacturing plant is located at potential site i during the period t, 0, otherwise

Y_{rt} 1, if the distribution center is located at potential site r during the period t, 0, otherwise

Z_{lt} 1, if the collection center is located at potential site l during the period t, 0, otherwise

B_{nt} 1, if the recycling center is located at potential site n during the period t, 0, otherwise

W_{st} 1, if the supplier s is selected during the period t, 0, otherwise

3-3-2- Objective function

In terms of the above notation, the problem models can be formulated as:

$$\begin{aligned}
\text{Max } Z_1 = & \sum_{\forall m}\sum_{\forall j}\sum_{\forall i}\sum_{\forall r}\sum_{\forall t} \tilde{S}_{jirt}.TPP^m_{jirt} - [\sum_{\forall j}\sum_{\forall i}\sum_{\forall t}\left(\widetilde{cP}_{jit}.QP_{jit}\right) + \sum_{\forall s}\sum_{\forall t}(\widetilde{cR}_{st}.QR_{st}) \\
& + \sum_{\forall m}\sum_{\forall s}\sum_{\forall i}\sum_{\forall t} \widetilde{tcS}^m_{sit}.\ eS_{si}.TRS^m_{sit} + \sum_{\forall m}\sum_{\forall j}\sum_{\forall i}\sum_{\forall r}\sum_{\forall t} \widetilde{tcP}^m_{jirt}.\ eP_{ir}.TPP^m_{jirt} \\
& + \sum_{\forall m}\sum_{\forall j}\sum_{\forall r}\sum_{\forall k}\sum_{\forall t} \widetilde{tcD}^m_{jrkt}.\ eD_{rk}.TPD^m_{jrkt} + \sum_{\forall m}\sum_{\forall j}\sum_{\forall k}\sum_{\forall l}\sum_{\forall t} \widetilde{tcK}^m_{jklt}.\ eK_{kl}.TPK^m_{jklt} \\
& + \sum_{\forall m}\sum_{\forall j}\sum_{\forall l}\sum_{\forall i}\sum_{\forall t} (-\widetilde{CS}_{jt} + \widetilde{tcC}^m_{jlit}.\ eC_{li})TPC^m_{jlit} \\
& + \sum_{\forall m}\sum_{\forall j}\sum_{\forall l}\sum_{\forall n}\sum_{\forall t} (\widetilde{RC}_{jnt} + \widetilde{tcN}^m_{jlnt}.\ eN_{ln})TPN^m_{jlnt} \\
& + \sum_{\forall j}\sum_{\forall r}\sum_{\forall t}\left(\widetilde{HC}_{jrt}.ID_{jrt}\right) + \sum_{\forall j}\sum_{\forall k}\sum_{\forall t}\left(\widetilde{SHC}_{jkt}.SH_{jkt}\right) + \sum_{\forall m}\sum_{\forall s}\sum_{\forall i}\sum_{\forall t}(\widetilde{ftS}^m_{sit}.NS^m_{sit}) \\
& + \sum_{\forall m}\sum_{\forall i}\sum_{\forall r}\sum_{\forall t}(\widetilde{ftP}^m_{irt}.NP^m_{irt}) + \sum_{\forall m}\sum_{\forall r}\sum_{\forall k}\sum_{\forall t}(\widetilde{ftD}^m_{rkt}.ND^m_{rkt}) \\
& + \sum_{\forall m}\sum_{\forall k}\sum_{\forall l}\sum_{\forall t}(\widetilde{ftK}^m_{klt}.NK^m_{klt}) + \sum_{\forall m}\sum_{\forall l}\sum_{\forall i}\sum_{\forall t}(\widetilde{ftC}^m_{lit}.NC^m_{lit}) \\
& + \sum_{\forall m}\sum_{\forall l}\sum_{\forall n}\sum_{\forall t}(\widetilde{ftN}^m_{lnt}.NN^m_{lnt}) + \sum_{\forall i}\sum_{\forall t}\left(\widetilde{fcP}_{it}.X_{it}\right) + \sum_{\forall r}\sum_{\forall t}\left(\widetilde{fcD}_{rt}.Y_{rt}\right) \\
& + \textstyle\sum_{\forall l}\sum_{\forall t}\left(\widetilde{fcC}_{lt}.Z_{lt}\right) + \sum_{\forall n}\sum_{\forall t}(\widetilde{fcN}_{nt}.B_{nt}) + \sum_{\forall s}\sum_{\forall t}(\widetilde{fcS}_{st}.W_{st})]
\end{aligned} \tag{1}$$

The first objective function (1) is to maximize the total profit in the CLSC network. The first term is related to the profit of selling products to distribution centers. The next part considers the production costs, including production cost of each product, costs of purchased raw material, transportation costs, holding costs, lack of inventory at customer centers costs, fixed costs of transportation, and cost of locating facilities at potential sites. The second and third terms are the cost of producing products and purchased raw material from suppliers. Note that, purchasing of raw materials is performed at the beginning of the time period$t$, and suppliers should be sent the raw materials during the period to the manufacturing centers. The fourth to ninth terms are transportation costs. The transportation cost depends on the distances between locations and the transportation system provided by the supplier. The next two terms are related to holding costs and lack of inventory at customer centers. The twelfth to seventeenth are fixed costs transportation. The Fixed cost transportation system depends on the number of transportation system trips in the network. The eighteenth to twenty-first terms deal with the construction cost of manufacturing/remanufacturing, distribution, collection, and recycling centers. The last term is related to the cost of suppliers' selected.

The second objective function is presented in (2).

$$\text{Min } Z_2 = \sum_{\forall m}\sum_{\forall s}\sum_{\forall i}\sum_{\forall t}(\tilde{\theta}^m.\ eS_{si}.TRS^m_{sit}) + \sum_{\forall m}\sum_{\forall j}\sum_{\forall i}\sum_{\forall r}\sum_{\forall t}(\tilde{\theta}^m.eP_{ir}.TPP^m_{jirt})$$
$$+ \sum_{\forall m}\sum_{\forall j}\sum_{\forall r}\sum_{\forall k}\sum_{\forall t}(\tilde{\theta}^m.eD_{rk}.TPD^m_{jrkt}) + \sum_{\forall m}\sum_{\forall j}\sum_{\forall k}\sum_{\forall l}\sum_{\forall t}(\tilde{\theta}^m.eK_{kl}.TPK^m_{jklt})$$
$$+ \sum_{\forall m}\sum_{\forall j}\sum_{\forall l}\sum_{\forall i}\sum_{\forall t}(\tilde{\theta}^m.eC_{li}.\ TPC^m_{jlit}) + \sum_{\forall m}\sum_{\forall j}\sum_{\forall l}\sum_{\forall n}\sum_{\forall t}(\tilde{\theta}^m.eN_{ln}.\ TPN^m_{jlnt})$$
$$+ \sum_{\forall s}\sum_{\forall t}(\widetilde{EIS}_{st}.W_{st}) + \sum_{\forall i}\sum_{\forall t}(\widetilde{EIP}_{it}.X_{it}) + \sum_{\forall r}\sum_{\forall t}(\widetilde{EID}_{rt}.Y_{rt}) + \sum_{\forall l}\sum_{\forall t}(\widetilde{EIC}_{lt}.Z_{lt})$$
$$+ \sum_{\forall n}\sum_{\forall t}(\widetilde{EIN}_{nt}.B_{nt}) \qquad (2)$$

The second objective function (2) minimizes the environmental impacts of the network. Terms one to six of the objective function (2) minimizes the equivalent CO_2 emissions caused by transportation. The CO_2 emission depends on the transportation model, fuel usage, and geographical distances; additionally, it is assumed that the manufacturing/remanufacturing, supplier, distribution, customer, collection, recycle centers are committed to green development goals. The seventh term of the objective function (2) expresses the environmental effects of the raw materials purchased from the suppliers. Note that the environmental impact of raw materials that are more expensive is lower; for example, the cost of natural caoutchouc versus artificial caoutchouc is high, but the environmental impact is much lower. The remaining terms of the objective function (2) minimizes total environmental impacts made by opening manufacturing/remanufacturing plants, distribution, collection, and recycling centers at divergent potential locations of the CLSC network.

3-3-3-Constraints

This subsection is devoted to present the constraints of the proposed model. The constraints are categorized into different categories explained in what follows.

Balance constraints: These equalities $(3)-(10)$, are used to ensure the balance inflow, raw material, product, inventory, and shortage throughout the entire CLSC.

$$\sum_{\forall m}\sum_{\forall i} TRS^m_{sit} = QR_{st} \qquad \forall s,\ t \qquad (3)$$

$$\sum_{\forall m}\sum_{\forall r} TPP^m_{jirt} = QP_{jit} \qquad \forall j,\ i,t \qquad (4)$$

$$\sum_{\forall m}\sum_{\forall j}\sum_{\forall r}(TPP^m_{jirt}.ur_{jt}) = \sum_{\forall m}\sum_{\forall s} TRS^m_{sit} + \sum_{\forall m}\sum_{\forall j}\sum_{\forall l}(TPC^m_{jlit}.uru_{jt}) \qquad \forall i,t \qquad (5)$$

$$\sum_{\forall m}\sum_{\forall r} TPD^m_{jrkt} = \tilde{d}_{jkt} - SH_{jkt} + SH_{jk(t-1)} \qquad \forall j,\ k,t \qquad (6)$$

$$\sum_{\forall m}\sum_{\forall l} TPK^m_{jklt} = (\tilde{d}_{jk(t-1)} - SH_{jk(t-1)}) \times \widetilde{RT}_j \qquad \forall j,\ k,t \qquad (7)$$

$$\sum_{\forall m}\sum_{\forall i} TPC^m_{jlit} = (\widetilde{RR}_j.\sum_{\forall m}\sum_{\forall k} TPK^m_{jklt}) \qquad \forall j,\ l,t \qquad (8)$$

$$\sum_{\forall m}\sum_{\forall n} TPN^m_{jlnt} = ((1-\widetilde{RR}_j).\sum_{\forall m}\sum_{\forall k} TPK^m_{jklt}) \qquad \forall j,\ l,t \qquad (9)$$

$$\sum_{\forall m}\sum_{\forall k} TPD_{jrkt}^{m} = \sum_{\forall m}\sum_{\forall i} TPP_{jirt}^{m} - ID_{jrt} + ID_{jr(t-1)} \qquad \forall j, r, t \qquad (10)$$

Constraint (3) ensures that all raw materials produced by each supplier must be shipped to plants within the same time period. Constraint (4) ensure that all products produced in each plant must be shipped to distribution centers within the same time period. Constraint (5) ensure that the rate of using the raw material for each plant to manufacture tires in each period is equal to the total received raw materials from suppliers and the percentage of using the raw material for recoverable tires to remanufacturing within the same time period. Constraint (6) ensure the shortage balance equation in the past period. Constraints (7) − (9) ensure that the rate of returning, recovering, and recycling tires are balanced. Constraint (10) ensure that the balance of inventory in distribution centers.

Capacity constraints: The following constraints are to define and apply the capacities of facilities.

$$\sum_{\forall j}(ID_{jrt}.\tilde{v}_j) \le \widetilde{capD}_{rt} \qquad \forall\, r, t \qquad (11)$$

$$(\tilde{v}r\,.TRS_{sit}^{m}) \le \left(\widetilde{capL}_{mt}.NS_{sit}^{m}\right) \qquad \forall\, m, s, i, t \qquad (12)$$

$$\sum_{\forall j}(\tilde{v}_j.TPP_{jirt}^{m}) \le (\widetilde{capL}_{mt}.NP_{irt}^{m}) \qquad \forall\, m, i, r, t \qquad (13)$$

$$\sum_{\forall j}(\tilde{v}_j.TPD_{jrkt}^{m}) \le (\widetilde{capL}_{mt}.ND_{rkt}^{m}) \qquad \forall\, m, r, k, t \qquad (14)$$

$$\sum_{\forall j}(\tilde{v}_j.TPK_{jklt}^{m}) \le (\widetilde{capL}_{mt}.NK_{klt}^{m}) \qquad \forall\, m, k, l, t \qquad (15)$$

$$\sum_{\forall j}(\tilde{v}_j.TPC_{jlit}^{m}) \le (\widetilde{capL}_{mt}.NC_{lit}^{m}) \qquad \forall\, m, l, i, t \qquad (16)$$

$$\sum_{\forall j}(\tilde{v}_j.TPN_{jlnt}^{m}) \le (\widetilde{capL}_{mt}.NN_{lnt}^{m}) \qquad \forall\, m, l, i, t \qquad (17)$$

$$\sum_{\forall m}\sum_{\forall i} TRS_{sit}^{m} \le (\widetilde{capS}_{st}.W_{st}) \qquad \forall s, t \qquad (18)$$

$$\sum_{\forall m}\sum_{\forall s} TRS_{sit}^{m} + \sum_{\forall m}\sum_{\forall j}\sum_{\forall l} TPC_{jlit}^{m} \le (\widetilde{capPR}_{it}.X_{it}) \qquad \forall i, t \qquad (19)$$

$$\sum_{\forall m}\sum_{\forall j}\sum_{\forall r} TPP_{jirt}^{m} \le (\widetilde{capP}_{it}.X_{it}) \qquad \forall i, t \qquad (20)$$

$$\sum_{\forall m}\sum_{\forall j}\sum_{\forall i} TPP_{jirt}^{m} \le (\widetilde{capD}_{rt}.Y_{rt}) \qquad \forall r, t \qquad (21)$$

$$\sum_{\forall m}\sum_{\forall j}\sum_{\forall k} TPK_{jklt}^{m} \le (\widetilde{capC}_{lt}.Z_{lt}) \qquad \forall l, t \qquad (22)$$

$$\sum_{\forall m}\sum_{\forall j}\sum_{\forall l} TPN_{jlnt}^{m} \le \left(\widetilde{capN}_{nt}.B_{nt}\right) \qquad \forall\, n, t \qquad (23)$$

Constraint (11) controls the remaining inventory at the distribution center at the end of each period. Constraint (12) − (17) ensures the transportation system capacity. Constraint (18) ensures that the total flow of output from each supplier to all manufacturing plants does not exceed the suppliers' capacity. Constraint (19) ensures that the total input flow to each manufacturing/remanufacturing plant from all suppliers and collection centers does not exceed the manufacturing capacity. Constraint (20) ensures that, for all products, the total flow of output from each manufacturing plant to all distribution centers does not exceed the manufacturing plant capacity. Constraint (21) ensures that, for all products, the total flow of input to each distribution center from all manufacturing plants does not exceed the distribution centers' capacity. Constraint (22) ensures that, for all products, the total flow of input to each collection center from all customer centers does not exceed the collection centers' capacity. Constraint (23) ensures that, for all products, the total flow of input to each recycling center from all collection centers does not exceed the recycling centers capacity. Also, constraint (18) − (23) ensure that which the facilities are constructed and which suppliers are selected.

Logical constraints: Constraints (24) and (25) impose the non-negativity and binary restriction on the corresponding decision variables, respectively.

$$QR_{st}, QP_{jit}, ID_{jrt}, SH_{jkt}, TRS_{sit}^{m}, TPP_{jirt}^{m}, TPD_{jrkt}^{m}, TPK_{jklt}^{m}, TPC_{jlit}^{m}, TPN_{jlnt}^{m}, NS_{sit}^{m}, NP_{irt}^{m}, ND_{rkt}^{m}, NK_{klt}^{m}, NC_{lit}^{m}, NN_{lnt}^{m} \geq 0 \qquad \forall\, i, j, r, k, m, t, l, n, s \tag{24}$$

$$X_{it}, Y_{rt}, Z_{lt}, B_{nt}, W_{st} \in \{0,1\} \qquad \forall\, i, r, t, l, n, s \tag{25}$$

The proposed CSCND model is actually a bi-objective possibilistic mixed-integer linear programming one (BOPMILP). Since, in the real world, uncertainty is an inevitable factor, most of the parameters used are considered triangular fuzzy numbers because of their uncertain nature. In general, the fuzzy programming problem must first be transformed into a definite equivalent problem and then solved with standard methods, and the optimal answer is obtained. As a result, the final solution of the problem is obtained with respect to the fuzzy structure of the problem. .To solve this model, a two-phased approach is proposed; In the first phase, the proposed model with fuzzy parameters is transformed into a certain auxiliary model by Jiménez, Arenas, Bilbao, and Rodrı (2007) method. In the second stage, using the augmented ε-constraint method (Mavrotas & Florios, 2013), we solve the bi-objective certain model, which was obtained in the first stage.

3-4-Jiménez et al. method

First, Yager (1981) and Dubois and Prade (1987) developed the definition of the "expected value" and the "expected interval" of a fuzzy number, respectively, which was the method of the Jiménez et al. (2007) is based on them. These concepts were later followed by Heilpern (1992) and Jiménez (1996). Assume that $\tilde{c} = (c^{o}, c^{m}, c^{p})$ is a triangular fuzzy number, the following equation can be defined as the membership:

$$\mu_{\tilde{c}}(x) = r = \begin{cases} f_c(x) = \dfrac{x - c^{o}}{c^{m} - c^{o}} & \text{if } c^{p} \leq x \leq c^{m} \\ 1 & \text{if } \quad x = c^{m} \\ g_c(x) = \dfrac{c^{p} - x}{c^{p} - c^{m}} & \text{if } c^{m} \leq x \leq c^{o} \\ 0 & \text{f } x \leq c^{p} \text{ or } x \geq c^{o} \end{cases} \tag{26}$$

Jiménez et al. presented a method for ranking fuzzy numbers. In this method, the Expected Interval (EI) and the expected value (EV) of triangular fuzzy number$\tilde{c} = (c^{o}, c^{m}, c^{p})$ defined as relations (27) and (28).

$$\begin{aligned} EI(\tilde{c}) &= [E_1^c, E_2^c] = \left[\int_0^1 f_c^{-1}(r)dr\,, \int_0^1 g_c^{-1}(r)dr\right] \\ &= \left[\int_0^1 (r(c^{m} - c^{o}) + c^{o})dr\,, \int_0^1 (r(c^{m} - c^{p}) + c^{p})dr\right] \\ &= \left[\frac{1}{2}(c^{m} - c^{o}) + c^{o}, \frac{1}{2}(c^{m} - c^{p}) + c^{p}\right] = \left[\frac{1}{2}(c^{m} + c^{o}), \frac{1}{2}(c^{m} + c^{p})\right] \end{aligned} \tag{27}$$

$$EV(\tilde{c}) = \frac{E_1^c + E_2^c}{2} = \frac{\frac{1}{2}(c^{m} + c^{o}) + \frac{1}{2}(c^{m} + c^{p})}{2} = \frac{c^{o} + 2c^{m} + c^{p}}{4} \tag{28}$$

Note that we can use a trapezoidal fuzzy number for similar equations. Moreover, Based on the ranking fuzzy numbers method of Jiménez (1996) for any couple of fuzzy numbers $\tilde{b}$ and $\tilde{a}$, the degree in which $\tilde{b}$ is bigger than $\tilde{a}$ is defined as follows:

$$\mu_M(\tilde{b},\tilde{a}) = \begin{cases} 0 & \text{if } E_2^a - E_1^b < 0 \\ \dfrac{E_2^b - E_1^a}{(E_2^a - E_1^a) + (E_2^b - E_1^b)} & \text{if } 0 \in [E_1^a - E_2^b, E_2^a - E_1^b] \\ 1 & \text{if } E_1^a - E_2^b > 0 \end{cases} \quad (29)$$

We can say that $\tilde{b}$ is bigger than, or equal to, $\tilde{a}$ at least in degree β when $\mu_M(\tilde{b},\tilde{a}) \geq \beta$ and it will be shown as $\tilde{b} \geq_\beta \tilde{a}$. According to the definition of fuzzy equations in Parra, Terol, Gladish, and Urıa (2005) for any pair of fuzzy numbers $\tilde{b}$ and $\tilde{a}$, we can say that $\tilde{b}$ indifferent (equal) to $\tilde{a}$ in degree of β if the following relationships hold simultaneously:

$$\tilde{b} \geq_{\frac{\beta}{2}} \tilde{a}\ ,\ \ \tilde{b} \leq_{\frac{\beta}{2}} \tilde{a} \quad (30)$$

The above equations can be rewritten as follows:

$$\frac{\beta}{2} \leq \mu_M(\tilde{b},\tilde{a}) \leq 1 - \frac{\beta}{2} \quad (31)$$

To get the answer, since we can use $\mathrm{Max}(-Z_2)$ instead of $\mathrm{Min}Z_2$, generally, we consider the following fuzzy mathematical programming model in which all parameters are defined as triangular fuzzy numbers:

$$\begin{aligned} &\mathrm{Max}\ Z = \tilde{c}^t x \\ &\text{s.t.} \\ &\quad \tilde{a}_i x \leq \tilde{b}_i, && i = 1, 2, \dots, l \\ &\quad \tilde{a}_i x = \tilde{b}_i, && i = l+1, 2, \dots, m \\ &\quad x \geq 0 \end{aligned} \quad (32)$$

As mentioned by Jiménez et al. (2007), a decision vector $x \in \Re^n$ is feasible in degree β if $\mathrm{Min}_{i=1,2,\dots,m}\{\mu_M(\tilde{b},\tilde{a}_i x)\} = \beta$ or $x \in \Re^n$ is infeasible in degree $(1-\beta)$ if $\mathrm{Max}_{i=1,2,\dots,m}\{\mu_M(\tilde{a}_i x, \tilde{b})\} = 1-\beta$. According to (29) and(30), the equations $\tilde{a}_i x \leq \tilde{b}_i$ and $\tilde{a}_i x = \tilde{b}_i$ are equivalent to the following ones, respectively:

$$\frac{E_2^{b_i} - E_1^{a_i x}}{(E_2^{a_i x} - E_1^{a_i x}) + (E_2^{b_i} - E_1^{b_i})} \geq \beta \qquad i = 1, 2, \dots, l \quad (33)$$

$$\frac{\beta}{2} \leq \frac{E_2^{b_i} - E_1^{a_i x}}{(E_2^{a_i x} - E_1^{a_i x}) + (E_2^{b_i} - E_1^{b_i})} \leq 1 - \frac{\beta}{2} \qquad i = l+1, 2, \dots, m \quad (34)$$

These equations can be rewritten as follows:

$$\begin{aligned} &\left[(1-\beta)\,E_1^{a_i} + \beta\,E_2^{a_i}\right] \times x \leq \left[(1-\beta)\,E_2^{b_i} + \beta\,E_1^{b_i}\right] && i = 1, 2, \dots, l \\ &\left[\frac{\beta}{2}\,E_2^{a_i} + \left(1-\frac{\beta}{2}\right) E_1^{a_i}\right] \times x \leq \left[\frac{\beta}{2}\,E_1^{b_i} + \left(1-\frac{\beta}{2}\right) E_2^{b_i}\right] && i = l+1, 2, \dots, m \\ &\left[\frac{\beta}{2}\,E_1^{a_i} + \left(1-\frac{\beta}{2}\right) E_2^{a_i}\right] \times x \geq \left[\frac{\beta}{2}\,E_2^{b_i} + \left(1-\frac{\beta}{2}\right) E_1^{b_i}\right] && i = l+1, 2, \dots, m \end{aligned} \quad (35)$$

Similarly, by using Jiménez (1996) ranking method, it can be proved that a feasible solution like x^0 is an β-acceptable optimal solution of the model (32) if and only if for all feasible decision vectors say x such that $\tilde{a}_i x \leq_\beta \tilde{b}_i$, $i = 1, 2, \dots, l$ and $\tilde{a}_i x \approx_\beta \tilde{b}_i$, $i = l+1, 2, \dots, m$, $x \geq 0$, the following equation holds:

$$\tilde{c}^t x \geq_{\frac{1}{2}} \tilde{c}^t x^0 \quad (36)$$

Therefore, x^0 is a better choice (with the objective of maximizing) at least in degree $\frac{1}{2}$ as opposed to the other feasible vectors. The above equation can be rewritten as follows:

$$\frac{E_2^{\tilde{c}^t x} + E_1^{\tilde{c}^t x}}{2} \geq \frac{E_2^{\tilde{c}^t x^0} + E_1^{\tilde{c}^t x^0}}{2} \tag{37}$$

Consequently, using the definition of expected interval and the expected value of a fuzzy number, the equivalent crisp $\beta-$parametric model of the model (32) can be written as follows:

$$\begin{aligned}
&\text{Max} \quad EV(\tilde{c})x \\
&\text{s.t.} \\
&\left[(1-\beta)\ \frac{{a_i}^m + {a_i}^o}{2} + \beta\frac{{a_i}^m + {a_i}^p}{2}\right] \times\ x\ \leq \left[(1-\beta)\ \frac{{b_i}^m + {b_i}^p}{2} + \beta\frac{{b_i}^m + {b_i}^o}{2}\right] \\
&i = 1, 2, \ldots, l \\
&\left[\frac{\beta}{2}\frac{{a_i}^m + {a_i}^p}{2} + \left(1-\frac{\beta}{2}\right)\frac{{a_i}^m + {a_i}^o}{2}\right] \times\ x\ \leq \left[\frac{\beta}{2}\frac{{b_i}^m + {b_i}^o}{2} + \left(1-\frac{\beta}{2}\right)\frac{{b_i}^m + {b_i}^p}{2}\right] \\
&i = l+1, 2, \ldots, m \\
&\left[\frac{\beta}{2}\frac{{a_i}^m + {a_i}^o}{2} + \left(1-\frac{\beta}{2}\right)\frac{{a_i}^m + {a_i}^p}{2}\right] \times\ x\ \geq \left[\frac{\beta}{2}\frac{{b_i}^m + {b_i}^p}{2} + \left(1-\frac{\beta}{2}\right)\frac{{b_i}^m + {b_i}^o}{2}\right] \\
&i = l+1, 2, \ldots, m \\
&x \geq 0
\end{aligned} \tag{38}$$

Given that if the pessimistic value is the highest, we have $\tilde{c} = (c^o, c^m, c^p)$ and the Expected Interval (EI) and the Expected value (EV) of triangular fuzzy number $\tilde{c} = (c^o, c^m, c^p)$ defined as relations (27) and (28), and the rest of the formulas are the same as before. Also, if the pessimistic value is the lowest, we have $\tilde{c} = (c^p, c^m, c^o)$ and the Expected Interval (EI) and the Expected value (EV) of triangular fuzzy number $\tilde{c} = (c^p, c^m, c^o)$ defined as $\left[\frac{1}{2}(c^m + c^p), \frac{1}{2}(c^m + c^o)\right]$ and $\frac{c^p+2c^m+c^o}{4}$ respectively. In the latter case, the equations can be rewritten as follows:

$$\begin{aligned}
&\left[(1-\beta)\frac{{a_i}^m + {a_i}^p}{2} + \beta\frac{{a_i}^m + {a_i}^o}{2}\right] \times\ x\ \leq \left[(1-\beta)\ \frac{{b_i}^m + {b_i}^o}{2} + \beta\frac{{b_i}^m + {b_i}^p}{2}\right] \\
&i = 1, 2, \ldots, l \\
&\left[\frac{\beta}{2}\frac{{a_i}^m + {a_i}^o}{2} + \left(1-\frac{\beta}{2}\right)\frac{{a_i}^m + {a_i}^p}{2}\right] \times\ x\ \leq \left[\frac{\beta}{2}\frac{{b_i}^m + {b_i}^p}{2} + \left(1-\frac{\beta}{2}\right)\frac{{b_i}^m + {b_i}^o}{2}\right] \\
&i = l+1, 2, \ldots, m \\
&\left[\frac{\beta}{2}\frac{{a_i}^m + {a_i}^p}{2} + \left(1-\frac{\beta}{2}\right)\frac{{a_i}^m + {a_i}^o}{2}\right] \times\ x\ \geq \left[\frac{\beta}{2}\frac{{b_i}^m + {b_i}^o}{2} + \left(1-\frac{\beta}{2}\right)\frac{{b_i}^m + {b_i}^p}{2}\right] \\
&i = l+1, 2, \ldots, m
\end{aligned} \tag{39}$$

According to the above descriptions, the equivalent auxiliary crisp model of the CSCND model can be formulated as follows:

$$\begin{aligned}
\text{Max}\, Z_1 = &\sum_{\forall m}\sum_{\forall j}\sum_{\forall i}\sum_{\forall r}\sum_{\forall t}\left(\frac{\tilde{S}^{\,p}_{jirt} + 2\tilde{S}^{\,m}_{jirt} + \tilde{S}^{\,o}_{jirt}}{4}\right).TPP^m_{jirt} \\
&-[\sum_{\forall j}\sum_{\forall i}\sum_{\forall t}\left(\frac{\widetilde{cP}^o_{jit} + 2\widetilde{cP}^m_{jit} + \widetilde{cP}^p_{jit}}{4}\right).QP_{jit} + \sum_{\forall s}\sum_{\forall t}\left(\frac{\widetilde{cR}^o_{st} + 2\widetilde{cR}^m_{st} + \widetilde{cR}^p_{st}}{4}\right).QR_{st} \\
&+\sum_{\forall m}\sum_{\forall s}\sum_{\forall i}\sum_{\forall t}\left(\frac{{\widetilde{tcS}^m_{sit}}^{\,o} + 2{\widetilde{tcS}^m_{sit}}^{\,m} + {\widetilde{tcS}^m_{sit}}^{\,p}}{4}\right).\, eS_{si}.TRS^m_{sit} \\
&+\sum_{\forall m}\sum_{\forall j}\sum_{\forall i}\sum_{\forall r}\sum_{\forall t}\left(\frac{{\widetilde{tcP}^m_{jirt}}^{\,o} + 2{\widetilde{tcP}^m_{jirt}}^{\,m} + {\widetilde{tcP}^m_{jirt}}^{\,p}}{4}\right).\, eP_{ir}.TPP^m_{jirt}
\end{aligned}$$

$$+\sum_{\forall m}\sum_{\forall j}\sum_{\forall r}\sum_{\forall k}\sum_{\forall t}\left(\frac{\widetilde{tcD}^{m}_{jrkt}{}^{o}+2\widetilde{tcD}^{m}_{jrkt}{}^{m}+\widetilde{tcD}^{m}_{jrkt}{}^{p}}{4}\right).\,eD_{rk}.TPD^{m}_{jrkt}$$

$$+\sum_{\forall m}\sum_{\forall j}\sum_{\forall k}\sum_{\forall l}\sum_{\forall t}\left(\frac{\widetilde{tcK}^{m}_{jklt}{}^{o}+2\widetilde{tcK}^{m}_{jklt}{}^{m}+\widetilde{tcK}^{m}_{jklt}{}^{p}}{4}\right).\,eK_{kl}.TPK^{m}_{jklt}$$

$$+\sum_{\forall m}\sum_{\forall j}\sum_{\forall l}\sum_{\forall i}\sum_{\forall t}\left(-\left(\frac{\widetilde{CS}_{jt}{}^{p}+2\widetilde{CS}_{jt}{}^{m}+\widetilde{CS}_{jt}{}^{o}}{4}\right)+\left(\frac{\widetilde{tcC}^{m}_{jlit}{}^{o}+2\widetilde{tcK}^{m}_{jklt}{}^{m}+\widetilde{tcK}^{m}_{jklt}{}^{p}}{4}\right).\,eC_{li}\right)TPC^{m}_{jlit}$$

$$+\sum_{\forall m}\sum_{\forall j}\sum_{\forall l}\sum_{\forall n}\sum_{\forall t}\left(\left(\frac{\widetilde{RC}_{jnt}{}^{p}+2\widetilde{RC}_{jnt}{}^{m}+\widetilde{RC}_{jnt}{}^{o}}{4}\right)+\left(\frac{\widetilde{tcN}^{m}_{jlnt}{}^{o}+2\widetilde{tcN}^{m}_{jlnt}{}^{m}+\widetilde{tcN}^{m}_{jlnt}{}^{p}}{4}\right).\,eN_{ln}\right)TPN^{m}_{jlnt}$$

$$+\sum_{\forall j}\sum_{\forall r}\sum_{\forall t}\left(\frac{\widetilde{HC}_{jrt}{}^{o}+2\widetilde{HC}_{jrt}{}^{m}+\widetilde{HC}_{jrt}{}^{p}}{4}\right).ID_{jrt}+\sum_{\forall j}\sum_{\forall k}\sum_{\forall t}\left(\frac{\widetilde{SHC}_{jkt}{}^{o}+2\widetilde{SHC}_{jkt}{}^{m}+\widetilde{SHC}_{jkt}{}^{p}}{4}\right).SH_{jkt}$$

$$+\sum_{\forall m}\sum_{\forall s}\sum_{\forall i}\sum_{\forall t}\left(\frac{\widetilde{ftS}^{m}_{sit}{}^{o}+2\widetilde{ftS}^{m}_{sit}{}^{m}+\widetilde{ftS}^{m}_{sit}{}^{p}}{4}\right).NS^{m}_{sit}+\sum_{\forall m}\sum_{\forall i}\sum_{\forall r}\sum_{\forall t}\left(\frac{\widetilde{ftP}^{m\,o}_{irt}+2\widetilde{ftP}^{m\,m}_{irt}+\widetilde{ftP}^{m\,p}_{irt}}{4}\right).NP^{m}_{irt}$$

$$+\sum_{\forall m}\sum_{\forall r}\sum_{\forall k}\sum_{\forall t}\left(\frac{\widetilde{ftD}^{m\,o}_{rkt}+2\widetilde{ftD}^{m\,m}_{rkt}+\widetilde{ftD}^{m\,p}_{rkt}}{4}\right).ND^{m}_{rkt}+\sum_{\forall m}\sum_{\forall k}\sum_{\forall l}\sum_{\forall t}\left(\frac{\widetilde{ftK}^{m\,o}_{klt}+2\widetilde{ftK}^{m\,m}_{klt}+\widetilde{ftK}^{m\,p}_{klt}}{4}\right).NK^{m}_{klt}$$

$$+\sum_{\forall m}\sum_{\forall l}\sum_{\forall i}\sum_{\forall t}\left(\frac{\widetilde{ftC}^{m\,o}_{lit}+2\widetilde{ftC}^{m\,m}_{lit}+\widetilde{ftC}^{m\,p}_{lit}}{4}\right).NC^{m}_{lit}+\sum_{\forall m}\sum_{\forall l}\sum_{\forall n}\sum_{\forall t}\left(\frac{\widetilde{ftN}^{m}_{lnt}{}^{o}+2\widetilde{ftN}^{m}_{lnt}{}^{m}+\widetilde{ftN}^{m}_{lnt}{}^{p}}{4}\right).NN^{m}_{lnt}$$

$$+\sum_{\forall i}\sum_{\forall t}\left(\frac{\widetilde{fcP}_{it}{}^{o}+2\widetilde{fcP}_{it}{}^{m}+\widetilde{fcP}_{it}{}^{p}}{4}\right).X_{it}+\sum_{\forall r}\sum_{\forall t}\left(\frac{\widetilde{fcD}_{rt}{}^{o}+2\widetilde{fcD}_{rt}{}^{m}+\widetilde{fcD}_{rt}{}^{p}}{4}\right).Y_{rt}$$

$$+\sum_{\forall l}\sum_{\forall t}\left(\frac{\widetilde{fcC}_{lt}{}^{o}+2\widetilde{fcC}_{lt}{}^{m}+\widetilde{fcC}_{lt}{}^{p}}{4}\right).Z_{lt}+\sum_{\forall n}\sum_{\forall t}\left(\frac{\widetilde{fcN}_{nt}{}^{o}+2\widetilde{fcN}_{nt}{}^{m}+\widetilde{fcN}_{nt}{}^{p}}{4}\right).B_{nt}$$

$$+\sum_{\forall s}\sum_{\forall t}\left(\frac{\widetilde{fcS_{st}}{}^{o}+2\widetilde{fcS_{st}}{}^{m}+\widetilde{fcS_{st}}{}^{p}}{4}\right).W_{st}]$$

$$\mathrm{Max}-Z_{2}=\sum_{\forall m}\sum_{\forall s}\sum_{\forall i}\sum_{\forall t}\left(\frac{-\tilde{\theta}^{m\,o}-2\tilde{\theta}^{m\,m}-\tilde{\theta}^{m\,p}}{4}\right).\,eS_{si}.TRS^{m}_{sit}$$

$$+\sum_{\forall m}\sum_{\forall j}\sum_{\forall i}\sum_{\forall r}\sum_{\forall t}\left(\frac{-\tilde{\theta}^{m\,o}-2\tilde{\theta}^{m\,m}-\tilde{\theta}^{m\,p}}{4}\right).eP_{ir}.TPP^{m}_{jirt}$$

$$+\sum_{\forall m}\sum_{\forall j}\sum_{\forall r}\sum_{\forall k}\sum_{\forall t}\left(\frac{-\tilde{\theta}^{m\,o}-2\tilde{\theta}^{m\,m}-\tilde{\theta}^{m\,p}}{4}\right).eD_{rk}.TPD^{m}_{jrkt}$$

$$+\sum_{\forall m}\sum_{\forall j}\sum_{\forall k}\sum_{\forall l}\sum_{\forall t}\left(\frac{-\tilde{\theta}^{m\,o}-2\tilde{\theta}^{m\,m}-\tilde{\theta}^{m\,p}}{4}\right).eK_{kl}.TPK^{m}_{jklt}$$

$$+\sum_{\forall m}\sum_{\forall j}\sum_{\forall l}\sum_{\forall i}\sum_{\forall t}\left(\frac{-\tilde{\theta}^{m\,o}-2\tilde{\theta}^{m\,m}-\tilde{\theta}^{m\,p}}{4}\right).eC_{li}.TPC^{m}_{jlit}$$

$$+\sum_{\forall m}\sum_{\forall j}\sum_{\forall l}\sum_{\forall n}\sum_{\forall t}\left(\frac{-\tilde{\theta}^{m\,o}-2\tilde{\theta}^{m\,m}-\tilde{\theta}^{m\,p}}{4}\right).eN_{ln}.\,TPN^{m}_{jlnt}$$

$$+\sum_{\forall i}\sum_{\forall s}\left(\frac{-\widetilde{EIS}_{st}{}^{o}-2\widetilde{EIS}_{st}{}^{m}-\widetilde{EIS}_{st}{}^{p}}{4}\right).W_{st}+\sum_{\forall i}\sum_{\forall t}\left(\frac{-\widetilde{EIP}_{it}{}^{o}-2\widetilde{EIP}_{it}{}^{m}-\widetilde{EIP}_{it}{}^{p}}{4}\right).X_{it}$$

$$+\sum_{\forall r}\sum_{\forall t}\left(\frac{-\widetilde{EID}_{rt}{}^{o}-2\widetilde{EID}_{rt}{}^{m}-\widetilde{EID}_{rt}{}^{p}}{4}\right).Y_{rt}+\sum_{\forall l}\sum_{\forall t}\left(\frac{-\widetilde{EIC}_{lt}{}^{o}-2\widetilde{EIC}_{lt}{}^{m}-\widetilde{EIC}_{lt}{}^{p}}{4}\right).Z_{lt}$$

$$+\sum_{\forall n}\sum_{\forall t}\left(\frac{-\widetilde{EIN}_{nt}{}^{o}-2\widetilde{EIN}_{nt}{}^{m}-\widetilde{EIN}_{nt}{}^{p}}{4}\right).B_{nt}$$

$$\sum_{\forall m}\sum_{\forall i} \mathrm{TRS}^{m}_{sit} = \mathrm{QR}_{st} \qquad \forall s, t$$

$$\sum_{\forall m}\sum_{\forall r} \mathrm{TPP}^{m}_{jirt} = \mathrm{QP}_{jit} \qquad \forall j, i, t$$

$$\sum_{\forall m}\sum_{\forall j}\sum_{\forall r} (\mathrm{TPP}^{m}_{jirt}.\mathrm{ur}_{jt}) = \sum_{\forall m}\sum_{\forall s} \mathrm{TRS}^{m}_{sit} + \sum_{\forall m}\sum_{\forall j}\sum_{\forall l} (\mathrm{TPC}^{m}_{jlit}.\mathrm{uru}_{jt}) \qquad \forall i,t$$

$$\sum_{\forall m}\sum_{\forall r} \mathrm{TPD}^{m}_{jrkt} + \mathrm{SH}_{jkt} - \mathrm{SH}_{jk(t-1)} \le \left[\frac{\beta}{2}\frac{\tilde{d}_{jkt}{}^{m} + \tilde{d}_{jkt}{}^{p}}{2} + \left(1-\frac{\beta}{2}\right)\frac{\tilde{d}_{jkt}{}^{m} + \tilde{d}_{jkt}{}^{o}}{2}\right] \qquad \forall j, k, t$$

$$\sum_{\forall m}\sum_{\forall r} \mathrm{TPD}^{m}_{jrkt} + \mathrm{SH}_{jkt} - \mathrm{SH}_{jk(t-1)} \ge \left[\frac{\beta}{2}\frac{\tilde{d}_{jkt}{}^{m} + \tilde{d}_{jkt}{}^{o}}{2} + \left(1-\frac{\beta}{2}\right)\frac{\tilde{d}_{jkt}{}^{m} + \tilde{d}_{jkt}{}^{p}}{2}\right] \qquad \forall j, k, t$$

$$\sum_{\forall m}\sum_{\forall l} \mathrm{TPK}^{m}_{jklt} + \left[\frac{\beta}{2}\frac{\widetilde{RT}_{j}{}^{m} + \widetilde{RT}_{j}{}^{o}}{2} + \left(1-\frac{\beta}{2}\right)\frac{\widetilde{RT}_{j}{}^{m} + \widetilde{RT}_{j}{}^{p}}{2}\right]\mathrm{SH}_{jk(t-1)}$$
$$\le \left[\frac{\beta}{2}\frac{\widetilde{RT}_{j}.\,\tilde{d}_{jk(t-1)}{}^{m} + \widetilde{RT}_{j}.\,\tilde{d}_{jk(t-1)}{}^{p}}{2} + \left(1-\frac{\beta}{2}\right)\frac{\widetilde{RT}_{j}.\,\tilde{d}_{jk(t-1)}{}^{m} + \widetilde{RT}_{j}.\,\tilde{d}_{jk(t-1)}{}^{o}}{2}\right] \qquad \forall j, k, t$$

$$\sum_{\forall m}\sum_{\forall l} \mathrm{TPK}^{m}_{jklt} + \left[\frac{\beta}{2}\frac{\widetilde{RT}_{j}{}^{m} + \widetilde{RT}_{j}{}^{p}}{2} + \left(1-\frac{\beta}{2}\right)\frac{\widetilde{RT}_{j}{}^{m} + \widetilde{RT}_{j}{}^{o}}{2}\right]\mathrm{SH}_{jk(t-1)}$$
$$\ge \left[\frac{\beta}{2}\frac{\widetilde{RT}_{j}.\,\tilde{d}_{jk(t-1)}{}^{m} + \widetilde{RT}_{j}.\,\tilde{d}_{jk(t-1)}{}^{o}}{2} + \left(1-\frac{\beta}{2}\right)\frac{\widetilde{RT}_{j}.\,\tilde{d}_{jk(t-1)}{}^{m} + \widetilde{RT}_{j}.\,\tilde{d}_{jk(t-1)}{}^{p}}{2}\right] \qquad \forall j, k, t$$

$$\sum_{\forall m}\sum_{\forall i} \mathrm{TPC}^{m}_{jlit} \ge \left[\frac{\beta}{2}\frac{\widetilde{RR}_{j}{}^{m} + \widetilde{RR}_{j}{}^{o}}{2} + \left(1-\frac{\beta}{2}\right)\frac{\widetilde{RR}_{j}{}^{m} + \widetilde{RR}_{j}{}^{p}}{2}\right].\sum_{\forall m}\sum_{\forall k} \mathrm{TPK}^{m}_{jklt} \qquad \forall j, l, t$$

$$\sum_{\forall m}\sum_{\forall i} \mathrm{TPC}^{m}_{jlit} \le \left[\frac{\beta}{2}\frac{\widetilde{RR}_{j}{}^{m} + \widetilde{RR}_{j}{}^{p}}{2} + \left(1-\frac{\beta}{2}\right)\frac{\widetilde{RR}_{j}{}^{m} + \widetilde{RR}_{j}{}^{o}}{2}\right].\sum_{\forall m}\sum_{\forall k} \mathrm{TPK}^{m}_{jklt} \qquad \forall j, l, t$$

$$\sum_{\forall m}\sum_{\forall n} \mathrm{TPN}^{m}_{jlnt} \ge \left[\frac{\beta}{2}\frac{(1-\widetilde{RR}_{j})^{m} + (1-\widetilde{RR}_{j})^{o}}{2} + \left(1-\frac{\beta}{2}\right)\frac{(1-\widetilde{RR}_{j})^{m} + (1-\widetilde{RR}_{j})^{p}}{2}\right].\sum_{\forall m}\sum_{\forall k} \mathrm{TPK}^{m}_{jklt}$$
$\forall j, l, t$

$$\sum_{\forall m}\sum_{\forall n} \mathrm{TPN}^{m}_{jlnt} \le \left[\frac{\beta}{2}\frac{(1-\widetilde{RR}_{j})^{m} + (1-\widetilde{RR}_{j})^{p}}{2} + \left(1-\frac{\beta}{2}\right)\frac{(1-\widetilde{RR}_{j})^{m} + (1-\widetilde{RR}_{j})^{o}}{2}\right].\sum_{\forall m}\sum_{\forall k} \mathrm{TPK}^{m}_{jklt}$$
$\forall j, l, t$

$$\sum_{\forall m}\sum_{\forall k} \mathrm{TPD}^{m}_{jrkt} = \sum_{\forall m}\sum_{\forall i} \mathrm{TPP}^{m}_{jirt} - \mathrm{ID}_{jrt} + \mathrm{ID}_{jr(t-1)} \qquad \forall j, r, t$$

$$\sum_{\forall j}\left[(1-\beta)\,\frac{\tilde{v}_{j}{}^{m} + \tilde{v}_{j}{}^{o}}{2} + \beta\frac{\tilde{v}_{j}{}^{m} + \tilde{v}_{j}{}^{p}}{2}\right].\,\mathrm{ID}_{jrt} \le \left[(1-\beta)\frac{\widetilde{capD}_{rt}{}^{m} + \widetilde{capD}_{rt}{}^{o}}{2} + \beta\,\frac{\widetilde{capD}_{rt}{}^{m} + \widetilde{capD}_{rt}{}^{p}}{2}\right]$$
$\forall$ r,t

$$\left[(1-\beta)\,\frac{\widetilde{vr}^{m} + \widetilde{vr}^{o}}{2} + \beta\frac{\widetilde{vr}^{m} + \widetilde{vr}^{p}}{2}\right].\mathrm{TRS}^{m}_{sit} \le \left[(1-\beta)\,\frac{\widetilde{capL}^{m}_{mt} + \widetilde{capL}^{p}_{mt}}{2} + \beta\frac{\widetilde{capL}^{m}_{mt} + \widetilde{capL}^{o}_{mt}}{2}\right].\mathrm{NS}^{m}_{sit}$$
$\forall$ m, s, i, t

$$\sum_{\forall j}\left[(1-\beta)\,\frac{\tilde{v}_{j}{}^{m} + \tilde{v}_{j}{}^{o}}{2} + \beta\frac{\tilde{v}_{j}{}^{m} + \tilde{v}_{j}{}^{p}}{2}\right].\mathrm{TPP}^{m}_{jirt} \le \left[(1-\beta)\,\frac{\widetilde{capL}^{m}_{mt} + \widetilde{capL}^{p}_{mt}}{2} + \beta\frac{\widetilde{capL}^{m}_{mt} + \widetilde{capL}^{o}_{mt}}{2}\right].\mathrm{NP}^{m}_{irt}$$
$\forall$ m, i, r, t

$$\sum_{\forall j}\left[(1-\beta)\,\frac{\tilde{v}_{j}{}^{m} + \tilde{v}_{j}{}^{o}}{2} + \beta\frac{\tilde{v}_{j}{}^{m} + \tilde{v}_{j}{}^{p}}{2}\right].\mathrm{TPD}^{m}_{jrkt} \le \left[(1-\beta)\,\frac{\widetilde{capL}^{m}_{mt} + \widetilde{capL}^{p}_{mt}}{2} + \beta\frac{\widetilde{capL}^{m}_{mt} + \widetilde{capL}^{o}_{mt}}{2}\right].\mathrm{ND}^{m}_{rkt}$$
$\forall$ m, r, k, t

$$\sum_{\forall j}\left[(1-\beta)\ \frac{\tilde{v}_j{}^{m}+\tilde{v}_j{}^{o}}{2}+\beta\frac{\tilde{v}_j{}^{m}+\tilde{v}_j{}^{p}}{2}\right].TPK^m_{jklt} \le \left[(1-\beta)\ \frac{\widetilde{capL}^m_{mt}+\widetilde{capL}^p_{mt}}{2}+\beta\frac{\widetilde{capL}^m_{mt}+\widetilde{capL}^o_{mt}}{2}\right].NK^m_{klt}$$
$$\forall\ m, k, l, t$$

$$\sum_{\forall j}\left[(1-\beta)\ \frac{\tilde{v}_j{}^{m}+\tilde{v}_j{}^{o}}{2}+\beta\frac{\tilde{v}_j{}^{m}+\tilde{v}_j{}^{p}}{2}\right].TPC^m_{jlit} \le \left[(1-\beta)\ \frac{\widetilde{capL}^m_{mt}+\widetilde{capL}^p_{mt}}{2}+\beta\frac{\widetilde{capL}^m_{mt}+\widetilde{capL}^o_{mt}}{2}\right].NC^m_{lit}$$
$$\forall\ m, l, i, t$$

$$\sum_{\forall j}\left[(1-\beta)\ \frac{\tilde{v}_j{}^{m}+\tilde{v}_j{}^{o}}{2}+\beta\frac{\tilde{v}_j{}^{m}+\tilde{v}_j{}^{p}}{2}\right].TPN^m_{jlnt} \le \left[(1-\beta)\ \frac{\widetilde{capL}^m_{mt}+\widetilde{capL}^p_{mt}}{2}+\beta\frac{\widetilde{capL}^m_{mt}+\widetilde{capL}^o_{mt}}{2}\right].NN^m_{lnt}$$
$$\forall\ m, l, n, t$$

$$\sum_{\forall m}\sum_{\forall i} TRS^m_{sit} \le \left[(1-\beta)\ \frac{\widetilde{capS}_{st}{}^{m}+\widetilde{capS}_{st}{}^{p}}{2}+\beta\frac{\widetilde{capS}_{st}{}^{m}+\widetilde{capS}_{st}{}^{o}}{2}\right].W_{st} \qquad \forall s, t$$

$$\sum_{\forall m}\sum_{\forall s} TRS^m_{sit} + \sum_{\forall m}\sum_{\forall j}\sum_{\forall l} TPC^m_{jlit} \le \left[(1-\beta)\ \frac{\widetilde{capPR}_{it}{}^{m}+\widetilde{capPR}_{it}{}^{p}}{2}+\beta\frac{\widetilde{capPR}_{it}{}^{m}+\widetilde{capPR}_{it}{}^{o}}{2}\right].X_{it}$$
$$\forall i, t$$

$$\sum_{\forall m}\sum_{\forall j}\sum_{\forall r} TPP^m_{jirt} \le \left[(1-\beta)\ \frac{\widetilde{capP}_{it}{}^{m}+\widetilde{capP}_{it}{}^{p}}{2}+\beta\frac{\widetilde{capP}_{it}{}^{m}+\widetilde{capP}_{it}{}^{o}}{2}\right].X_{it} \qquad \forall i, t$$

$$\sum_{\forall m}\sum_{\forall j}\sum_{\forall i} TPP^m_{jirt} \le \left[(1-\beta)\ \frac{\widetilde{capD}_{rt}{}^{m}+\widetilde{capD}_{rt}{}^{p}}{2}+\beta\frac{\widetilde{capD}_{rt}{}^{m}+\widetilde{capD}_{rt}{}^{o}}{2}\right].Y_{rt} \qquad \forall r, t$$

$$\sum_{\forall m}\sum_{\forall j}\sum_{\forall k} TPK^m_{jklt} \le \left[(1-\beta)\ \frac{\widetilde{capC}_{lt}{}^{m}+\widetilde{capC}_{lt}{}^{p}}{2}+\beta\frac{\widetilde{capC}_{lt}{}^{m}+\widetilde{capC}_{lt}{}^{o}}{2}\right].Z_{lt} \qquad \forall l, t$$

$$\sum_{\forall m}\sum_{\forall j}\sum_{\forall l} TPN^m_{jlnt} \le \left[(1-\beta)\ \frac{\widetilde{capN}_{nt}{}^{m}+\widetilde{capN}_{nt}{}^{p}}{2}+\beta\frac{\widetilde{capN}_{nt}{}^{m}+\widetilde{capN}_{nt}{}^{o}}{2}\right].B_{nt} \qquad \forall\ n, t$$

$$QR_{st}, QP_{jit}, ID_{jrt}, SH_{jkt}\ , TRS^m_{sit}, TPP^m_{jirt}, TPD^m_{jrkt}, TPK^m_{jklt}, TPC^m_{jlit}\ , TPN^m_{jlnt}, NS^m_{sit}, NP^m_{irt}, ND^m_{rkt}, NK^m_{klt}\ , NC^m_{lit}, NN^m_{lnt} \ge 0 \qquad \forall\ i, j, r, k, m, t, l, n, s$$

$$X_{it}, Y_{rt}, Z_{lt}, B_{nt}\ , W_{st} \in \{0,1\} \qquad \forall\ i, r, t, l, n, s \qquad (40)$$

4-Solution methods

The proposed model is a bi-objective mixed-integer linear programming model. One of the most widely used methods for solving multi-objective problems is the Epsilon constraint method. The ε-constraint method has been developed for general multi-objective problems. It solves problems $P_k(\varepsilon)$ obtained by transforming one of the objectives into a constraint (Bérubé, Gendreau, & Potvin, 2009). For the bi-objective case, the problems $P_1(\varepsilon_2)$ and $P_2(\varepsilon_1)$ are:

$$\begin{array}{lcl} \text{Min } f_1(\vec{x}) & & \text{Min } f_2(\vec{x}) \\ \text{s.t. } \vec{x} \in \mathcal{X} & \text{And,} & \text{s.t. } \vec{x} \in \mathcal{X} \\ \quad f_2(\vec{x}) \leqslant \varepsilon_2 & & \quad f_1(\vec{x}) \leqslant \varepsilon_1 \end{array} \qquad (41)$$

The Epsilon constraint method has undeniable advantages compared to the other exact methods like the weighted sum method, especially in the presence of discrete variables (problems with integer or mixed-integer variables). In this study, we first delineate a medium-sized problem and solve this model using the augmented ε-constraint method. The model is computed in the GAMS software 25.1.3 using the BARON solver. Due to the integer complexity of the model, the solution time for the large size of the problem increases significantly. In fact, when integer variables are entered into the proposed model, the solution time increases. Therefore, this study uses the metaheuristic grasshopper optimization algorithm to solve large-scale problems in logical computational time, which will be explained in detail in the following sections.

4-1-Augmented ε-constraint method

Multiple-Objective Mathematical Programming (MOMP) solving algorithms can be divided into three groups: a priori methods, Interactive methods and posteriori methods (Hwang, Paidy, Yoon, & Masud, 1980). In a priori methods, the decision-makers have the ability to express objective function weights prior to solving the problem. In interactive methods analysts and decision-makers have a constant dialogue in order to get synchronized priorities with solutions. And finally, in a posteriori methods, the decision-makers can choose based on their preferences from the effective Pareto solutions, which are found after solving the problem. Because of the decision-makers having difficulty in a complete overview of the Pareto front associated with interactive methods, as well as the lack of early knowledge and quantification capacity of their preference model, a posteriori method to solving a MOMP problem as follows:

$$\begin{aligned} &\text{Max}\left\{f_1(x), f_2(x), \ldots, f_p(x)\right\} \\ &\text{s.t.} \\ &\quad x \in S \end{aligned} \tag{42}$$

Where $f_1(x), f_2(x), \ldots, f_p(x)$ are the p objective functions, x is the vector of decision variables, and S is the space of efficient solutions. The ε-constraint algorithm optimizes one objective function, while considering all other objective functions as constraints. is thus transformed to:

$$\begin{aligned} &\text{Max}\left\{f_1(x)\right\} \\ &\text{s.t.} \\ &\quad f_2(x) \geq e_2 \\ &\quad f_3(x) \geq e_3 \\ &\quad \ldots \\ &\quad f_p(x) \geq e_p \\ &\quad x \in S \end{aligned} \tag{43}$$

The model is solved on a step-by-step basis on an $N_2 \times N_3 \times \ldots \times N_p$ grid point, where N_i is the integer range of the objective function f_i. Also, efficient solutions are obtained by changing the e_i (right-hand side of the constrained objective functions).

We can control the number of efficient solutions by adjusting the number of grid points on which each optimization is solved, along with the scope of each objective function. However, it cannot be secured that solutions are not weak but effective, and this range must be calculated. These weaknesses and the time-consuming of solving any problem with more than two objective functions motivated the development of augmented ε-constraint or AUGMECON (Mavrotas, 2009), In this method, one of the objective functions (e.g., the most important one) is considered as the objective of the corresponding single-objective problem, and another objective function is transmitted to the constraint, which transforms the problem into the following:

$$\begin{aligned} &\text{Max}\left\{f_1(x) + eps \times \left(S_2 + S_3 + \ldots + S_p\right)\right\} \\ &\text{s.t.} \\ &\quad f_2(x) - S_2 = e_2 \\ &\quad f_3(x) - S_3 = e_3 \\ &\quad \ldots \\ &\quad f_p(x) - S_p = e_p \\ &\quad x \in S \text{ and } S_i \in R^+ \end{aligned} \tag{44}$$

Where $e_2, e_3, \ldots, e_p$ are the parameters for the right-hand side for the particular iteration drawn from the grid points of the objective functions 2, 3, …,p. The parameters $r_2, r_3, \ldots, r_p$ are the ranges of the respective objective functions. $S_2, S_3, \ldots, S_p$ are the surplus variables of the respective constraints and $eps \in [10^{-6}, 10^{-3}]$.

AUGMECON modifies the original ε-constraint method by changing all constraints corresponding to the $p - 1$ objective functions to strict inequalities and introducing slack (or surplus) variables to the primary objective function and the constrained ones. To ensure that only effective Pareto solutions are obtained. Mavrotas and Florios (2013) further extended this algorithm in AUGMECON-2, by presenting a bypass coefficient as well as a type of lexicographic optimization to all objective functions, the order of which was insignificant in AUGMECON:

$$\text{Max}\ (f_1(x) + eps \times \left(\frac{S_2}{r_2} + 10^{-1} \times \frac{S_3}{r_3} + \ldots + 10^{-(p-2)} \times \frac{S_p}{r_p}\right)) \tag{45}$$

To avoid unnecessary iterations and accelerate the solution, AUGMECON-2 uses the information of the slack/surplus variables of the constrained objective functions by means of the bypass coefficient. And, to help accelerate grid scanning, we can identify the exact Pareto set by decreasing the step of the process and increasing the grid points which are derived from the jumps in the innermost loop.

4-2-Grasshopper optimization algorithm (GOA)

The grasshopper optimization algorithm is an evolutionary computation technique developed by mimicking the food source-seeking tendencies of grasshopper's swarms (Saremi, Mirjalili, & Lewis, 2017; Momeni et al, 2019). By utilizing the characteristic swarming behavior of grasshoppers while searching for food, the mathematical equations are developed for GOA. The grasshoppers swarming behavior is impressed by social interaction among themselves, gravitational force and wind advection. The position of the grasshopper in the search space can be mathematically formulated by the following equation (Luo, Chen, Xu, Huang, & Zhao, 2018; Saremi et al., 2017; Abazari et al., 2021).

$$X_i = S_i + G_i + W_i \tag{46}$$

Where X_i is the position of the i^{th} grasshopper in the search space, S_i is the benefit of social interaction gained by the i^{th} grasshopper. S_i, G_i and W_i are the social interaction, gravitational and wind advection effects on the grasshopper.

$$S_i = \sum_{\substack{j=1 \\ j\neq i}}^{NGH} s(|x_j - x_i|)\frac{(x_j - x_i)}{D_{ij}} \tag{47}$$

$$s(u) = fe^{-u/lg} - e^{-u} \tag{48}$$

The social forces between the grasshoppers is calculated by the 's' function described by $s(u)$ where 'u' is the distance between grasshoppers, 'f' is the intensity of attraction and 'lg' is the length of attraction. In this work, the value of 'f' is 0.5, and lg is 1.5 taken for running optimization. The gravitational force effect is not considered because its effect is negligible on the swarm behavior of grasshoppers, and the wind effect is modeled as the global best solution. Accordingly, the grasshopper position can be updated by the following statement.

$$x_i^k = C(\sum_{\substack{j=1 \\ j\neq i}}^{NGH} C\frac{(x_{max}^k - x_{min}^k)}{2} s(|x_j^k - x_i^k|)\frac{(x_j^k - x_i^k)}{D_{ij}^k} + x_{gbest}^k \tag{49}$$

$$C = C_{max} - iter\frac{C_{max} - C_{min}}{iter_{max}} \tag{50}$$

Where x_i^k is the k^{th} variable i^{th} position in the population, D_{ij}^k is the distance between i^{th} and j^{th} position of the k^{th} variable and x_{gbest}^k is the global best of k^{th} variable. The variables$C$, C_{max} and C_{min} are the GOA parameters and in this work C_{max} is 1 and C_{min} is 0.00001.

5-Numerical results

5-1-Computational experiments

In this section, to illustrate the effectiveness of the proposed bi-objective model, we will compare the model in several problems with different sizes, which different sizes of the problem shown in table 2. The third column in table 2 indicates the size of each problem. In other words, the problems are labeled as$(J, S, K, R, I, L, N, T, M)$. For example, problem $(3, 3, 4, 4, 4, 4, 4, 3, 4)$ represents an instance is solved in multi-product mode and considering three products with three suppliers, four potential locations for manufacturing/remanufacturing, distribution, collection, customer and recycling centers, three-time periods and four types of transportation vehicles.

Table 2. Size and level of problems

Problem levels		**Problem size (J, S, K, R, I, L, N, T, M)**
Small scale	**1**	(2, 2, 2 ,2, 2, 2, 2, 2, 2)
	2	(2, 2, 3, 3, 3, 3, 3, 2, 3)
Medium scale	**3**	(3, 3, 3, 3, 3, 3, 3, 3, 3)
	4	(3, 3, 4, 4, 4, 4, 4, 3, 4)
Large scale	**5**	(4, 4, 4, 4, 4 ,4, 4, 4, 4)
	6	(4, 4, 5, 5, 5, 5, 5, 4, 5)

First, we delineate small and medium-size examples and solve these problems by using the AUGMECON-2 method. Some parameters (e.g., capacity, cost and time) of the problems have been given in table 3. The problems are computed in the GAMS software 25.1.3 using the BARON solver. All calculations are made using a computer with a Core i7.1.99GHz processor with a 12.00GB RAM of the operating system Windows 10 (64 bit).

Table 3. Parameters' values/ranges for the test problems

Value	**Parameter**	**Value**	**Parameter**	**Value**	**Parameter**
$\tilde{\boldsymbol{\theta}}^{\mathbf{m}}$	~ [1]U(0.04, 0.07)	$\widetilde{fcS}_{st}$	~ U(65, 70)	$\widetilde{ftS}^{m}_{sit}$	~ U(11, 21)
$\tilde{\mathbf{v}}_{\mathbf{j}}$	~ U(0.007, 0.014)	$\widetilde{fcP}_{it}$	~ U(850, 1050)	$\widetilde{ftP}^{m}_{irt}$	~ U(15, 21)
$\widetilde{\mathbf{RR}}_{\mathbf{j}}$	~ U(0.4, 0.45)	$\widetilde{fcD}_{rt}$	~ U(850, 1050)	$\widetilde{ftD}^{m}_{rkt}$	~ U(15, 21)
$\widetilde{\mathbf{RT}}_{\mathbf{j}}$	~ U(0.6, 0.8)	$\widetilde{fcC}_{lt}$	~ U(850, 1050)	$\widetilde{ftK}^{m}_{klt}$	~ U(15, 21)
$\mathbf{eS}_{\mathbf{si}}$	~ U(10, 13)	$\widetilde{fcN}_{nt}$	~ U(850, 1050)	$\widetilde{ftN}^{m}_{lnt}$	~ U(15, 21)
$\mathbf{eP}_{\mathbf{ir}}$	~ U(10, 25)	$\widetilde{EIS}_{st}$	~ U(3,10)	$\widetilde{ftC}^{m}_{lit}$	~ U(15, 21)
$\mathbf{eD}_{\mathbf{rk}}$	~ U(10, 34)	$\widetilde{EIP}_{it}$	~ U(8,15)	$\widetilde{tcS}^{m}_{sit}$	~ U(0.8, 1)
$\mathbf{eK}_{\mathbf{kl}}$	~ U(10, 29)	$\widetilde{EID}_{rt}$	~ U(8,15)	$\widetilde{tcP}^{m}_{jirt}$	~ U(0.8, 0.97)
$\mathbf{eN}_{\mathbf{ln}}$	~ U(12, 19)	$\widetilde{EIC}_{lt}$	~ U(8,15)	$\widetilde{tcD}^{m}_{jrkt}$	~ U(0.8, 0.97)
$\mathbf{eC}_{\mathbf{li}}$	~ U(12, 22)	$\widetilde{EIN}_{nt}$	~ U(8,15)	$\widetilde{tcK}^{m}_{jklt}$	~ U(0.8, 0.97)
$\mathbf{ur}_{\mathbf{jt}}$	~ U(0.6, 0.9)	$\widetilde{capP}_{it}$	~ U(4850, 4880)	$\widetilde{tcN}^{m}_{jlnt}$	~ U(0.8, 0.97)
$\mathbf{uru}_{\mathbf{jt}}$	~ U(0.6, 0.7)	$\widetilde{capPR}_{it}$	~ U(3850, 3880)	$\widetilde{tcC}^{m}_{jlit}$	~ U(0.8, 0.97)
$\widetilde{\mathbf{CS}}_{\mathbf{jt}}$	~ U(250, 257)	$\widetilde{capD}_{rt}$	~ U(4000, 5045)	$\tilde{S}_{jirt}$	~ U(1500, 1670)
$\widetilde{\mathbf{cR}}_{\mathbf{st}}$	~ U(10, 17)	$\widetilde{capC}_{lt}$	~ U(4800, 5815)	$\widetilde{HC}_{jrt}$	~ U(38.3, 48.5)
$\widetilde{\mathbf{RC}}_{\mathbf{jnt}}$	~ U(30, 35)	$\widetilde{capN}_{nt}$	~ U(3800, 4815)	$\widetilde{SHC}_{jkt}$	~ U(49, 58)
$\widetilde{\mathbf{cP}}_{\mathbf{jit}}$	~ U(22, 37)	$\widetilde{capS}_{st}$	~ U(3836, 3915)		
$\tilde{\mathbf{d}}_{\mathbf{jkt}}$	~ U(4715, 4720)	$\widetilde{capL}_{mt}$	~ U(22, 25)		

5-2-Model validation

To show the validity and reliability of the represented model, several numerical experiments are executed and relevant solution results are provided in this section. As it is shown in table 4 the second medium-sized problem is solved for Beta 0.9, 0.85, 0.6 and the Pareto solutions, total profit, CO_2 emission, solving time (in seconds), the number of located facilities, and the number of transportation in the first period of the Pareto solutions are considered. Table 4 indicates the fact that two objective functions are in conflict.

[1] Continuous uniform distribution

Table 4. Numerical experiments for the test problem

Beta	Pareto Solution	Objective Function		Time (s)	Num. of located facilities					Num. of Transportation					
		Profit	CO_2 emission		s	i	r	l	n	NS	NP	ND	NK	NC	NN
0.9	1	8.97E+07	2.78E+05	182.938	4	4	4	3	2	40	12	15	7	7	4
	2	8.93E+07	2.45E+05		4	4	4	4	3	46	11	13	6	6	4
	3	8.77E+07	2.12E+05		4	4	4	4	3	45	11	13	6	6	4
	4	8.57E+07	1.79E+05		4	4	4	4	2	46	11	13	6	6	4
	5	8.27E+07	1.46E+05		4	4	2	2	3	44	12	9	7	7	4
	6	7.88E+07	1.14E+05		4	4	1	1	3	65	12	10	3	4	2
0.85	1	9.00E+07	2.77E+05	151.125	4	4	4	3	2	40	13	16	7	7	4
	2	8.95E+07	2.45E+05		4	4	4	4	3	46	11	13	6	6	4
	3	8.79E+07	2.12E+05		4	4	4	4	3	45	11	13	6	6	4
	4	8.59E+07	1.79E+05		4	4	4	4	2	47	11	12	6	6	4
	5	8.29E+07	1.46E+05		4	4	2	2	3	44	13	10	7	7	4
	6	7.90E+07	1.13E+05		4	4	1	1	3	66	13	10	3	4	2
0.6	1	9.12E+07	2.79E+05	177.734	4	4	4	3	2	45	13	16	7	7	5
	2	9.07E+07	2.46E+05		4	4	4	4	3	52	12	14	6	6	4
	3	8.91E+07	2.12E+05		4	4	4	4	3	52	12	13	6	6	5
	4	8.70E+07	1.79E+05		4	4	4	4	2	52	12	13	6	6	5
	5	8.40E+07	1.46E+05		4	4	2	2	3	68	12	10	4	4	2
	6	8.00E+07	1.13E+05		4	4	1	1	3	68	13	9	4	4	2

Figure 2 and 2a-2b reveal that the changes in β (the minimum level of satisfaction of the constraints) are conformable with the direction of the objective functions. Since the constraints in the solution space are specified by the less than or equal sign (i.e., ≤), then the relation $\beta_1 < \beta_2 \rightarrow N(\beta_1) \supset N(\beta_2)$ is true for the set of the β-feasible vectors that are represented in N(β), so as the β increases, the solution space of the model and the possibility of finding a better answer for Z_1 and Z_2 decreases. In this case, the decision-maker is faced with two opposing goals of improving the Z as much as possible and improving the minimum degree of satisfaction of the constraints (i.e., β). So as can be seen in figure 2, the validity of the model is confirmed.

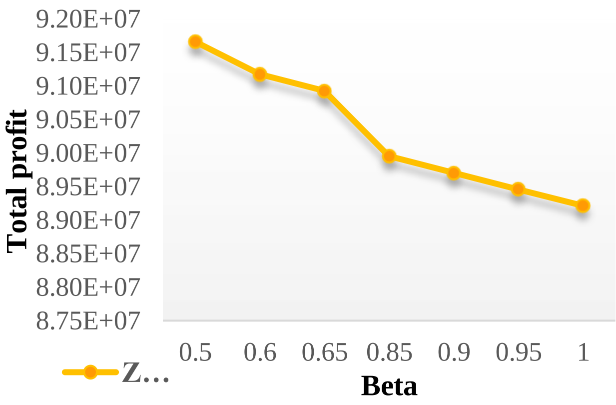


Fig 2a. Objective function Z_1 obtained through the Augmecon2 method and different Betas

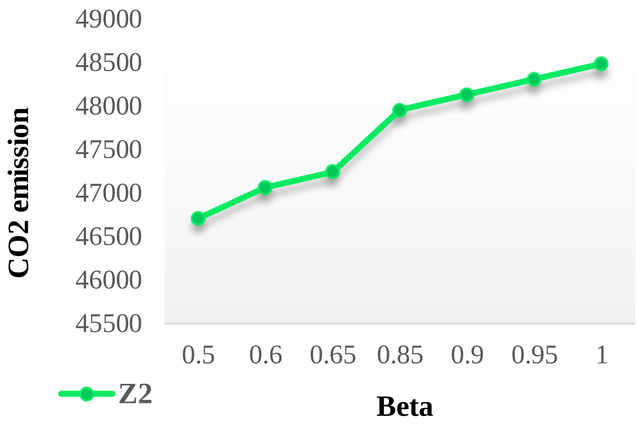


Fig 2b. Objective function Z_2 obtained through the Augmecon2 method and different Betas

Figure 3 shows changes in total profit and carbon emission in each Pareto solution. With respect to the Pareto solutions trend, it is clear that two objective functions conflict with each other. This means that the lower the carbon emission is, the lower the total profit is to achieve, and vice versa. We can see in figure 3, for a given Beta, unlike the amount of carbon emission, the total profit isn't improved among the number of Pareto solutions, which means the CLSC model works correctly.

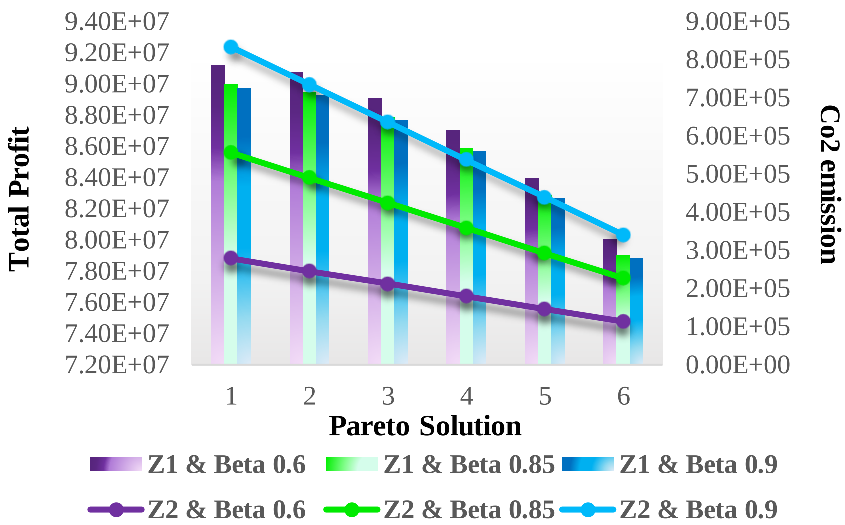


Fig 3. Pareto's Objective functions obtained through the Augmecon2 method and different Betas

The execution time for different Betas is also shown in figure 4. This chart shows that when the Beta gets closer to one, or the decision-maker tends to choose a higher percentage for the minimum level of satisfaction of the constraints, the execution time is almost everywhere gradually shortened. We can interpret that the bigger beta is, the less possibility of the better answer becomes to find. In fact, when the algorithm searches for the best answer, the problem tends to be infeasible, and naturally, the execution time is decreased.

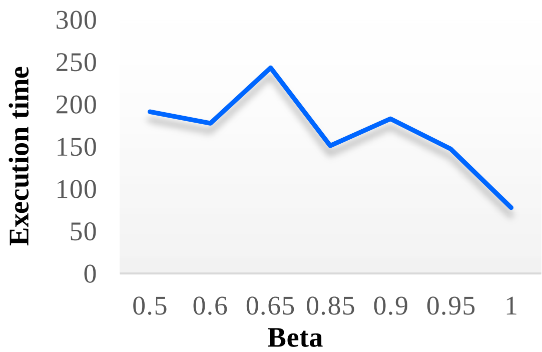


Fig 4. Pareto's execution time obtained through the Augmecon2 method and different Betas

5-3-Parameter tuning

In this sub-section, we adjust the parameters of the Grasshopper optimization algorithm (GOA). The Taguchi technique is used for tuning parameters. Taguchi's result for tuning some GOA's parameters like iteration, N_{Pop} (the number of grasshoppers) are determined in table 5. If the objective minimizes the variables, the lowest state is used, and if the objective maximizes the variables, the highest state is used. According to figure 10, the best parameters which help to the efficiency of the algorithm for problem 6 (see table 2) are selected to use in the algorithm (Max-Iteration=100, N_{Pop}=50). The results for other problems are presented in table 11. Also, figure 6 and table 6 show the effect of Max-It and N_{Pop} on total profits and execution time in problem size 6.

Table 5. Size and level of problems

Parameters	State		
	Low	**Medium**	**High**
Max-It	50	75	100
N_{Pop}	40	50	60

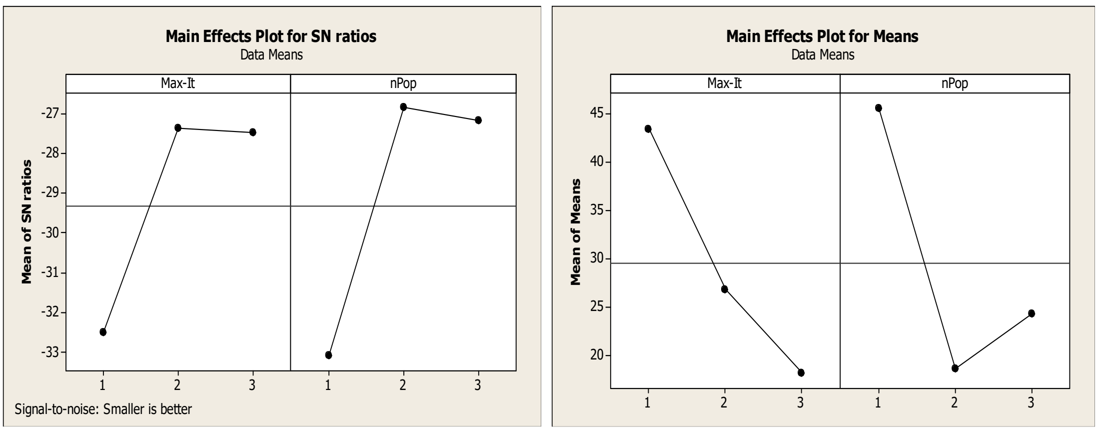


Fig 5. Taguchi's result for Problem size 6

Table 6. Best profit

[Max − It,nPop]	Best profit	Time(s)
[50,40]	83905616218	437
[50,50]	1.02014E+11	433
[50,60]	1.29321E+11	668
[75,40]	1.09894E+11	510
[75,50]	1.65517E+11	622
[75,60]	1.31754E+11	759
[100,40]	1.09412E+11	657
[100,50]	1.85517E+11	835
[100,60]	1.6022E+11	1182

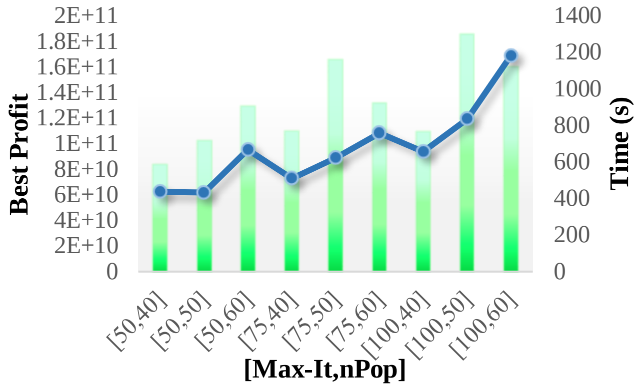


Fig 6. Effect of Max-It and N_{Pop} for Problem size 6

5-4-Result

We redesigned figure 1 as presented in section 3-1, in the period t as follows (see figure 7), which is the schematic view of our CLSCND model. The Pareto solutions can be achieved by changing the values of the right-hand side of the constraint that corresponding to the transmitted objective function and solving the obtained single-objective problem at each run to obtain computational results (Mavrotas & Florios, 2013).

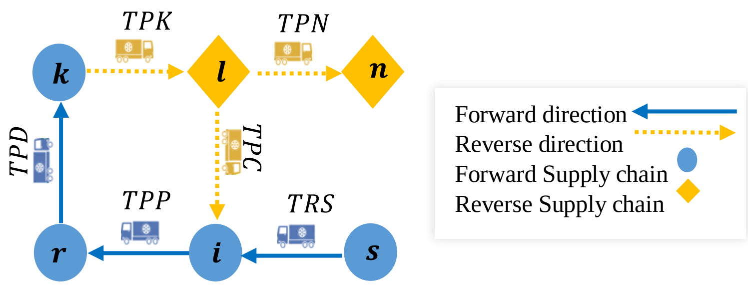


Fig 7. Schematic view of the proposed CLSCND model

The Payoff table of the second medium-sized problem is shown in table 9. Also, the results of the problem and the Pareto solutions obtained are shown in table 10.

Table 9. Payoff table

	Z_1	Z_2
Max Z_1	8.99E+07	277273.654
Min Z_2	951380.009	47954.086

Table 10. Pareto Solution of the second medium-sized problem

Obj. function	Pareto Solution					
	1	2	3	4	5	6
Z_1	9.00E+07	8.95E+07	8.79E+07	8.59E+07	8.29E+07	7.90E+07
Z_2	2.77E+05	2.45E+05	2.12E+05	1.79E+05	1.46E+05	1.13E+05

Figure 8 and 8a-8b depict the resulting Pareto front of the test problem. As the figure shows, logical results are achieved regarding the Pareto frontier 1 and 3 and feasible solutions for $t = 1$ by considering the Augmecon-2 method.

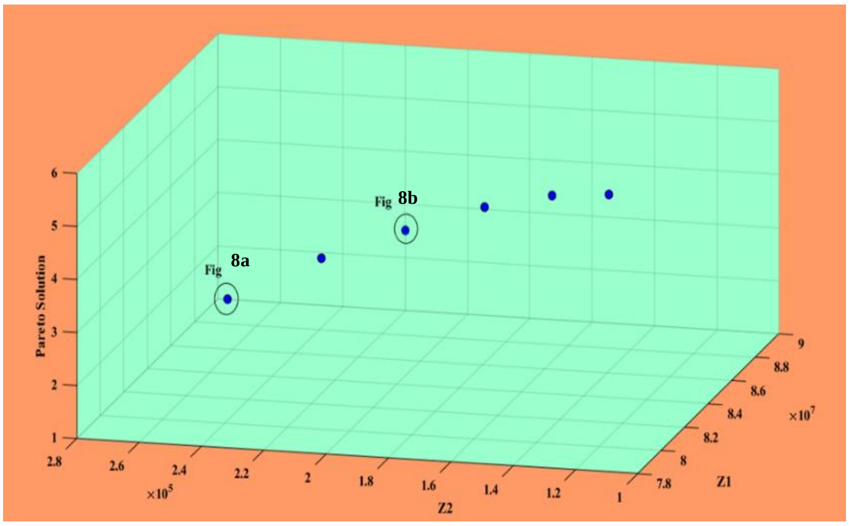
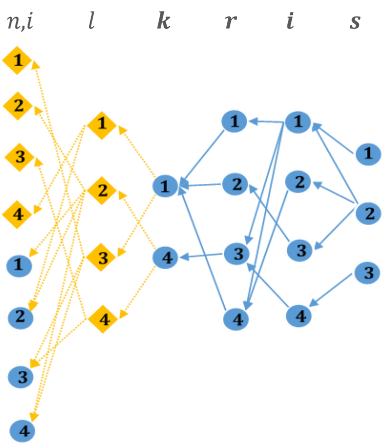


Fig 8. Pareto frontier and feasible solutions by considering the Augmecon-2 method



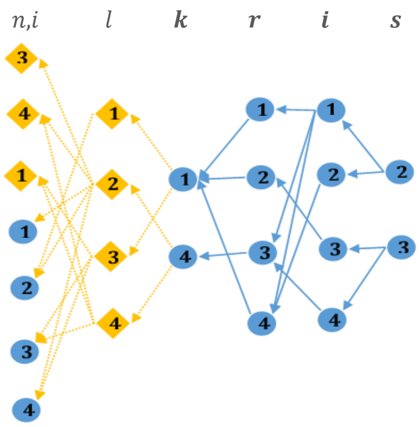


Fig 8b. Feasible solution for $t = 1$ and $\beta = 0.85$ **Fig 8a.** Feasible solution for $t = 1$ and $\beta = 0.85$

The first and second rows in table 11 give the best setting for the main parameters of the GOA algorithms for six problem samples in this study, and the next two rows present the objective values (profits) obtained from the Grasshopper optimization algorithm and execution time (second).

Table 11. Best level of parameters for Grasshopper Optimization Algorithm

Parameter	**Parameter tuning**					
	1	**2**	**3**	**4**	**5**	**6**
Max-It	75	100	50	50	75	100
N_{Pop}	40	50	50	50	50	50
Total Profit	3282129585	14418774605	25390136602	67976828600	87994953853	1.85517E+11
Time (s)	21	54	52	139	393	835

In more detail, we provided GOA algorithm results of the problem sample 6 (the problem which is labeled (4, 4, 5, 5, 5, 5, 5, 4, 5), and then we analyzed results in detail. For problem sample 6, four diagrams have been drawn (see figure 9).

- Worst Profit curve: This diagram shows the objective value of the worst solutions obtained so far (target) in each iteration.
- Mean Profit curve: This diagram indicates the average objective value of all grasshoppers in each iteration.
- Best Profit curve: This diagram shows the objective value of the best solutions obtained so far (target) in each iteration

- Total Profit curve: This diagram shows the total profit objective value of all grasshoppers in each iteration.

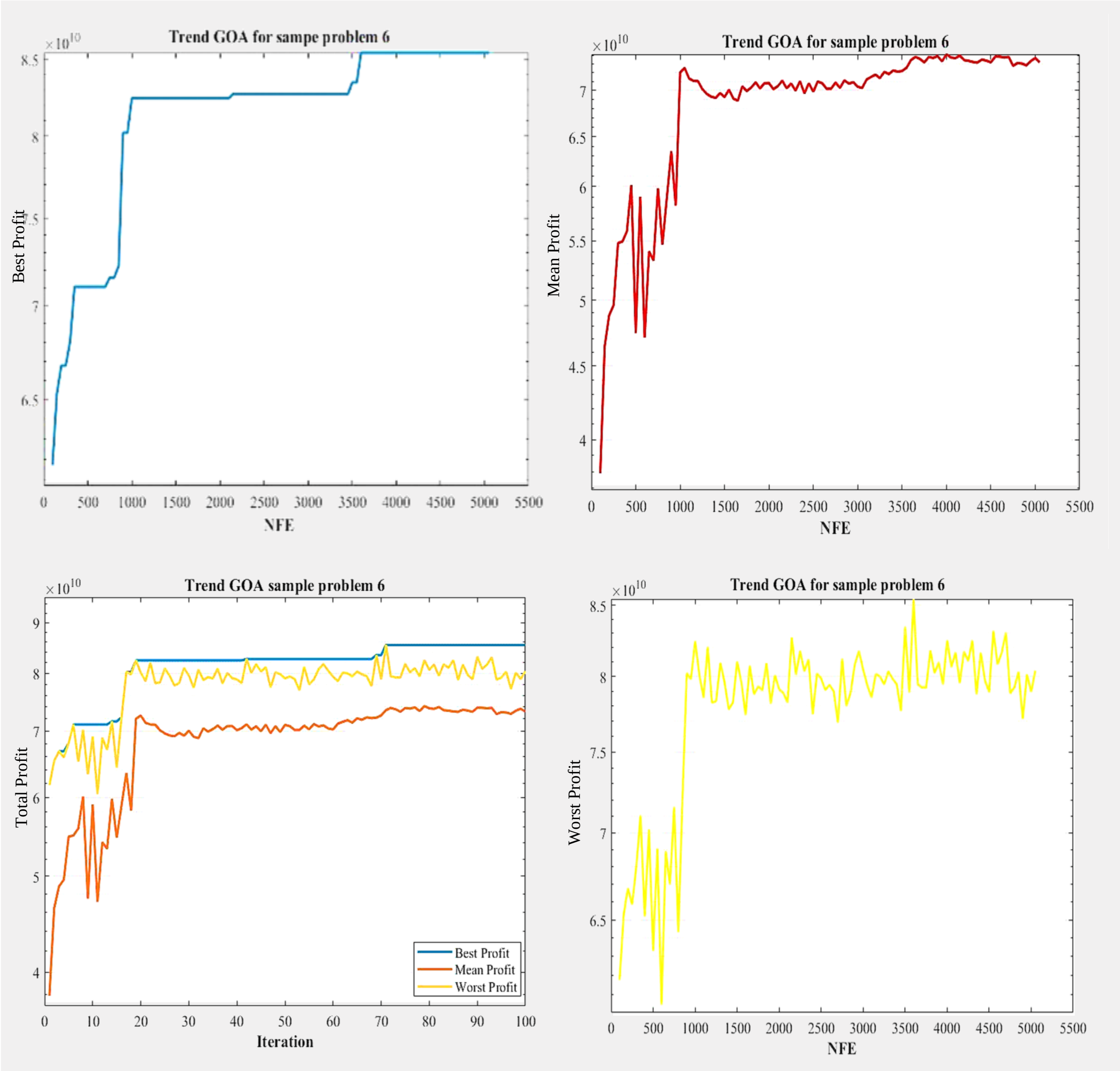
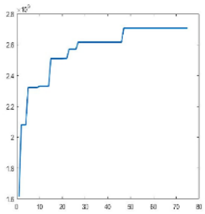
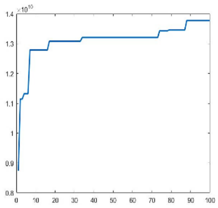
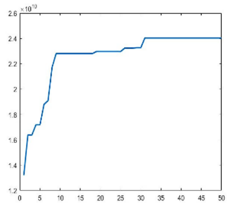
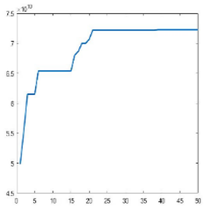
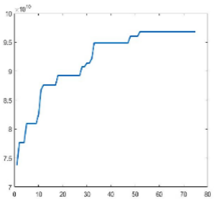
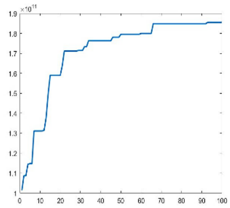


Fig 9. Trend GOA for sample problem 6

As shown in figure 9, grasshoppers eventually tend to explore the different search space regions around the global optimal. These results show that the GOA algorithm beneficially balances exploration and exploitation to drive the grasshoppers towards the global optimum. Generally, table 12 indicates the trend GOA for six sample problems.

Table 12. Convergence GOA diagram

Problem	Figure	Problem	Figure	Problem	Figure
1		**2**		**3**	
4		**5**		**6**	

The curves show the ascending behavior and it proves that the GOA enhances the initial random population and improves the accuracy of the approximated optimum over the course of iterations. Table 13 shows the Results of GOA and a comparison with actual values for the second medium-sized problem. The trajectory curves in figure 9 show that the grasshoppers largely made abrupt changes in initial steps of optimization. Exploration of search space is taking place due to the high repulsive rate of GOA. It is also seen that, as the optimization approaches further, the fluctuation decreased gradually. This is done due to the attraction forces as well as the comfort zone between grasshoppers. This guarantees that the algorithm will converge to a point eventually because of exploration and exploitation.

Table 13. Results of GOA and comparison with actual values

Function	Actual (GAMZ)	GOA		
		Best Profit	**Mean Profit**	**Worst Profit**
$\mathbf{Z_1}$(Profit)	8.54707E+10	85461880636.9177	73215170804.7486	80406027915.9712

To ensure the validity of the Grasshopper Optimization Algorithm results, we compared exact method and metaheuristic GOA with single objective. The results of this comparison are shown in table 14.

Table 14. Results of GOA and comparison with exact values

Problem size $(J, S, K, R, I, L, N, T, M)$	Gap	exact		GOA	
		Profit	**Time (s)**	**Best Profit**	**Time (s)**
(**3**, **3**, **4**, **4**, **4**, **4**, **4**, **3**, **3**)	1.17E-01	6.635E+10	980	7.510E+10	280
(**4**, **3**, **3**, **3**, **3**, **3**, **3**, **3**, **3**)	7.37E-02	8.633E+10	1853	9.320E+10	303
(**4**, **3**, **4**, **4**,**4**, **4**, **4**, **4**, **3**)	1.43E-01	11.042E+10	1965	12.891E+10	421

5-5-Sensitivity analysis

In this section, to evaluate the efficiency of the proposed method, we apply a sensitivity analysis on it, so we will compare the model in several problems that are solved by changing the value of some important parameters to analyze the model's sensitivity.

5-5-1-Demand

Figure 10 illustrates that decreasing demands consequences significantly impact on the number of located facilities in the first period. When demand decrease, it has the greatest impact on the number of collection and recycling centers, as the amount of collecting or recycling used tires in these centers, respectively, depending on a specific ratio of $\widetilde{RT}$ and $1-\widetilde{RR}$ for each type of tires, so decreasing demands lead to closing a number of these centers.

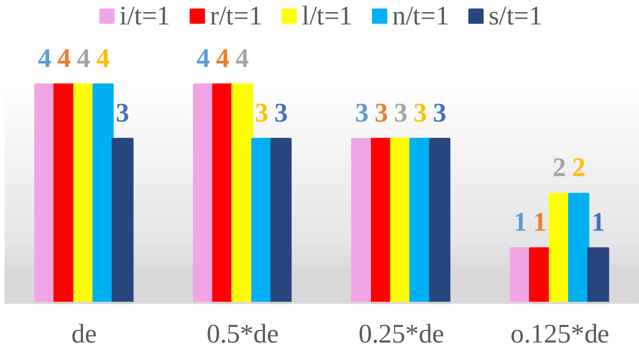


Fig 10. Impacts of decreasing demands on the number of located facilities

The table below shows the number of facilities located in the sixth Pareto Solution due to the decreasing demands in each period for the second medium-sized problem.

Table 15. Number of located facilities due to the decreasing demands in each period

Sixth Pareto Solution	de			0.5*de			0.25*de			0.125*de		
	t=1	t=2	t=3	t=1	t=2	t=3	t=1	t=2	t=3	t=1	t=2	t=3
i	4	4	4	4	4	4	3	4	4	1	2	1
r	4	4	4	4	4	4	3	4	4	1	2	2
l	4	3	3	4	3	2	3	3	1	2	2	1
n	4	3	2	3	2	1	3	2	1	2	1	1
s	3	3	3	3	2	3	3	3	3	1	2	2

As can be seen in the following figures, the number of located facilities decreases as long as the demand decreases (in a given period). It is also observed that this analysis between the two factors is still valid from one period to another.

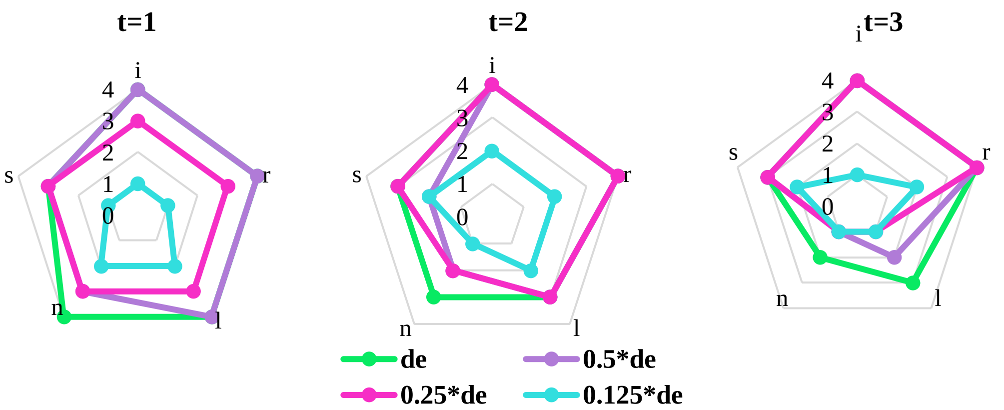


Fig 11. Impacts of decreasing demands on the number of located facilities in each period

5-5-2-Rate of return

Figure 12 shows the effect of increasing the rate of return used tires on total profits and carbon dioxide emissions. As seen, with the increasing rate of return used tires, the amount of carbon dioxide emissions has increased and supply chain total profits have decreased. Carbon dioxide emissions increase because of increasing transportation for collecting used tires and increasing the number of located facilities. Note that we have not considered the positive impact of collecting tires and returning them to collection centers on the environment. That is why the value of the second objective function is continuously increasing.

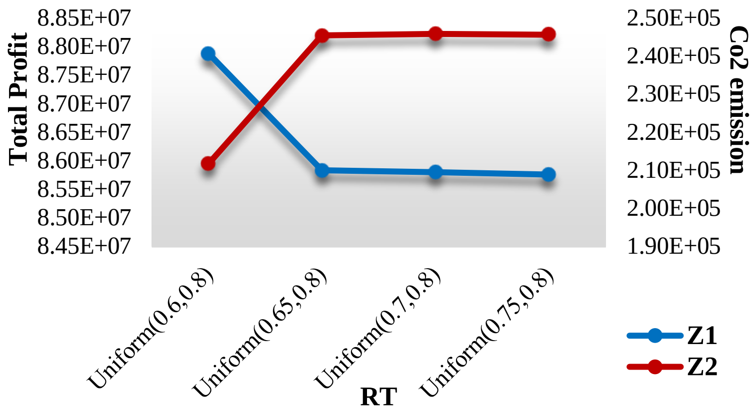


Fig 12. Impacts of increasing the rate of return used tires on total profits and Co_2 emission

5-5-3-Price of raw materials

Table 16 indicates the main results of solving the six test problems with sensitivity analyses on the price of raw materials and their effects on total profits and carbon dioxide emissions.

Table 16. The sensitivity analyses on the price of raw materials

cR	Obj. Function	Pareto Solution					
		1	2	3	4	5	6
uniform(10,17)	Z1	8.79E+07	8.78E+07	8.66E+07	8.50E+07	8.26E+07	7.89E+07
	Z2	3.17E+05	2.79E+05	2.42E+05	2.05E+05	1.68E+05	1.30E+05
uniform(10,15)	Z1	8.85E+07	8.79E+07	8.67E+07	8.51E+07	8.27E+07	7.90E+07
	Z2	3.19E+05	2.81E+05	2.44E+05	2.06E+05	1.69E+05	1.31E+05
uniform(10,13)	Z1	8.79E+07	8.79E+07	8.67E+07	8.50E+07	8.26E+07	7.90E+07
	Z2	3.16E+05	2.79E+05	2.42E+05	2.05E+05	1.67E+05	1.30E+05
uniform(10,11)	Z1	8.79E+07	8.85E+07	8.79E+07	8.67E+07	8.51E+07	8.26E+07
	Z2	3.16E+05	3.16E+05	2.79E+05	2.42E+05	2.05E+05	1.68E+05

Figure 13 shows the effect of decreasing the price of raw materials on total profits and carbon dioxide emissions in the second Pareto Solution. It can be seen that as the purchase cost of raw materials decreases, both objective functions gradually increase. In fact, by reducing the purchase cost of raw materials, on the one hand, the cost of the tire is reduced, which leads to an increase in profits, and on the other hand, more facilities are opened, which leads to increased environmental impact.

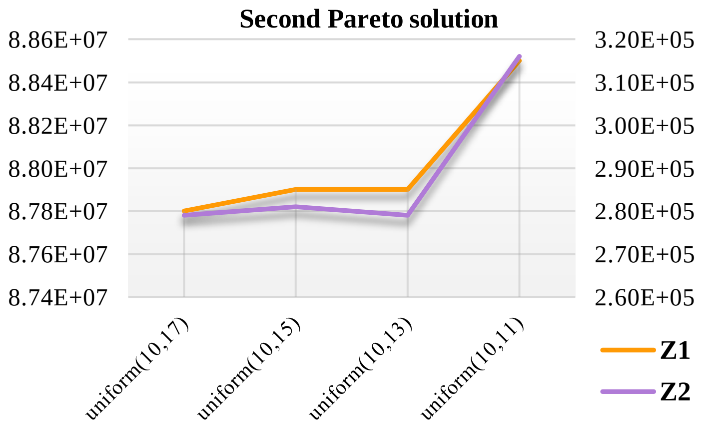


Fig 13. Impacts of decreasing the purchase cost of raw materials on total profits and Co_2 emission

5-6-Discussion

In this study six test problems in various dimension are designed. The test problems 1–2, test problems 3–4, and test problems 5–6 are considered small size, medium size, and large size, respectively. It should be noted that the test problems 1–4 have been solved by using the Augmecon-2 method and using the GOA algorithms for the test problems 5–6 and three additional test problems with medium sizes (see table 14). The main results of solving the test problem 4 is provided in table 4 and we provided GOA algorithm results of the test problem 6 in section 5-4 in detail. By using these results, and based on table 14 and figure 9, we understand that the GOA algorithm has good performance in terms of CPU time in large-scale test problems.

Based on the model and by evaluating the relationship between demands and opening different facilities, managers can determine the number of facilities they need to open in each period and allocate the appropriate funds and resources to them at the right time. So, they can manage their demand and financial constraints more efficiently. Also, as the purchase price of raw materials decreases, revenue increases, but the model shows that pollution also increases. Therefore, managers must control environmental impacts by adopting appropriate policies and environmental restrictions, in situations where they can purchase raw materials at low prices.

This paper design a closed-loop supply chain network for the automotive tire industry by proposing a bi-objective mathematical model that thinks of a bi-objective mathematical model whose environmental aspects are also considered in this formulation. This network attempt to help managers for finding proper suppliers, suitable facilities locations, and optimal shipped quantity of products and proposed managerial implications. Thus, results confirm that considering the uncertainty and integrating it with a bi-objective mathematical model caused the model to be closed the real world. Also, considering the environmental aspects can help the company achieve fund or avoid being penalties by environmental officials and from the perspective of the people be popular. In most of the literature cases, uncertainty has been considered in one or two parameters (see table 1). In this study, by using the proposed model, it is straightforward to take into account the effects of uncertainty in all parameters, especially the rate of returned products in Tire CLSC network.

6-Conclusion

In recent years, the field of closed-loop supply chain (CLSC) has received more attention from manufacturers from different economic, environmental, and political points of view. Accordingly, considering reverse supply chains along with forward supply chains has become essential more than ever. On the other hand, the ever-increasing number of used tires brings on serious environmental problems. In addition, the approach followed to deal with used tires plays an important role in terms of economic benefits, market demand, etc. In this regard, a comprehensive and effective planning is needed to collect and recycle end-of-life tires in an appropriate way.

In this work, a bi-objective mixed-integer linear programming model was proposed to design a green closed-loop supply chain tire remanufacturing network. This model includes some of the customer centers, collection centers, recycling centers, manufacturing/remanufacturing plants, and distribution centers. The network design of this tire industry, considering the uncertainty in parameters such as demand, the rate of return used tires, makes the model closer to reality. A mathematical model that takes into account two indispensable dimensions of a green closed-loop supply chain (exhaust gases, and supply chain profit). The purpose of this model is to maximize the total profit in the CLSC network and minimize exhaust gases to achieve the best structure for the green closed-loop network by determining the location and number of facilities in each echelon and the amount of flow of tires between the facilities of each echelon. To achieve this, different potential locations of facilities and flows of tires between them were defined and the corresponding decisions, considering their estimated costs, were modeled as binary variables and positive variables, respectively. To solve the proposed fuzzy model, it was converted to an equivalent counterpart by Jimenez method. In this method as the β decreases, the solution space of the model and the possibility of finding a better answer for both objective functions increase. As we can see in figure 4 with decreasing the level β, the computational time, it has also been uptrend. Also, an augmented ε-constraint method was applied for obtaining an efficient solution with the bi-objective functions of the model. To illustrate the efficiency of the proposed model, a numerical example is considered. Also, to obtain computational results, the proposed model is computed in the Gams software and using the BARON solver. In order to adjust the parameters and operators of the GOA algorithms, the relevant parameters are tuned. The computational results show that the proposed GOA is capable of obtaining closer solutions compared with actual values in sample problem 6. Finally, for future research, the following directions can be useful.

- Combining other topics such as pricing and vehicle routing with the issue
- Considering the environmental impact of released tire type on the environment
- Analyzing cannibalization effects on the volume of new manufactured tires
- Reviewing the conditions of other nascent industries and modeling for their improvement and development

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