



# A Robust Multi-objective Fuzzy Model for a Green Closed-loop Supply Chain Network under Uncertain Demand and Reliability (A Case Study in Engine Oil Industry)

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## ABSTRACT

Given the importance of supply chain and environmental issues, this paper presents a new mathematical model for a green closed-loop supply chain (GCLSC) network with the objectives of maximizing profits, maximizing the number of jobs created, and maximizing reliability. Due to the uncertainty on some parameters such as demand and transportation costs, the new method of robust fuzzy programming model was utilized. Multi-objective Grey Wolf Optimizer (MOGWO) and Non-dominated Sorting Genetic Algorithm II (NSGA II) were used to tackle the problems for larger sizes. A number of instances of the problem in larger sizes were solved. The results from comparing the algorithms considering some criteria including means of objective functions, spacing index, distance index from ideal point, maximum amplitude index, Pareto response number index and computational time showed the fast convergence and high efficiency of MOGWO algorithm for this problem. Finally, the implementation of the model for a real case study in Iranian engine oil industry, showed the efficiency of the obtained solutions for this network.

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## 1. INTRODUCTION

In today's world, economic and industrial change is happening faster than ever before. The goal of organizations and companies is to maintain and increase profits as well as greater survival and durability in the market. The globalization of economic activities, along with the rapid growth of technology as well as limited resources, has put companies in an intense competition. One of the competitive advantages for companies is to make activities such as supply chain more efficient and effective. The term supply chain management (SCM) was coined in the late 1980s and became more widely used in 1990s. In this view, in order to survive in competitive markets, organizations must not only manage and optimize their organizational units, but must integrate all the organizational units in the network, including the suppliers and the customers. However, in

recent years, increasing competition in the global market to quickly meet customer needs and provide quality products has led to negative environmental effects, including an increase in greenhouse gas emission. Government laws, environmental pressures, and growing public awareness have forced companies to collect discarded products and goods and to consider more environmental factors in future products. This has led to the creation of a new management concept called green supply chain, which is actually a new paradigm for environmental protection along with SCM [1].

Supply chain is an attitude that has been considered by organizations and companies in recent years. In this approach, all components and circles that are together to provide a product or service to the customer, are considered and try to make strategic, tactical, and operational decisions in such a way that the entire supply chain is more efficient and effective against competing

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chains. A supply chain is not limited to components and places of production, but includes all components of production and services from the initial suppliers to the final customers [2]. Lack of coordination and integration between different parts of the supply chain result in to an increase in the cost of goods and consequently an increase in price, failure to deliver products on time, etc., which ultimately cause to an increase in consumer dissatisfaction. A supply chain is a flow of materials and information between different levels of a manufacturing or service network that includes suppliers, manufacturers, distributors, wholesalers, retailers, and end customers. In recent years, organizations and companies have taken responsibility for waste products based on the nature of the products, legal and environmental requirements, as well as the re-acquisition of value. In view of the above, the supply chain network is broader and includes product collection, inspection, repair, recycling and destruction centers [3].

Since the introduction of the first supply chain design ideas in the late 1970s, nothing has attracted the attention of governments, corporate executives and the public as much as green supply chain design, which is the most important tool for organizations to adapt their activities to the environment. It should be noted that the concept of green supply chain is not just a general slogan for idealistic people, but in many countries, organizations have made every effort to implement it. Today, some of the leading companies are already actively implementing green projects, for example IKEA, the world's largest furniture maker, has set up a train network emphasizing green train operations. In addition, General Electric, IBM, and HP have all considered green products with the adoption of new energy-saving technologies, and in addition to product design, they have considered SCM to relieve environmental concerns [4].

On the other hand, government regulations and increasing customer awareness of the environment have made environmental aspects important in the work of researchers, building models and working frameworks for the effectiveness of the ecosystem in the supply chain networks. China, for example, has set a target of reducing carbon emissions by 10% in the Ninth Eleventh Development Plan, and the central government is studying and preparing for environmental protection oversight policies which are expected to play a positive role in solving the environmental problems. To implement a green supply chain network, it is not just enough to pay attention to being green; on the other hand, it is important to implement the green factors when designing the physical facilities and operating the supply chain. Furthermore, a good design can reduce CO<sub>2</sub> emissions all over the supply chain network.

Due to the importance of the GCLSC (which is a combination of forward and reverse supply chain), this paper presents a new model of multi-objective GCLSC

which incorporates some real-world features. The importance of implementing new models to reduce operational costs as well as pollution has been emphasized in this article by addressing a three-objective model including maximizing network profits, recruitment rates and reliability. Considering the governmental restrictions and laws on the amount of greenhouse gas emissions, the addressed restrictions have implemented in the given mathematical model. Uncertainty on demand and some other cost parameters has also led to the use of the new fuzzy robust method. Finally, for the assessment of the model performance in the real world, a real case study in the Iranian engine oil industry has been studied.

The structure of the paper is as follows: In section 2, the literature review is given and the research gap is presented. In section 3, the initial version of the uncertain multi-objective GCLSC model is proposed and then its converted version is given. In this section, a solid fuzzy optimization method is used to control the uncertainty of the model. In section 4, the solution algorithms, the design of the primary chromosome, as well as the comparison indicators of the algorithms are presented. In section 5, the results from model implementation in an Iranian engine oil industry are discussed. Finally, in section 6, the conclusions from this research together with further research ideas are presented.

## 2. LITERATURE REVIEW

In this section, some of the most important researches in the field of closed-loop supply chain (CLSC) network design are reviewed. Kim et al. [5] established a multi-cycle CLSC with the objective of maximizing factory profit. The network was designed to start with the return of used products and return by the customer and then accumulated and dismantled in the collection center. Some of the returned products were sent to the reproduction department and the usable parts were transferred to the renovation department and repaired. Finally, the parts were assembled, reproduced and classified for sale to foreign suppliers as new products [5]. Ahmadi-javid and Hoseinpour [6] modeled a distribution network considering location-inventory decisions and pricing with limited inventory capacity. They used Lagrange release algorithm to solve their problem [6]. Kaya and Urek [2] developed a definitive CLSC network model with simultaneous location-inventory and pricing decisions. They used the refrigeration and forbidden search simulation algorithm to tackle the problem [2]. Ahmadzadeh and Vahdani [7] presented a model for integrated location-inventory and pricing decisions in the CLSC network. Their main purpose was to decide on the optimal locations of facilities, taking into account inventory costs and product

pricing. They used genetic algorithms, firewalls and colonial competition algorithms to solve their problem [7]. Amin et al. [4] in their research, designed and optimized a CLSC network with tire remanufacturing based on tire retrieval options, with the objective of maximization of the total profit. The application of this model based on a realistic network in Toronto, Canada has been discussed using a geographical map. In this model, he uses a new decision tree-based method to calculate the net present value of the income over several periods under various sources of uncertainty, such as demand and return. In addition, discount cash flow in this method was considered as a new innovative approach. This method can be used to compare the profitability of different design options for a CLSC [4]. In a study, Hajiaghahi-Keshteli and Fard [8] developed a new mixed-integer programming model to create a multi-purpose stable CLSC network scheme for the first time, assuming a reduction in transportation costs. To address the problem, not only traditional and recent metaphors are used, but also algorithms are combined according to their strengths, especially in intensification and diversification. To evaluate the efficiency and effectiveness of these algorithms, they are compared with four evaluation criteria for optimal Pareto analysis [8]. Mardan et al. [9] provided a comprehensive mathematical model for the multi-cycle, multi-product, multi-model, and two-objective GCLSC. The purpose of this model was to minimize the total cost and emission of ambient gases by deciding on the locations of the facilities, the amount of transportation and the inventory balance. The results showed that the proposed solution approach reduced the total cost by more than 13 percent and can even be used for larger and more complex industrial applications in the real world [9]. Yadegari et al. [10] developed a memetic algorithm (MA) with priority-based coding/decoding method based on a flexible neighborhood search (NS) strategy to improve strategies for simultaneous configuration of the chains. In addition, to avoid the time-consuming repair process in the discrete solution dealership, it provided a way to convert the discrete dealership to a continuous method, and finally, to accelerate the proposed algorithm, the multi-stage simulation (MSA) re-embedding was embedded into the MA [10]. In a study, Yavari and Zaker [11] examined the design of a GCLSC network for biodegradable products under uncertain conditions. Demand, rate of return and quality of returned products were considered as uncertain parameters of the model [11]. Saedinia et al. [12] proposed a nonlinear mixed-integer programming model to consider the price and position of facilities in a CLSC in the information and communication technology (ICT) industry to obtain the total profit generated by the sale of new ICT products. The structure of this network included suppliers, collection and distribution centers (C-D centers),

disassembly centers and customer areas. In C-D centers, an inventory policy of continuous review was applied and it was assumed that the ordering time is random. Numerical results showed how to allocate facilities to each other, inventory management and pricing of ICT products; therefore, the proposed models and methods could help ICT companies in determining their policies for maximum profit [12]. In a research, Nayeri et al. [13] presented a robust multi-objective fuzzy optimization model in the design of a stable CLSC network. In this study, they considered parameters such as demand and transportation costs to be uncertain [13]. Prakash et al. [14] presented a model of a CLSC network in which parameters such as risk and demand were considered. They optimized the developed model using the combined robust method [14]. Fatollahi fard et al. [15] presented a model for CLSC network system in case of uncertainty for water reverse purification and developed a multi-objective stochastic optimization model with triple bottom line optimization. Fazli-Khalaf and Hamidieh [16] designed a reliable multi-echelon CLSC network model which maximized the social responsibility while minimized the fixed establishing and variable processing costs of the network. To cope with the uncertainty of parameters, stochastic programming was applied and an effective reliable modelling method was employed to appropriately control unpleasant economic impacts of disruptions. On the uncertainty in supply chain, Hamidieh et al. [17] proposed a robust reliable bi-objective supply chain network design model which was capable of controlling different kinds of uncertainties, concurrently. Stochastic bi-level scenario based programming approach was used to model various scenarios related to strike of disruptions. Tables 1 and 2 give some abbreviated forms of employed terms and comparison of the GCLSC researches.

**TABLE 1.** Abbreviated forms of employed terms

Abbreviation	Term
SPR	Single Product
MPR	Multi Product
SPE	Single Period
MPE	Multi Period
QN	Quantitative
QA	Qualitative
FS	Forward Supply Chain
RS	Reverse Supply Chain
CS	Closed-Loop Supply Chain
L	Location
A	Allocation
R	Routing
SH	Shortage

SS	Supplier Selection	MRE	Max Reliability
D	Discount	MQL	Min Queue Length
Q	Queueing System	MSC	Max Supply Chain Responsiveness
FP	Fuzzy Programming	MNV	Max Net Value
SP	Stochastic Programming	MPR	Max Profit
RP	Robust Programming	MSL	Max Service Level
RFP	Robust-Fuzzy Programming	MDL	Min Number of Days Lost
RSP	Robust-Stochastic Programming	MDT	Min Delivery Time
FSP	Fuzzy-Stochastic Programming	MCO	Min Cost
RFSP	Robust-Fuzzy-Stochastic Programming	MLR	Min Loss of Raw Materials
DE	Deterministic	MNV	Min Number of vehicles
CS	GAMS-Lingo	MCE	Min Co2 Emission
MO	Multi Objective Decision Method	MSH	Min Shortage
MH	Meta-Heuristics Algorithm	MNJ	Max Number of Jobs
FO	Fuzzy Optimization Method	MRI	Min Risk

**TABLE 2.** Comparison of the GCLSC researches

Research	Year	Model	Objective	Variable	Uncertainty	Solution	Case Study
Alshamsi and Diabat [18]	2018	SPR, SPE, QN	MPR	L, A,	DE	CS	
Rad and Nahavandi [19]	2018	MPR, MPE, QN	MCO, MCE	L, A, SH, D	DE	MO	*
Fakhrzad et al. [20]	2018	MPR, MPE, QN	MCO, MDT, MCE, MRE	L, A, R, SS	DE	MH	
Pourjavad and Mayorga [21]	2019a	MPR, MPE, QN	MCO	L, A, SH	DE	CS	*
Yadegari et al. [10]	2019	SPR, MPE, QN	MCO	L, A	DE	CS	*
Polo et al. [22]	2019	SPR, MPE, QN	MPR	L, A, SH	RP	CS	
Ghahremani Nahr et al. [23]	2019	MPR, MPE, QN	MCO	L, A, SH, SS, D	RFP	MH	
Pourjavad and Mayorga [24]	2019b	MPR, MPE, QN	MCO, MCE, MNJ	L, A, SS	FP	MO	
Darestani and Hemmati [25]	2019	MPR, MPE, QN	MCO, MCE	L, A, SH, SS, D, Q	RP	MO	
Zhang et al. [26]	2019	SPR, SPE, QN	MDT, MDL	L, A	RFP	MO	
Fazli khalaf et al. [27]	2019	MPR, MPE, QN	MCO, MDT, MRE	L, A, SH, R	RFP	FO	*
Alkhayyal [28]	2019	MPR, SPE, QN	MCO, MCE	L, A	DE	MO	*
Mardan et al. [9]	2019	MPR, MPE, QN	MCO, MCE	L, A, R, SS	DE	CS	
Ghahremani- Nahr et al. [29]	2020b	MPR, MPE, QN	MCO, MCE	L, A, SH, D	RP	MO	
Jiang et al. [30]	2020	SPR, SPE, QN	MPR, MSL	L, A	DE	MO	
Gholizadeh et al. [31]	2020	MPR, MPE, QN	MPR	A, R	RP	MH	
Prakash et al. [14]	2020	SPR, SPE, QN	MCO	L, A	RP	CS	*
Pourmehdi et al. [32]	2020	SPR, SPE, QN	MCE, MPR, MSL	L, A	SP	FO	*
Mohtashemi et al. [33]	2020	SPR, SPE, QN	MCO, MCE	L, A, SS, Q	DE	MH	
Liu et al. [34]	2021	MPR, MPE, QN	MCO, MCE	L, A	RFP	CS	*
Zahedi et al. [35]	2021	MPR, MPE, QN	MNV, MSL	L, A, R	DE	MH	*
Boronoos et al. [36]	2021	MPR, MPE, QN	MCO, MCE	L, A	RFP	MO	*
Habib et al. [37]	2021	SPR, MPE, QN	MCO	L, A	RFP	CS	*
This paper		MPR, MPE, QN	MPR, MRE, MNJ	L, A, R, SH, SS, D, Q	RFP	MO	*

As a research gap, according to the given literature, a comprehensive uncertain model which includes three aspects of economic, social and environmental with uncertainty on some key parameters of the model has not been studied. Furthermore, the application of the model in engine oil industry has not been studied. The major novelties and features of this paper are:

- Developing a three-objective model for CLSC design of engine oil industry
- Using robust fuzzy programming to tackle with the uncertainties in demand, transportation costs and capacity levels of facilities
- Development of two meta-heuristic algorithms in order to solve the problem for large sizes
- Solving the model for small and large sizes of the problem
- Solving the model utilizing the real data of engine oil industry

### 3. PROBLEM DESCRIPTION AND MODELING

In this paper, a GCLSC network is modeled under the uncertainty of some of the most important parameters of the problem (i.e. demand and transportation costs). Figure 1 shows the under-study GCLSC network in which the main purpose is to supply engine oil products to customers in the primary market and to increase the energy recovery and to meet the secondary market demand of returned products. In this case, the suppliers, who are actually in charge of supplying the raw materials, send the raw materials to the manufacturers who produce the final products. Manufacturers produce the final products using a combination of some predetermined materials and send them to distributors. Distributors distribute the final products according to the uncertain demand of customers for each product, taking into account the shortage. In the given model, the reverse supply chain is also considered. The main purpose of designing such a network is to properly manage and reuse

returned products from customers. In this network, according to various issues, a percentage of products are collected at the collection center and after inspection are sent to one of the specified centers for energy recovery, recycling or disposal in the landfill. Recycled products can be reused in the primary market or sold to the secondary market as lower level quality product by adding some raw materials or changing the structure of the product. In the meantime, some returned products may no longer be reusable, even after recycling because of the poor quality; In this case, they are sent to the landfill for disposal.

There are three types of strategic, tactical and operational decisions in this model. At the strategic level, the problem is to determine the number and capacities of potential network facilities including production, distribution, recycling and collection centers. At the tactical level, the optimal flows of materials, products and returned items are determined between different facilities of the network. At the operational level, the appropriate vehicles between facilities are selected. According to the following assumptions, the model of the problem can be formulated.

1. The objective functions of the problem include maximizing the profit of the entire supply chain network, maximizing the number of created jobs and maximizing the reliability of the CLSC network.
2. Demand, supply capacities, transportation costs and some operating costs are considered to be uncertain.
3. Shortage is permitted.
4. The transport fleet is considered heterogeneous.
5. The cost of greenhouse gas emissions is considered as part of the first objective function.
6. Establishment of facility capacity at different levels has different costs.

According to the mentioned assumptions, the set, parameters and decision variables of the model are as follows:

#### 3. 1. Sets

- $A$  Set of customers fixed points  $a = \{1,2, \dots, A\}$
- $K$  set of potential distribution centers  $k = \{1,2, \dots, K\}$
- $J$  set of potential manufacturing centers  $j = \{1,2, \dots, J\}$
- $I$  set of raw material supply centers  $i = \{1,2, \dots, I\}$
- $L$  set of disposal centers  $l = \{1,2, \dots, L\}$
- $N$  set of potential recycling centers  $n = \{1,2, \dots, N\}$
- $M$  set of potential collection centers  $m = \{1,2, \dots, M\}$
- $E$  set of energy recovery centers  $e = \{1,2, \dots, E\}$
- $B$  Set of secondary market fixed points  $b = \{1,2, \dots, B\}$
- $G$  Set of potential facility capacity levels  $g = \{1,2, \dots, G\}$
- $P$  Product range (i.e. engine oil and its products in the case study)  $p = \{1,2, \dots, P\}$
- $H$  set of raw materials  $h = \{1,2, \dots, H\}$
- $V$  set of vehicles  $v = \{1,2, \dots, V\}$

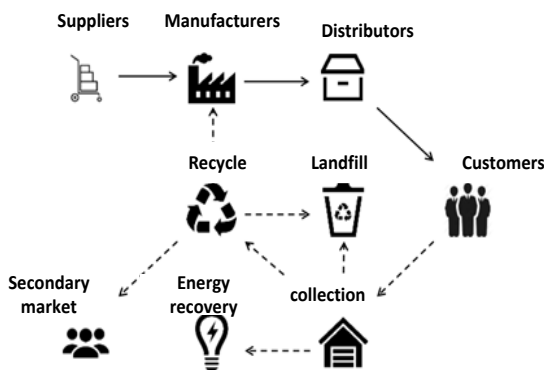


Figure 1. The under-study GCLSC network

### 3. 2. Parameters

$\overline{Dem}_{ap}$	Demand of customer $a$ for product $p$	$D_{ml}$	Distance of collection center $m$ from disposal center $l$
$O_{hp}$	The amount of raw material $h$ required to produce one unit of product $p$	$D_{nl}$	Distance of recycling center $n$ from disposal center $l$
$\alpha_{ap}$	Percentage of product $p$ returned by customer $a$	$D_{nb}$	Distance of recycling center $n$ from secondary market $b$
$\beta_{mp}$	Percentage of product $p$ transferable to energy recovery center by collection center $m$	$\pi_{ap}$	Shortage cost of product $p$ at customer $a$
$\gamma_{mp}$	Percentage of product $p$ transferable to recycling center by collection center $m$ , $\beta_{mp} + \gamma_{mp} < 1, \forall m, p$	$\overline{PC}_{jp}$	Production cost of product $p$ in manufacturing center $j$
$\delta_{np}$	Percentage of product $p$ transferred to disposal center by recycling center $n$	$\overline{SC}_{ih}$	Cost of supplying raw material $h$ by supplier $i$
$\sigma_{np}$	Percentage of product $p$ transferred to production center by recycling center $n$ , $\delta_{np} + \sigma_{np} < 1, \forall n, p$	$\overline{DC}_{kp}$	Shipping Cost of one unit of product $p$ from distribution center $k$
$CapJ_{jpg}$	Capacity for producing product $p$ at Manufacturer center $j$ at capacity level $g$	$\overline{CC}_{mp}$	Cost of collecting one unit of product $p$ at collection center $m$
$CapK_{kp}$	Capacity allocated by distributor $k$ to product $p$ at capacity level $g$	$\overline{RC}_{np}$	Cost of recycling one unit of product $p$ in recycling center $n$
$CapM_{mi}$	Capacity allocated by collection center $m$ to product $p$ at capacity level $g$	$\overline{LC}_{lp}$	Disposal cost of one unit of product $p$ at disposal center $l$
$CapN_{np}$	Capacity allocated by recycling center $n$ to product $p$ at capacity level $g$	$\overline{RPC}_{jp}$	Cost of remanufacturing product $p$ in remanufacturing center $j$
$\overline{CapI}_{ih}$	Capacity of supplier $i$ for replenishment of raw material $h$	$Co2_v$	Amount of carbon dioxide emission by vehicle $v$ per unit distance
$CapL_{lp}$	Capacity allocated by disposal center $l$ to product $p$	$CO_2^{GOV}$	The acceptable amount of carbon dioxide emissions in the supply chain network determined by government
$Capw_v$	Weight capacity of vehicle $v$	$E_{jg}$	Amount of carbon dioxide emissions due to construction of manufacturing center $j$ with capacity level $g$
$Capv_v$	Volume capacity of vehicle $v$	$E_{kg}$	Amount of carbon dioxide emission due to construction of distribution center $k$ with capacity level $g$
$w_h$	Weight of one unit of raw material $h$	$E_{mg}$	Amount of carbon dioxide emission due to construction of collection center $m$ with capacity level $g$
$w_p$	Weight of one unit of product $p$	$E_{ng}$	Amount of carbon dioxide emission due to construction of recycling center $n$ with a capacity level $g$
$v_h$	Volume of one unit of raw material $h$	$Pe_{jp}$	Amount of carbon dioxide emission due to producing one unit of product $p$ in the production center $j$
$v_p$	Volume of one unit of product unit $p$	$Ce_{mp}$	Amount of carbon dioxide emission due to collection of one unit of product $p$ in collection center $m$
$Pr_{ap}$	Selling price of one unit of product $p$ to customer $a$	$Re_{np}$	Amount of carbon dioxide emission due to recycling one unit of product $p$ at recycling center $n$
$Pr_{ep}$	Selling price of one unit of product $p$ to energy recovery center $e$	$Le_{lp}$	Amount of carbon dioxide emission due to disposal of one unit of product $p$ at disposal center $l$
$Pr_{bp}$	Selling price of one unit of product $p$ to secondary market $b$	$RPe_{jp}$	Amount of carbon dioxide emission due to remanufacturing product $p$ in manufacturing center $j$
$F_{jg}$	Fixed cost of constructing manufacturing center $j$ at capacity level $g$	$\vartheta$	Fixed cost of excess carbon dioxide emission
$F_{kg}$	Fixed cost of constructing distribution center $k$ with capacity level $g$	$JOB_{jg}$	Number of job opportunities created by constructing manufacturing center $j$ with capacity level $g$
$F_{mg}$	Fixed cost of constructing collection center $m$ with capacity level $g$	$JOB_{kg}$	Number of job opportunities created by constructing distribution center $k$ with a capacity level $g$
$F_{ng}$	Fixed cost of constructing recycling center $n$ with capacity level $g$	$JOB_{mg}$	Number of job opportunities created by constructing collection center $m$ with capacity level $g$
$FC_v$	Fixed cost of utilizing vehicle $v$		
$\overline{FV}_v$	The variable cost of vehicle $v$ per unit distance between two facilities		
$D_{ka}$	Distance of distribution center $k$ from customer $a$		
$D_{jk}$	Distance of production center $j$ from distribution center $k$		
$D_{ij}$	Distance of supplier $i$ from manufacturing center $j$		
$D_{nj}$	Distance of recycling center $n$ from manufacturing center $j$		
$D_{am}$	Distance of customer $a$ from collection center $m$		
$D_{me}$	Distance of the collection center $m$ from energy recovery center $e$		
$D_{mn}$	Distance of collection center $m$ from recycling center $n$		

$JOB_{ng}$	Number of job opportunities created by constructing recycling center $n$ with capacity level $g$
$ALD_{jg}$	Average number of days lost because of work injuries due to construction of manufacturing center $j$ with capacity level $g$
$ALD_{kg}$	Average number of days lost because of work injuries due to construction of distribution center $k$ with capacity level $g$
$ALD_{mg}$	Average number of days lost because of work injuries due to construction of collection center $m$ with capacity level $g$
$ALD_{ng}$	Average number of days lost because of work injuries due to construction of recycling center $n$ with capacity level $g$
$\varphi_{ALD}$	Significance factor of the total number of lost days due to injuries in the workplace
$\theta_{job}$	Significance factor of the number of job opportunities created
$Re_{ijh}$	Reliability of shipping raw material $h$ from supplier $i$ to manufacturing center $j$
$Re_{jkp}$	Reliability of shipping product $p$ from manufacturing center $j$ to distribution center $k$
$Re_{kap}$	Reliability of shipping product $p$ from distribution center $k$ to customer $a$

$Y_{jkv}$	If vehicle $v$ is assigned to the rout from manufacturing center $j$ to distribution center $k$ , it takes 1, otherwise it takes 0.
$Y_{ijv}$	If vehicle $v$ is assigned to the rout from supplier $i$ to manufacturing center $j$ , it takes 1 and otherwise 0.
$Y_{nfv}$	If vehicle $v$ is assigned to the rout from recycling center $n$ to manufacturing center $j$ , it takes 1 and otherwise 0.
$Y_{amv}$	If vehicle $v$ is assigned to the rout from customer $a$ to collection center $m$ , it takes 1 and otherwise 0.
$Y_{mev}$	If vehicle $v$ is assigned to the rout from collection center $m$ to energy recovery center $e$ , it takes 1, otherwise it takes 0.
$Y_{mnv}$	If vehicle $v$ is assigned to the rout from collection center $m$ to recycling center $n$ , it takes 1, otherwise it takes 0.
$Y_{mlv}$	If vehicle $v$ is assigned to the rout from collection center $m$ to disposal center $l$ , it takes 1, otherwise it takes 0.
$Y_{nlv}$	If vehicle $v$ is assigned to the rout from recycling center $n$ to disposal center $l$ , it takes 1, otherwise it takes 0.
$Y_{nbv}$	If vehicle $v$ is assigned to the rout from recycling center $n$ to secondary market $b$ , it takes 1, otherwise it takes 0.

**3. 3. Decision Variables**

$Q_{kap}$	The amount of product $p$ shipped from distribution center $k$ to customer $a$
$Q_{jkp}$	The amount of product $p$ shipped from manufacturing center $j$ to distribution center $k$
$Q_{ijh}$	The amount of raw material $h$ shipped from supplier $i$ to manufacturing center $j$
$Q_{njp}$	The amount of product $p$ returned from the recycling center $n$ to production center $j$
$Q_{amp}$	The amount of product $p$ returned from customer $a$ to collection center $m$
$Q_{mep}$	The amount of product $p$ returned from collection center $m$ to energy recovery center $e$
$Q_{mnp}$	The amount of product $p$ returned from collection center $m$ to recycling center $n$
$Q_{mlp}$	The amount of product $p$ returned from collection center $m$ to disposal center $l$
$Q_{nlp}$	The amount of product $p$ returned from recycling center $n$ to disposal center $l$
$Q_{nbp}$	The amount of product $p$ returned from recycling center $n$ to secondary market $b$
$S_{ap}$	The amount of shortage of product $p$ at customer $a$
$U_{jg}$	If manufacturing center $j$ is established with capacity level of $g$ , it takes 1 and otherwise it takes 0.
$U_{kg}$	If distribution center $k$ is established with capacity level of $g$ , it takes 1, otherwise it takes 0.
$U_{mg}$	If collection center $m$ is established with capacity level of $g$ , it takes 1, otherwise it takes 0.
$U_{ng}$	If recycling center $n$ is established with capacity level of $g$ , it takes 1, otherwise it takes 0.
$Y_{kav}$	If vehicle $v$ is assigned for shipping to customer $a$ from distribution center $k$ , it takes 1, otherwise it takes 0.

**3. 4. Proposed Model**

$$\begin{aligned}
 \max Z_1 = & \sum_k \sum_a \sum_p Pr_{ap} Q_{kap} + \\
 & \sum_m \sum_e \sum_p Pr_{ep} Q_{mep} + \sum_n \sum_b \sum_p Pr_{bp} Q_{nbp} - \\
 & \sum_j \sum_g F_{jg} U_{jg} - \sum_k \sum_g F_{kg} U_{kg} - \sum_m \sum_g F_{mg} U_{mg} \\
 & - \sum_n \sum_g F_{ng} U_{ng} - \sum_i \sum_j \sum_v FC_v Y_{ijv} - \\
 & \sum_j \sum_k \sum_v FC_v Y_{jkv} - \sum_k \sum_a \sum_v FC_v Y_{kav} - \\
 & \sum_a \sum_m \sum_v FC_v Y_{amv} - \sum_m \sum_l \sum_v FC_v Y_{mlv} - \\
 & \sum_m \sum_e \sum_v FC_v Y_{mev} - \sum_m \sum_n \sum_v FC_v Y_{mnv} - \\
 & \sum_n \sum_l \sum_v FC_v Y_{nlv} - \sum_n \sum_b \sum_v FC_v Y_{nbv} - \\
 & \sum_n \sum_j \sum_v FC_v Y_{njv} - \sum_i \sum_j \sum_v \bar{F}\bar{V}_v D_{ij} Y_{ijv} - \\
 & \sum_j \sum_k \sum_v \bar{F}\bar{V}_v D_{jk} Y_{jkv} - \sum_k \sum_a \sum_v \bar{F}\bar{V}_v D_{ka} Y_{kav} - \\
 & \sum_a \sum_m \sum_v \bar{F}\bar{V}_v D_{am} Y_{amv} - \sum_m \sum_l \sum_v \bar{F}\bar{V}_v D_{ml} Y_{mlv} - \\
 & \sum_m \sum_e \sum_v \bar{F}\bar{V}_v D_{me} Y_{mev} - \sum_m \sum_n \sum_v \bar{F}\bar{V}_v D_{mn} Y_{mnv} \\
 & - \sum_n \sum_l \sum_v \bar{F}\bar{V}_v D_{nl} Y_{nlv} - \sum_n \sum_b \sum_v \bar{F}\bar{V}_v D_{nb} Y_{nbv} \\
 & - \sum_n \sum_j \sum_v \bar{F}\bar{V}_v D_{nj} Y_{njv} - \sum_i \sum_j \sum_h \bar{S}C_{ih} Q_{ijh} - \\
 & \sum_j \sum_k \sum_p \bar{P}C_{jp} Q_{jkp} - \sum_k \sum_a \sum_p \bar{D}C_{kp} Q_{kap} - \\
 & \sum_a \sum_m \sum_p \bar{C}C_{mp} Q_{amp} - \sum_m \sum_n \sum_p \bar{R}C_{np} Q_{mnp} - \\
 & \sum_m \sum_l \sum_p \bar{L}C_{lp} Q_{mlp} - \sum_n \sum_l \sum_p \bar{L}C_{lp} Q_{nlp} - \\
 & \sum_n \sum_j \sum_p \bar{P}R_{jp} Q_{njp} - \vartheta \sum_i \sum_j \sum_v Co2_v D_{ij} Y_{ijv} \\
 & - \vartheta \sum_j \sum_k \sum_v Co2_v D_{jk} Y_{jkv} \\
 & - \vartheta \sum_k \sum_a \sum_v Co2_v D_{ka} Y_{kav}
 \end{aligned} \tag{1}$$

$$\begin{aligned}
 &-\vartheta \sum_a \sum_m \sum_v Co2_v D_{am} Y_{amv} \\
 &-\vartheta \sum_m \sum_l \sum_v Co2_v D_{ml} Y_{mlv} \\
 &-\vartheta \sum_m \sum_e \sum_v Co2_v D_{me} Y_{mev} \\
 &-\vartheta \sum_n \sum_b \sum_v Co2_v D_{nb} Y_{nbv} \\
 &-\vartheta \sum_n \sum_l \sum_v Co2_v D_{nl} Y_{nlv} \\
 &-\vartheta \sum_m \sum_n \sum_v Co2_v D_{mn} Y_{mnv} \\
 &-\vartheta \sum_n \sum_j \sum_v Co2_v D_{nj} Y_{njv} - \vartheta \sum_j \sum_g E_{jg} U_{jg} \\
 &-\vartheta \sum_k \sum_g E_{kg} U_{kg} - \vartheta \sum_m \sum_g E_{mg} U_{mg} - \\
 &\vartheta \sum_n \sum_g E_{ng} U_{ng} - \vartheta \sum_j \sum_k \sum_p R_{ejp} Q_{jkp} \\
 &-\vartheta \sum_a \sum_m \sum_p C_{emp} Q_{amp} - \\
 &\vartheta \sum_m \sum_n \sum_p R_{enp} Q_{mnp} \\
 &-\vartheta \sum_m \sum_l \sum_p L_{elp} Q_{mlp} - \vartheta \sum_n \sum_l \sum_p L_{elp} Q_{nlp} - \\
 &\vartheta \sum_n \sum_j \sum_p R_{pej} Q_{njp} + \vartheta CO_2^{GOV} \\
 &-\sum_a \sum_p \pi_{ap} S_{ap}
 \end{aligned}$$

$$\begin{aligned}
 &max Z_2 = \\
 &\theta_{job} \left\{ \sum_j \sum_g JOB_{jg} U_{jg} + \sum_k \sum_g JOB_{kg} U_{kg} + \right. \\
 &\left. \sum_m \sum_g JOB_{mg} U_{mg} + \sum_n \sum_g JOB_{ng} U_{ng} \right\} \\
 &-\varphi_{ALD} \left\{ \sum_j \sum_g ALD_{jg} U_{jg} + \sum_k \sum_g ALD_{kg} U_{kg} + \right. \\
 &\left. \sum_m \sum_g ALD_{mg} U_{mg} + \sum_n \sum_g ALD_{ng} U_{ng} \right\}
 \end{aligned} \tag{2}$$

$$\begin{aligned}
 &max Z_3 = 1 - \prod_i \prod_a \left( 1 - \right. \\
 &\left. \left( \prod_j \prod_k \prod_h \prod_p \prod_v \left( 1 - \left( \frac{Re_{ijh} Y_{ijv} *}{Re_{jhp} Y_{jpv} *}, \frac{Re_{kap} Y_{kav} *}{Re_{khp} Y_{kpv} *} \right) \right) \right) \right)
 \end{aligned} \tag{3}$$

s. t.:

$$\sum_k Q_{kap} + S_{ap} = \overline{Dem}_{ap}, \quad \forall a, p \tag{4}$$

$$\sum_a Q_{kap} = \sum_j Q_{jkp}, \quad \forall k, p \tag{5}$$

$$\sum_i \sum_h O_{hp} Q_{ijh} + \sum_n Q_{njp} = \sum_k Q_{jkp}, \quad \forall j, p \tag{6}$$

$$\alpha_{ap} \sum_k Q_{kap} = \sum_m Q_{amp}, \quad \forall a, p \tag{7}$$

$$\beta_{mp} \sum_a Q_{amp} = \sum_e Q_{mep}, \quad \forall m, p \tag{8}$$

$$\gamma_{mp} \sum_a Q_{amp} = \sum_n Q_{mnp}, \quad \forall m, p \tag{9}$$

$$\sum_a Q_{amp} = \sum_l Q_{mlp} + \sum_n Q_{mnp} + \sum_e Q_{mep}, \quad \forall m, p \tag{10}$$

$$\delta_{np} \sum_m Q_{mnp} = \sum_l Q_{nlp}, \quad \forall n, p \tag{11}$$

$$\sigma_{np} \sum_m Q_{mnp} = \sum_j Q_{njp}, \quad \forall n, p \tag{12}$$

$$\sum_m Q_{mnp} = \sum_l Q_{nlp} + \sum_j Q_{njp} + \sum_b Q_{nbp}, \quad \forall n, p \tag{13}$$

$$\sum_k Q_{jkp} \leq \sum_g Cap_{jgp} U_{jg}, \quad \forall j, p \tag{14}$$

$$\sum_a Q_{kap} \leq \sum_g Cap_{kgp} U_{kg}, \quad \forall k, p \tag{15}$$

$$\sum_a Q_{amp} \leq \sum_g Cap_{mpg} U_{mg}, \quad \forall m, p \tag{16}$$

$$\sum_m Q_{mnp} \leq \sum_g Cap_{npg} U_{ng}, \quad \forall n, p \tag{17}$$

$$\sum_j Q_{ijh} \leq \overline{Cap}_{ih}, \quad \forall i, h \tag{18}$$

$$\sum_m Q_{mlp} + \sum_n Q_{nlp} \leq Cap_{lp}, \quad \forall l, p \tag{19}$$

$$\sum_g U_{ng} \leq 1, \quad \forall n \tag{20}$$

$$\sum_g U_{mg} \leq 1, \quad \forall m \tag{21}$$

$$\sum_g U_{jg} \leq 1, \quad \forall j \tag{22}$$

$$\sum_g U_{kg} \leq 1, \quad \forall k \tag{23}$$

$$\sum_h Q_{ijh} w_h \leq \sum_v Cap_{wv} Y_{ijv}, \quad \forall i, j, v \tag{24}$$

$$\sum_p Q_{jkp} w_p \leq \sum_v Cap_{wv} Y_{jkv}, \quad \forall j, k, v \tag{25}$$

$$\sum_p Q_{kap} w_p \leq \sum_v Cap_{wv} Y_{kav}, \quad \forall k, a, v \tag{26}$$

$$\sum_p Q_{amp} w_p \leq \sum_v Cap_{wv} Y_{amv}, \quad \forall a, m, v \tag{27}$$

$$\sum_p Q_{mlp} w_p \leq \sum_v Cap_{wv} Y_{mlv}, \quad \forall m, l, v \tag{28}$$

$$\sum_p Q_{mnp} w_p \leq \sum_v Cap_{wv} Y_{mnv}, \quad \forall m, n, v \tag{29}$$

$$\sum_p Q_{mep} w_p \leq \sum_v Cap_{wv} Y_{mev}, \quad \forall m, e, v \tag{30}$$

$$\sum_p Q_{nlp} w_p \leq \sum_v Cap_{wv} Y_{nlv}, \quad \forall n, l, v \tag{31}$$

$$\sum_p Q_{njp} w_p \leq \sum_v Cap_{wv} Y_{njv}, \quad \forall n, j, v \tag{32}$$

$$\sum_p Q_{nbp} w_p \leq \sum_v Cap_{wv} Y_{nbv}, \quad \forall n, b, v \tag{33}$$

$$\sum_h Q_{ijh} v_h \leq \sum_v Cap_{v} Y_{ijv}, \quad \forall i, j, v \tag{34}$$

$$\sum_p Q_{jkp} v_p \leq \sum_v Cap_{v} Y_{jkv}, \quad \forall j, k, v \tag{35}$$

$$\sum_p Q_{kap} v_p \leq \sum_v Cap_{v} Y_{kav}, \quad \forall k, a, v \tag{36}$$

$$\sum_p Q_{amp} v_p \leq \sum_v Cap_{v} Y_{amv}, \quad \forall a, m, v \tag{37}$$



$$\sum_p Q_{mlp} v_p \leq \sum_v Capv_v Y_{mlv}, \quad \forall m, l, v \quad (38)$$

$$\sum_p Q_{mnp} v_p \leq \sum_v Capv_v Y_{mnv}, \quad \forall m, n, v \quad (39)$$

$$\sum_p Q_{mep} v_p \leq \sum_v Capv_v Y_{mev}, \quad \forall m, e, v \quad (40)$$

$$\sum_p Q_{nlp} v_p \leq \sum_v Capv_v Y_{nlv}, \quad \forall n, l, v \quad (41)$$

$$\sum_p Q_{njp} v_p \leq \sum_v Capv_v Y_{njv}, \quad \forall n, j, v \quad (42)$$

$$\sum_p Q_{nbp} v_p \leq \sum_v Capv_v Y_{nbv}, \quad \forall n, b, v \quad (43)$$

$$\begin{aligned} &Q_{kap}, Q_{jkp}, Q_{ijh}, Q_{njp}, Q_{amp}, Q_{mep}, Q_{mnp}, Q_{mlp}, \\ &Q_{nlp}, Q_{nbp}, S_{ap} \geq 0 \end{aligned} \quad (44)$$

$$\begin{aligned} &U_{jg}, U_{kg}, U_{mg}, U_{ng}, Y_{kav}, Y_{jkv}, Y_{ijv}, Y_{njv}, Y_{amv}, Y_{mev}, \\ &Y_{mnp}, Y_{mlv}, Y_{nlv}, Y_{nbv} \in \{0,1\} \end{aligned} \quad (45)$$

Equation (1) gives the first objective function of the model which maximizes the profit of the supply chain. The income part of the addressed profit is composed of the total sale amount of final products to the customers in the primary markets, the total sale amount of lower quality recycled products in the secondary market and the energy from lower quality returned products. The cost part of the addressed profit is composed of fixed construction costs, fixed and variable costs of using the vehicle, costs of producing excess carbon dioxide greater than the accepted amount, and operating costs of producing the final products. Equation (2) gives the second objective function which maximizes the number of jobs created by the establishment of new potential centers. In this regard, the average number of lost days because of work injuries is also included. Equation (3) gives the third objective function which maximizes the reliabilities of the routes of the final products from the supplier to the customers of the primary markets. Equation (4) shows how to meet the customers' demands at the primary markets considering the possible shortages. Equation (5) guarantees the equality of input to and output from each distribution center for each product. Equation (6) shows the equality of input to and output from each manufacturing center. Equation (7) calculates the fraction of products which are discarded by customers due to lower quality. Equation (8) gives the fraction of low quality products which are converted into energy and new products. Equation (9) gives the fraction of low quality products which are remanufacture or sold. Equation (10) gives the equality relation of collecting returned products in the collection center. Equation (11) gives the fraction of low quality returned products which cannot be used in any way and should be disposed. Equation (12) shows the percentage of returned products which can be remanufactured at the manufacturing centers. Equation (13) gives the equality relation at the

recycling center. Inequalities (14) to (19) give the capacity constraints and ensure that if any potential center is opened with a specific capacity level, the corresponding capacity level is observed. Equations (20) to (23) ensure that a maximum capacity level for each potential center can be used. Inequalities (24) to (33) are related to weight capacity constraint of vehicles for shipping raw materials and products. Inequalities (34) to (43) are related to volume capacity constraint of vehicles for shipping raw materials and products. Constraints (44) and (45) give the status of the decision variables of the model.

### 3. 5. Possibilistic Fuzzy Programming Method for Uncertain Numbers

Suppose that a parameter  $a_{ij}$  is an uncertain parameter with mean of  $\mu_{ij}$  and standard deviation of  $\sigma_{ij}$ . It is also assumed that all considered uncertain parameters are independent from each other; therefore, the mean and standard deviation of the estimated set of possible random numbers can be shown as follows [38]:

$$S_{ij} = \{x_k | x_k \in \text{assumed distribution}; k = 1, \dots, N\} \quad (46)$$

In the above relation  $x_k$  is a possible random data value. Value of  $N$  is a sufficient number of random sets that state all the conditions necessary to generate a possible random data. Also, for accurate estimation of the probabilistic data, the fuzzy constraint coefficient of the numbers  $T = \tilde{A} = (A^-, A^0, A^+)$  is defined. As a result, the function of the triangular fuzzy distribution is as follows:

<p><math>A^0</math> Represents the most reliable value of set <math>S_{ij}</math>. When a value of 1 is assigned to it as membership degree of a fuzzy number, then it is equal to mean of <math>S_{ij}</math> random distribution function.</p>	$A^0 = \frac{\sum_{i=1}^N x_i}{N}$
<p><math>A^-</math> Represents the minimum value of set <math>S_{ij}</math></p>	$A^- = \inf(x_i) \quad i = 1, \dots, N$
<p><math>A^+</math> Represents the maximum value of set <math>S_{ij}</math></p>	$A^+ = \sup(x_i) \quad i = 1, \dots, N$

As a result, according to the above-mentioned definitions, the following equation is used to control the possible parameter of  $a_{ij}$  with mean  $\mu_{ij}$  and standard deviation of  $\sigma_{ij}$ .

$$\begin{aligned} &\max C^T X \\ &\text{s. t.:} \\ &\frac{A^- + 4A^0 + A^+}{6} X \leq b \\ &X > 0 \end{aligned} \quad (47)$$

### 3. 6. Probabilistic Planning Method

Consider the following linear programming model given in Equation (48):

$$\begin{aligned}
 & \min E = cx + fy \\
 & \text{s. t.:} \\
 & Ax \geq_f d \\
 & Bx = 0 \\
 & Sx \leq_f Ny \\
 & Ty \leq 1 \\
 & y \in \{0,1\}, x \geq 0
 \end{aligned}
 \tag{48}$$

In the above model, the fixed cost of constructing new centers and the variable costs of transportation and operation are represented by  $f$  and  $c$ . Parameters related to constraint coefficients are represented by  $h$   $A$ ,  $B$ ,  $S$  and  $T$ .  $N$  and  $d$  represent the capacity of the facility and the customer demand for the products, respectively. Furthermore,  $x$  and  $y$  represent the continuous and binary variables, respectively. Capacity and demand parameters are assumed to be possibly fuzzy. Therefore, the model can be stated as in Equation (49):

$$\begin{aligned}
 & \min E = cx + fy \\
 & \text{s. t.:} \\
 & Ax \geq d - \tilde{t}(1 - \alpha) \\
 & Bx = 0 \\
 & Sx \leq Ny + [\tilde{r}(1 - \beta)]y \\
 & Ty \leq 1 \\
 & y \in \{0,1\}, x \geq 0
 \end{aligned}
 \tag{49}$$

In which,  $\tilde{t}$  and  $\tilde{r}$  are two fuzzy numbers representing to deal with the given soft constraints. In the above model,  $\alpha$  and  $\beta$  represent the minimum level of satisfaction index of flexible constraints. It is also assumed that  $\tilde{t}$  and  $\tilde{r}$  are considered as triangular fuzzy numbers shown as  $\tilde{t} = (t^p, t^m, t^o)$  and  $\tilde{r} = (r^p, r^m, r^o)$ . Consider that  $\alpha$  and  $\beta$  are parameters between zero and one; i.e.  $0 \leq \alpha, \beta \leq 1$ . To ensure that the considered constraints with uncertain parameters are feasible, it is necessary to control them using the flexible robust programming method. Thus, we use the penalty technique to prevent from non-feasibility as follows:

$$\begin{aligned}
 & \min E = cx + fy + \theta[t(1 - \alpha)] + \lambda[r(1 - \beta)]y \\
 & \text{s. t.:} \\
 & Ax \geq d - t(1 - \alpha) \\
 & Bx = 0 \\
 & Sx \leq Ny + [r(1 - \beta)]y \\
 & Ty \leq 1 \\
 & y \in \{0,1\}, x \geq 0
 \end{aligned}
 \tag{50}$$

where  $\lambda$  and  $\theta$  are the penalty coefficients. The final model of the problem is given as in Equations (51)-(95):

$$\begin{aligned}
 \max Z_1 = & \sum_k \sum_a \sum_p Pr_{ap} Q_{kap} + \\
 & \sum_m \sum_e \sum_p Pr_{ep} Q_{mep} + \sum_n \sum_b \sum_p Pr_{bp} Q_{nbp} - \\
 & \sum_j \sum_g F_{jg} U_{jg} - \sum_k \sum_g F_{kg} U_{kg} - \sum_m \sum_g F_{mg} U_{mg} \\
 & - \sum_n \sum_g F_{ng} U_{ng} - \sum_i \sum_j \sum_v FC_v Y_{ijv} - \\
 & \sum_j \sum_k \sum_v FC_v Y_{jkv} - \sum_k \sum_a \sum_v FC_v Y_{kav} - \\
 & \sum_a \sum_m \sum_v FC_v Y_{amv} - \sum_m \sum_l \sum_v FC_v Y_{mlv} - \\
 & \sum_m \sum_e \sum_v FC_v Y_{mev} - \sum_m \sum_n \sum_v FC_v Y_{mnv} - \\
 & \sum_n \sum_l \sum_v FC_v Y_{nlv} - \sum_n \sum_b \sum_v FC_v Y_{nbv} - \\
 & \sum_n \sum_j \sum_v FC_v Y_{njv} - \\
 & \sum_i \sum_j \sum_v \left( \frac{Fv_{ij}^- + 4Fv_{ij}^0 + Fv_{ij}^+}{6} \right) D_{ij} Y_{ijv} - \\
 & \sum_j \sum_k \sum_v \left( \frac{Fv_{jk}^- + 4Fv_{jk}^0 + Fv_{jk}^+}{6} \right) D_{jk} Y_{jkv} - \\
 & \sum_m \sum_e \sum_v \left( \frac{Fv_{me}^- + 4Fv_{me}^0 + Fv_{me}^+}{6} \right) D_{me} Y_{mev} - \\
 & \sum_k \sum_a \sum_v \left( \frac{Fv_{ka}^- + 4Fv_{ka}^0 + Fv_{ka}^+}{6} \right) D_{ka} Y_{kav} - \\
 & \sum_a \sum_m \sum_v \left( \frac{Fv_{am}^- + 4Fv_{am}^0 + Fv_{am}^+}{6} \right) D_{am} Y_{amv} - \\
 & \sum_m \sum_l \sum_v \left( \frac{Fv_{ml}^- + 4Fv_{ml}^0 + Fv_{ml}^+}{6} \right) D_{ml} Y_{mlv} - \\
 & \sum_n \sum_b \sum_v \left( \frac{Fv_{nb}^- + 4Fv_{nb}^0 + Fv_{nb}^+}{6} \right) D_{nb} Y_{nbv} - \\
 & \sum_n \sum_j \sum_v \left( \frac{Fv_{nj}^- + 4Fv_{nj}^0 + Fv_{nj}^+}{6} \right) D_{nj} Y_{njv} - \\
 & \sum_m \sum_n \sum_v \left( \frac{Fv_{mn}^- + 4Fv_{mn}^0 + Fv_{mn}^+}{6} \right) D_{mn} Y_{mnv} - \\
 & \sum_n \sum_l \sum_v \left( \frac{Fv_{nl}^- + 4Fv_{nl}^0 + Fv_{nl}^+}{6} \right) D_{nl} Y_{nlv} - \\
 & \sum_i \sum_j \sum_h \left( \frac{Sc_{ih}^- + 4Sc_{ih}^0 + Sc_{ih}^+}{6} \right) Q_{ijh} - \\
 & \sum_j \sum_k \sum_p \left( \frac{Pc_{jp}^- + 4Pc_{jp}^0 + Pc_{jp}^+}{6} \right) Q_{jkp} - \\
 & \sum_a \sum_m \sum_p \left( \frac{Cc_{mp}^- + 4Cc_{mp}^0 + Cc_{mp}^+}{6} \right) Q_{amp} - \\
 & \sum_m \sum_n \sum_p \left( \frac{Rc_{np}^- + 4Rc_{np}^0 + Rc_{np}^+}{6} \right) Q_{mnp} - \\
 & \sum_m \sum_l \sum_p \left( \frac{Lc_{lp}^- + 4Lc_{lp}^0 + Lc_{lp}^+}{6} \right) Q_{mlp} - \\
 & \sum_k \sum_a \sum_p \left( \frac{Dc_{kp}^- + 4Dc_{kp}^0 + Dc_{kp}^+}{6} \right) Q_{kap} - \\
 & \sum_n \sum_l \sum_p \left( \frac{Lc_{lp}^- + 4Lc_{lp}^0 + Lc_{lp}^+}{6} \right) Q_{nlp} - \\
 & \sum_n \sum_j \sum_p \left( \frac{Prc_{jp}^- + 4Prc_{jp}^0 + Prc_{jp}^+}{6} \right) Q_{njp} - \\
 & -\vartheta \sum_i \sum_j \sum_v Co2_v D_{ij} Y_{ijv} \\
 & -\vartheta \sum_j \sum_k \sum_v Co2_v D_{jk} Y_{jkv} \\
 & -\vartheta \sum_k \sum_a \sum_v Co2_v D_{ka} Y_{kav}
 \end{aligned}
 \tag{51}$$

$$\begin{aligned}
 &-\vartheta \sum_a \sum_m \sum_v Co2_v D_{am} Y_{amv} \\
 &-\vartheta \sum_m \sum_l \sum_v Co2_v D_{ml} Y_{mlv} \\
 &-\vartheta \sum_m \sum_e \sum_v Co2_v D_{me} Y_{mev} \\
 &-\vartheta \sum_n \sum_b \sum_v Co2_v D_{nb} Y_{nbv} \\
 &-\vartheta \sum_n \sum_l \sum_v Co2_v D_{nl} Y_{nlv} \\
 &-\vartheta \sum_m \sum_n \sum_v Co2_v D_{mn} Y_{mnv} \\
 &-\vartheta \sum_n \sum_j \sum_v Co2_v D_{nj} Y_{njv} - \vartheta \sum_j \sum_g E_{jg} U_{jg} \\
 &-\vartheta \sum_k \sum_g E_{kg} U_{kg} - \vartheta \sum_m \sum_g E_{mg} U_{mg} - \\
 &\vartheta \sum_n \sum_g E_{ng} U_{ng} - \vartheta \sum_j \sum_k \sum_p P_{ejp} Q_{jkp} \\
 &-\vartheta \sum_a \sum_m \sum_p C_{emp} Q_{amp} - \\
 &\vartheta \sum_m \sum_n \sum_p R_{enp} Q_{mnp} \\
 &-\vartheta \sum_m \sum_l \sum_p L_{elp} Q_{mlp} - \vartheta \sum_n \sum_l \sum_p L_{elp} Q_{nlp} - \\
 &\vartheta \sum_n \sum_j \sum_p R_{pejp} Q_{njp} + \vartheta CO_2^{GOV} \\
 &-\sum_a \sum_p \pi_{ap} S_{ap} - \sum_a \sum_p \theta [Dem_{ap}^+(1 - \alpha 1)] - \\
 &\sum_i \sum_h \lambda [CapI_{ih}^-(1 - \beta 1)]
 \end{aligned}$$

$$\begin{aligned}
 &max Z_2 = \\
 &\theta_{job} \left\{ \sum_j \sum_g JOB_{jg} U_{jg} + \sum_k \sum_g JOB_{kg} U_{kg} + \right. \\
 &\left. \sum_m \sum_g JOB_{mg} U_{mg} + \sum_n \sum_g JOB_{ng} U_{ng} \right\} \\
 &-\varphi_{ALD} \left\{ \sum_j \sum_g ALD_{jg} U_{jg} + \sum_k \sum_g ALD_{kg} U_{kg} + \right. \\
 &\left. \sum_m \sum_g ALD_{mg} U_{mg} + \sum_n \sum_g ALD_{ng} U_{ng} \right\}
 \end{aligned} \tag{52}$$

$$\begin{aligned}
 &max Z_3 = 1 - \prod_i \prod_a \left( 1 - \right. \\
 &\left. \left( 1 - \prod_j \prod_k \prod_h \prod_p \prod_v \left( 1 - \left( \begin{matrix} Re_{ijh} Y_{ijv} * \\ Re_{jkp} Y_{jkv} * \\ Re_{kap} Y_{kav} \end{matrix} \right) \right) \right) \right)
 \end{aligned} \tag{53}$$

s. t.:

$$\sum_k Q_{kap} + S_{ap} = (Dem_{ap}^o + [Dem_{ap}^+(1 - \alpha 1)]), \quad \forall a, p \tag{54}$$

$$\sum_a Q_{kap} = \sum_j Q_{jkp}, \quad \forall k, p \tag{55}$$

$$\sum_i \sum_h O_{hp} Q_{ijh} + \sum_n Q_{njp} = \sum_k Q_{jkp}, \quad \forall j, p \tag{56}$$

$$\alpha_{ap} \sum_k Q_{kap} = \sum_m Q_{amp}, \quad \forall a, p \tag{57}$$

$$\beta_{mp} \sum_a Q_{amp} = \sum_e Q_{mep}, \quad \forall m, p \tag{58}$$

$$\gamma_{mp} \sum_a Q_{amp} = \sum_n Q_{mnp}, \quad \forall m, p \tag{59}$$

$$\sum_a Q_{amp} = \sum_l Q_{mlp} + \sum_n Q_{mnp} + \sum_e Q_{mep}, \quad \forall m, p \tag{60}$$

$$\delta_{np} \sum_m Q_{mnp} = \sum_l Q_{nlp}, \quad \forall n, p \tag{61}$$

$$\sigma_{np} \sum_m Q_{mnp} = \sum_j Q_{njp}, \quad \forall n, p \tag{62}$$

$$\sum_m Q_{mnp} = \sum_l Q_{nlp} + \sum_j Q_{njp} + \sum_b Q_{nbp}, \quad \forall n, p \tag{63}$$

$$\sum_k Q_{jkp} \leq \sum_g CapJ_{jgp} U_{jg}, \quad \forall j, p \tag{64}$$

$$\sum_a Q_{kap} \leq \sum_g CapK_{kpg} U_{kg}, \quad \forall k, p \tag{65}$$

$$\sum_a Q_{amp} \leq \sum_g CapM_{mpg} U_{mg}, \quad \forall m, p \tag{66}$$

$$\sum_m Q_{mnp} \leq \sum_g CapN_{npg} U_{ng}, \quad \forall n, p \tag{67}$$

$$\sum_j Q_{ijh} \leq (CapI_{ih}^o + [CapI_{ih}^-(1 - \beta 1)]), \quad \forall i, h \tag{68}$$

$$\sum_m Q_{mlp} + \sum_n Q_{nlp} \leq CapL_{lp}, \quad \forall l, p \tag{69}$$

$$\sum_g U_{ng} \leq 1, \quad \forall n \tag{70}$$

$$\sum_g U_{mg} \leq 1, \quad \forall m \tag{71}$$

$$\sum_g U_{jg} \leq 1, \quad \forall j \tag{72}$$

$$\sum_g U_{kg} \leq 1, \quad \forall k \tag{73}$$

$$\sum_h Q_{ijh} w_h \leq \sum_v Capw_v Y_{ijv}, \quad \forall i, j, v \tag{74}$$

$$\sum_p Q_{jkp} w_p \leq \sum_v Capw_v Y_{jkv}, \quad \forall j, k, v \tag{75}$$

$$\sum_p Q_{kap} w_p \leq \sum_v Capw_v Y_{kav}, \quad \forall k, a, v \tag{76}$$

$$\sum_p Q_{amp} w_p \leq \sum_v Capw_v Y_{amv}, \quad \forall a, m, v \tag{77}$$

$$\sum_p Q_{mlp} w_p \leq \sum_v Capw_v Y_{mlv}, \quad \forall m, l, v \tag{78}$$

$$\sum_p Q_{mnp} w_p \leq \sum_v Capw_v Y_{mnv}, \quad \forall m, n, v \tag{79}$$

$$\sum_p Q_{mep} w_p \leq \sum_v Capw_v Y_{mev}, \quad \forall m, e, v \tag{80}$$

$$\sum_p Q_{nlp} w_p \leq \sum_v Capw_v Y_{nlv}, \quad \forall n, l, v \tag{81}$$

$$\sum_p Q_{njp} w_p \leq \sum_v Capw_v Y_{njv}, \quad \forall n, j, v \tag{82}$$

$$\sum_p Q_{nbp} w_p \leq \sum_v Capw_v Y_{nbv}, \quad \forall n, b, v \tag{83}$$

$$\sum_h Q_{ijh} v_h \leq \sum_v Capv_v Y_{ijv}, \quad \forall i, j, v \tag{84}$$

$$\sum_p Q_{jkp} v_p \leq \sum_v Capv_v Y_{jkv}, \quad \forall j, k, v \tag{85}$$

$$\sum_p Q_{kap} v_p \leq \sum_v Capv_v Y_{kav}, \quad \forall k, a, v \tag{86}$$

$$\sum_p Q_{amp} v_p \leq \sum_v Capv_v Y_{amv}, \quad \forall a, m, v \tag{87}$$

$$\sum_p Q_{mlp} v_p \leq \sum_v Cap v_v Y_{mlv}, \quad \forall m, l, v \quad (88)$$

$$\sum_p Q_{mnp} v_p \leq \sum_v Cap v_v Y_{mnv}, \quad \forall m, n, v \quad (89)$$

$$\sum_p Q_{mep} v_p \leq \sum_v Cap v_v Y_{mev}, \quad \forall m, e, v \quad (90)$$

$$\sum_p Q_{nlp} v_p \leq \sum_v Cap v_v Y_{nlv}, \quad \forall n, l, v \quad (91)$$

$$\sum_p Q_{njp} v_p \leq \sum_v Cap v_v Y_{njv}, \quad \forall n, j, v \quad (92)$$

$$\sum_p Q_{nbp} v_p \leq \sum_v Cap v_v Y_{nbv}, \quad \forall n, b, v \quad (93)$$

$$Q_{kap}, Q_{jkp}, Q_{ijh}, Q_{njp}, Q_{amp}, Q_{mep}, Q_{mnp}, Q_{mlp}, \quad (94)$$

$$Q_{nlp}, Q_{nbp}, S_{ap} \geq 0$$

$$U_{jg}, U_{kg}, U_{mg}, U_{ng}, Y_{kav}, Y_{jkv}, Y_{ijv}, Y_{njv}, Y_{amv}, \quad (95)$$

$$Y_{mev}, Y_{mnv}, Y_{mlv}, Y_{nlv}, Y_{nbv} \in \{0,1\}$$

### 4. SOLUTION ALGORITHM

In this section, the solution representation and the major solution algorithm are presented.

#### 4. 1. Designing Solution Representation

The complexity of supply chain network models has been demonstrated in many researches. The CLSC network models are studied to tackle the two problems of facility location and flow optimization [39]. The complexity of these models can be reduced to the complexity of the location problems; on the other hand, Np-Hard nature of these problems has been proven by many researchers [40]. As a result, meta-heuristic algorithms such as NSGA II and MOGWO can be used to tackle them. The first step is to design solution representation, which is the same in both algorithms. This coding is known as priority-based encryption, introduced by Gen et al. [41]. In this encoding, the supply chain network is divided into its constituent levels, and each level is considered in the design of the solution structure according to the capacity, demand, type of vehicle, and etc. Figure 2 shows an example of a two-tier supply chain network with three sources and four depots. In this structure, sources have been selected and replenish the demand of depots

Figure 3 shows a sample of the original solution and its decoding. The priority-based decoding modified in Figure 3 is in accordance with the following four steps:

Step 1. First, the largest priority (number) is selected from the chromosomes related to the sources. If the source is able to supply all the depots, the priority of other sources reduces to zero. In this case, location is done for sources which do not have zero priority.

Step 2. The highest priority (number) from the whole chromosome is selected as the first level of allocation

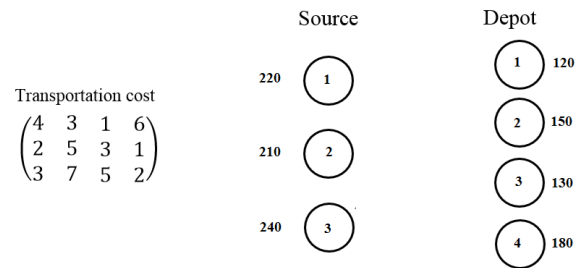


Figure 2. An example of a two-level supply chain network structure

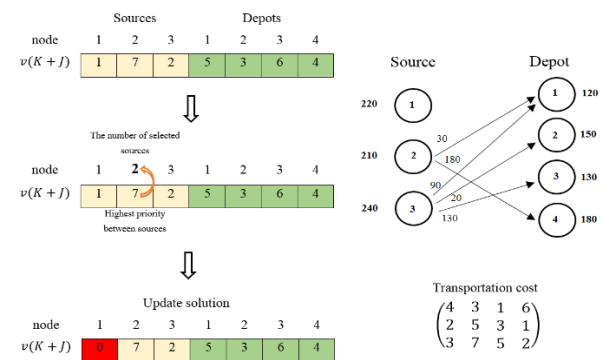


Figure 3. How priority-based encoding and decoding Modified

Step 3. Based on the shipping cost, the lowest shipping cost is obtained from the allocation level selected from step 2 (source/depot), with the new allocable level (depot/source), and the second allocation level is determined.

Step 4. After determining the source and depot, the minimum amount of depot demand and source capacity is considered as the optimal amount of allocation. After the allocation operation, the amount of depot demand as well as the capacity of the source is updated.

#### 4. 2. Performance of Mogwo

Gray wolves are predators at the top of the food pyramid or the food chain. Gray wolves mostly prefer to live in groups. The average group size is 5-12 wolves. Wolves have a very precise and orderly social dominant hierarchy shown in Figure 4 [42].

Leaders consist of a male and a female called Alpha. Alpha is primarily responsible for decisions about hunting, where to sleep, when to wake up, and so on. Alpha decisions are communicated to the group; however, some democratic behaviors have also been observed in which an Alpha follows the other wolves in the group. In communities, the entire herd endorses Alpha. Alpha Wolf is also known as the dominant wolf, because the commands must be executed by the group. Alpha wolves are only allowed to mate in the herd.

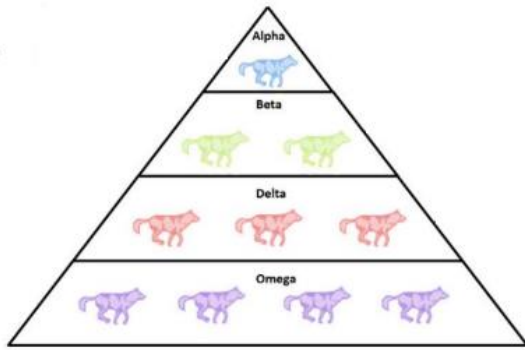


Figure 4. Gray wolf social hierarchy

It is important to note that Alpha is not necessarily the strongest member of the herd, but the best member in terms of management in the herd. The second level in the gray wolf hierarchy is Beta. Beta is the wolf that help Alpha make decisions or other herd decisions. The Beta wolf can be male or female, and he is the best replacement for Alpha in the event of his death or aging. Beta executes Alpha commands across the herd and gives feedback to Alpha. Omega wolf is the foot of the lowest class in the gray wolf hierarchy. Omega wolves usually have to follow all the high-level and dominant wolves. They are the last wolves allowed to eat. If the wolf is not an Alpha or Omega, it is called a Delta. Delta wolves must be subject to Alpha and Beta. However, they dominate Omega. In this paper, the behavior of gray wolf hunting is applied to solve the problem of CLSC. When designing the gray wolf algorithm, in order to mathematically model the social wolf hierarchy, Alpha ( $\alpha$ ) is considered as the most appropriate solution. Subsequently Beta ( $\beta$ ) and Delta ( $\delta$ ) are the second and third most suitable solutions. The rest of the candidate solutions are assumed to be Omega ( $X$ ). Gray wolves must find and surround their prey in order to hunt. Therefore, the following equations (96)-(97) update the positions of the wolves around the prey.

$$\vec{D} = |\vec{C} \cdot \vec{X}_p(t) - \vec{X}(t)| \tag{96}$$

$$\vec{X}(t + 1) = \vec{X}(t) - \vec{A} \cdot \vec{D} \tag{97}$$

In the above equations,  $\vec{C}$  and  $A$  are the coefficient vectors.  $\vec{X}_p$  represents the hunting position vector and  $X$  is the gray wolf position vector. This is an equilibrium equation between siege and hunting. Therefore, the search radius must be optimized during the process; for this purpose, the equations for the two coefficients used in the above equations are as (98)-(99).

$$\vec{A} = 2\vec{a} \cdot \vec{r}_1 - \vec{a} \tag{98}$$

$$\vec{C} = 2\vec{r}_2 \tag{99}$$

As a result, the following equations (100)-(102) are used to perform the hunting.

$$\vec{D}_\alpha = |\vec{C}_1 \cdot \vec{X}_\alpha - \vec{X}|, \vec{D}_\beta = |\vec{C}_2 \cdot \vec{X}_\beta - \vec{X}|, \vec{D}_\delta = |\vec{C}_3 \cdot \vec{X}_\delta - \vec{X}| \tag{100}$$

$$\vec{X}_1 = \vec{X}_\alpha - \vec{A}_1 \cdot \vec{D}_\alpha, \vec{X}_2 = \vec{X}_\beta - \vec{A}_2 \cdot \vec{D}_\beta, \vec{X}_3 = \vec{X}_\delta - \vec{A}_3 \cdot \vec{D}_\delta \tag{101}$$

$$\vec{X}(t + 1) = \frac{\vec{X}_1 + \vec{X}_2 + \vec{X}_3}{3} \tag{102}$$

5. COMPUTATIONAL RESULTS

In this section, initially, some numerical examples in different sizes are designed and solved. Due to the NP-Hard nature of the problem, the two algorithms of MOGWO and NSGA II were used in order to tackle the problem. At the end, we will implement the model for a real case study in Iranian engine oil industry.

5. 1. Solving the Problem for Small Sizes In this section, small sized numerical examples are designed as the given structure in Table 3. Furthermore, the required data are randomly generated as in Table 4.

All parameters generated in Tables 4 are randomly based on uniform distribution.

TABLE 3. The structure of the designed numerical examples for small size

Set	G	I	N	L	P	V	H	B	E	M	J	K	A
Values	3	3	3	3	2	3	3	3	3	3	3	3	4

TABLE 4. Limits of problem parameter intervals based on uniform distribution

Approximate range	Parameter
~U(0.03,0.05)	$w_h$
~U(0.08,0.1)	$w_p$
~U(0.3,0.5)	$v_h$
~U(0.5,0.8)	$v_p$
~U(10000,12000)	$F_{jg}, F_{kg}, F_{mg}, F_{ng}$
~U(1000,1200)	$FC_v$
~U(10,100)	$D_{ka}, D_{jk}, D_{ij}, D_{nj}, D_{am}$
~U(10,100)	$D_{me}, D_{mn}, D_{ml}, D_{nl}, D_{nb}$
~U(5,8)	$Co2_v$
~U(50,100)	$E_{jg}, E_{kg}, E_{mg}, E_{ng}$
0.5	$\vartheta$
1	$\varphi_{ALD}, \theta_{Job}$

$\sim U(0.1,0.4)$	$Re_{ijh}, Re_{jhp}, Re_{kap}$		
$\sim U(1,2)$	$O_{np}$		
$\sim U(0.1,0.2)$	$\alpha_{ap}$		
$\sim U(0.3,0.4)$	$\beta_{mp}, \gamma_{mp}$		
$\sim U(0.2,0.3)$	$\delta_{np}, \sigma_{np}$		
$\sim U(1000,1200)$	$Pr_{ap}, Pr_{ep}, Pr_{bp}, CapL_{1p}$		
$\sim U(5000,6000)$	$CapJ_{jppg}, CapK_{kpg}$		
$\sim U(2000,3000)$	$CapM_{mpg}, CapN_{npg}$		
$\sim U(500,700)$	$Capw_v, Capv_v$		
$\sim U(50,80)$	$\pi_{ap}$		
10000	$Co_2^{GOV}$		
$\sim U(1,3)$	$Pe_{jp}, Ce_{mp}, Re_{np}$		
$\sim U(1,3)$	$Le_{ip}, RPe_{jp}$		
$\sim U(500,1000)$	$JOB_{jg}, JOB_{kg}, JOB_{mg}, JOB_{ng}$		
$\sim U(10,20)$	$ALD_{jg}, ALD_{kg}, ALD_{mg}, ALD_{ng}$		
Level 3	Level 2	Level 1	Parameter
$\sim U(2000,3000)$	$\sim U(1500,2000)$	$\sim U(1000,1500)$	$\overline{Dem}_{ap}$
$\sim U(8000,9000)$	$\sim U(7000,8000)$	$\sim U(6000,700)$	$\overline{Cap}l_{ih}$
$\sim U(8,10)$	$\sim U(7,8)$	$\sim U(5,7)$	$\overline{FV}_v$
$\sim U(3,4)$	$\sim U(2,3)$	$\sim U(1,2)$	$\overline{Rc}_{np}, \overline{Lc}_{ip}, \overline{R\overline{Pc}}_{jp}$
$\sim U(3,4)$	$\sim U(2,3)$	$\sim U(1,2)$	$\overline{Pc}_{jp}, \overline{Sc}_{ih}, \overline{Dc}_{kp}, \overline{Cc}_{mp}$

After generating the values for the small size sample, the three-objective problem is solved utilizing optimization package of GAMS. For this purpose, the comprehensive criterion method has been used. Therefore, the optimal value of the first objective function turns out to be 18838690, the optimal value of the second objective function turns out to be 9683 and the optimal value of the third objective function turns out to be 1. As a result, with the same weight for all three objective functions, the efficient solution obtained from solving the problem includes the value of 18266820.14 for the first objective function, 9683 for the second objective function and 0.998 for the third objective function. Table 5 gives the optimal location of the facilities resulting from the addressed solution.

A set of efficient solutions using the comprehensive criterion method is given as in Table 6.

According to the results from Table 6, by increasing the number of facilities, including suppliers and manufacturing centers, the amount of total costs increases and at the same time the number of jobs created and the reliability rates increases due to increasing the number of facilities.

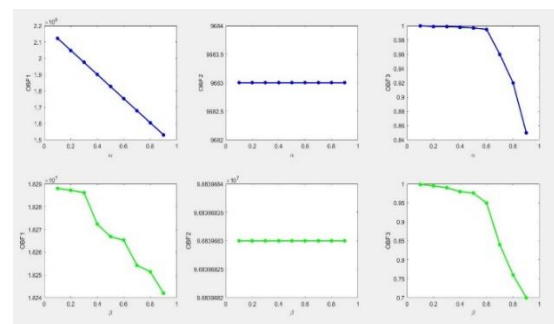
In the following, the sensitivity analysis of the CLSC network model is given under the parameters of the solid fuzzy optimization method. Figure 5 shows the changes of the values of the objective functions for different parameters  $\alpha 1$  and  $\beta 1$ , assuming that the values of  $\theta$  and  $\lambda$  are constant and equal to 1.

**TABLE 5.** Optimal location of selected facilities along with capacity level

Facilities	Selected location along with capacity level	Facilities	Selected location along with capacity level
Production center	Center 1 with capacity level 2	Collection center	Center 1 with capacity level 2
	Center 2 with capacity level 1		Center 2 with capacity level 3
	Center 3 with capacity level 3		Center 3 with capacity level 3
Distribution center	Center 1 with capacity level 3	Recycling Center	Center 1 with capacity level 3
	Center 2 with capacity level 2		Center 2 with capacity level 3
	Center 3 with capacity level 1		Center 3 with capacity level 2

**TABLE 6.** A set of efficient solutions obtained from solving the small size instances

Efficient solution	Objective function 1	Objective function 2	Objective function 3
1	18081104.67	9455	0.986
2	18135294.68	9459	0.988
3	18223710.81	9501	0.990
4	18266820.14	9683	0.998
5	18329116.28	9726	0.992
6	18338314.06	9737	0.994
7	18364072.99	9772	1.000
8	18369916.05	9784	1.000
9	18440417.30	9847	1.000



**Figure 5.** Changes in the values of the first objective function for stable fuzzy optimization parameters

According to the results of sensitivity analysis, by increasing the values of  $\alpha_1$  and  $\beta_1$ , the first and third objective functions increases. This indicates that the amount of demand increases as the uncertainty increases and as a result, shipping costs increase and reliability to meet customer demand decreases. On the other hand, by increasing the uncertainty rate, the amount of supplier capacity decreases and therefore the amount of transportation costs increases. As transportation costs increase, the profit of the chain decreases.

**5. 2. Comparing Solution for Small Size Problem**

In order to evaluate the performances of NSGA II and MOGWO algorithms, some indicators are considered for comparing the Pareto front solutions Table 7 shows the indicators obtained from NSGA II and MOGWO algorithms in comparison with the comprehensive criterion as a benchmark method. According to the results obtained from this table, the comprehensive criterion method outperforms other algorithms considering the average values of the objective functions. NSGA II works better considering maximum expansion index and metric distance index and finally MOGWO outperforms other algorithms considering the number of Pareto-optimal front (*NPF*) and computational time (CPU time).

**5. 3. Solving The Problem for Larger Sizes**

The following 15 sample problems are designed according to the data given in Table 2 for larger sizes. Each instance of the problem is run five times using MOGWO and NSGA II algorithms. The addressed indicators' values are given as in Table 8.

Table 9 shows the output results of the T-Test on the means of the objective functions and comparison results. According to Table 9 and considering the value of P test statistics, there is no significant difference between the means of the obtained objective functions and also the comparison indices of meta-heuristic algorithms.

**TABLE 7.** Indicators obtained from solving the problem for small size using different methods

Indicator	LP Metrics	NSGA II	MOGWO
The average of the first objective function	18283196.33	18242715.39	18280678.07
OBF1	9662.66	9598.56	9583.89
OBF2	0.994	0.992	0.993
<i>NPF</i>	9	16	19
<i>MSI</i>	359312.84	367355.83	336298.71
<i>MID</i>	157221.08	204193.5	170039.61
<i>SM</i>	0.6272	0.495	0.684
<i>CPU time</i>	14.67	8.16	5.99

**TABLE 8.** The indicators' values for comparing the algorithms for large size instances

Problem	OBF1* 100000	OBF2* 100	OBF3	<i>NPF</i>	<i>MSI</i> * 1000	<i>SM</i> * 1000	<i>MID</i>	CPU time
NSGA II								
1	292.2	17.0	0.986	15	2.5	3.0	0.63	18.2
2	354.9	30.5	0.994	17	3.9	2.8	0.88	54.0
3	380.1	38.1	0.993	25	3.5	4.6	0.59	85.1
4	415.6	63.2	0.991	12	3.0	5.3	0.64	121.2
5	603.2	72.9	0.994	23	3.1	3.3	0.55	167.7
6	767.5	72.9	0.993	20	3.9	5.1	0.79	217.2
7	821.4	81.2	0.984	16	2.8	4.7	0.84	272.8
8	856.4	86.5	0.983	13	4.5	2.0	0.77	334.5
9	880.6	111.8	1.000	16	4.1	4.4	0.71	409.8
10	1026.6	131.8	0.983	17	4.9	3.5	0.82	479.8
11	1173.6	152.7	0.981	11	4.9	4.6	0.82	520.0
12	1524.2	154.6	0.991	19	4.7	2.0	0.84	662.9
13	1729.0	180.6	0.998	13	2.6	3.8	0.82	763.6
14	1800.9	202.2	0.993	16	2.7	3.6	0.97	905.1
15	1824.9	232.9	0.984	19	3.6	3.8	0.6	1338.1
MOGWO								
1	290.3	16.9	0.982	14	4.8	4.3	0.85	11.23
2	353.4	31.2	0.987	14	5.1	2.9	0.62	12.99
3	377.0	40.6	0.984	19	4.5	4.3	0.56	16.88
4	413.9	63.5	0.99	14	5.5	3.4	0.80	31.45
5	609.6	73.5	0.987	23	5.2	2.1	0.73	43.46
6	768.8	75.2	0.999	25	5.9	2.5	0.73	91.88
7	858.0	82.4	0.998	21	4.8	4.1	0.83	118.71
8	865.1	87.5	0.981	15	4.3	3.4	0.89	165.12
9	874.4	109.3	0.995	19	3.7	2.4	0.68	241.44
10	1071.1	133.0	0.985	11	5.0	3.0	0.83	325.88
11	1230.6	157.6	0.989	24	5.4	3.8	0.71	442.66
12	1540.5	158.5	0.991	24	4.5	2.5	0.92	618.78
13	1707.9	176.8	0.999	23	3.7	4.2	0.92	774.56
14	1797.4	201.7	0.988	14	4.1	2.7	0.63	993.45
15	1840.7	248.8	1.000	19	3.8	4.7	0.81	1334.4

Therefore, other multi-criteria decision making methods should be used to select the most efficient algorithm in terms of comparable indicators.

**5. 4. Selecting the Most Efficient Algorithm using TOPSIS Method**

In the previous section, significant comparisons were made to determine the significant difference between the averages of the

computational index obtained by solving the problems using NSGA II and MOGWO algorithms. The results showed that there was no significant difference between the results. In this section, TOPSIS multi-criteria decision making method has been used in order to select the most efficient algorithm. Table 10 shows the total averages obtained from the solved 75 instances of the problem.

After scaling the results of Table 10, the result shows the efficiency of MOGWO algorithm with an obtained weight of 0.9675.

**5. 5. Implementation of the Model for a Real Case Study**

MOGWO algorithm is used to solve the

problem for a real case study in Iranian engine oil industry. The system of raw material supply, distribution as well as product recycling and disposal has been studied. 31 provinces of Iran are considered as suppliers, manufacturers, distribution centers and also the final consumers of the products. The main goal in solving such a problem is to select each province of the country as the main center of manufacturing, distribution, collection center, etc. The data used are estimated from the consensus of experts in the engine oil industry. According to the results, the efficient solutions obtained from problem solving are shown as in Table 11. The Pareto front is shown in Figure 6.

**TABLE 9.** T-Test results on the means of the objective functions

Indicator	Algorithm	Number of instances	Average	Standard deviation	95% confidence interval	T test statistics	P test statistics																																																																																
Mean of Object Function 1	NSGA II	75	96345248	13904657	(-41422359 39453573)	0.05	0.961																																																																																
	MOGWO	75	97329641	13966932				Mean of Object Function 2	NSGA II	75	10864	1681	(-5136 4766)	0.08	0.939	MOGWO	75	11049	1731	Mean of Object Function 3	NSGA II	75	0.989	0.0015	(-0.0051 .00417)	0.21	0.838	MOGWO	75	0.990	0.0017	Number of efficient answers	NSGA II	75	16.80	1	(-5.02 1.42)	1.15	0.261	MOGWO	75	18.60	1.2	Maximum Expansion	NSGA II	75	37002	2202	(-16087 4529)	1.24	0.197	MOGWO	75	47310	1748	Distance from the ideal point	NSGA II	75	38805	2896	(-2526 12347)	1.36	0.186	MOGWO	75	33895	2157	Metric distance	NSGA II	75	0.751	0.032	(-0.1045 0.0725)	0.37	0.714	MOGWO	75	0.767	0.029	Computational time	NSGA II	75	423	95	(-217 367)	0.53	0.601
Mean of Object Function 2	NSGA II	75	10864	1681	(-5136 4766)	0.08	0.939																																																																																
	MOGWO	75	11049	1731				Mean of Object Function 3	NSGA II	75	0.989	0.0015	(-0.0051 .00417)	0.21	0.838	MOGWO	75	0.990	0.0017	Number of efficient answers	NSGA II	75	16.80	1	(-5.02 1.42)	1.15	0.261	MOGWO	75	18.60	1.2	Maximum Expansion	NSGA II	75	37002	2202	(-16087 4529)	1.24	0.197	MOGWO	75	47310	1748	Distance from the ideal point	NSGA II	75	38805	2896	(-2526 12347)	1.36	0.186	MOGWO	75	33895	2157	Metric distance	NSGA II	75	0.751	0.032	(-0.1045 0.0725)	0.37	0.714	MOGWO	75	0.767	0.029	Computational time	NSGA II	75	423	95	(-217 367)	0.53	0.601	MOGWO	75	348	106								
Mean of Object Function 3	NSGA II	75	0.989	0.0015	(-0.0051 .00417)	0.21	0.838																																																																																
	MOGWO	75	0.990	0.0017				Number of efficient answers	NSGA II	75	16.80	1	(-5.02 1.42)	1.15	0.261	MOGWO	75	18.60	1.2	Maximum Expansion	NSGA II	75	37002	2202	(-16087 4529)	1.24	0.197	MOGWO	75	47310	1748	Distance from the ideal point	NSGA II	75	38805	2896	(-2526 12347)	1.36	0.186	MOGWO	75	33895	2157	Metric distance	NSGA II	75	0.751	0.032	(-0.1045 0.0725)	0.37	0.714	MOGWO	75	0.767	0.029	Computational time	NSGA II	75	423	95	(-217 367)	0.53	0.601	MOGWO	75	348	106																				
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**TABLE 10.** Average values of the indicators for the two algorithms

Algorithm	Objective function 1	Objective function 2	Objective function 3	NPF	MSI	MID	SM	CPU-Time
NSGA II	96345248	10864	0.989	16.80	37002	38805	0.751	423
MOGWO	97329641	11049	0.990	18.60	47310	33895	0.767	348

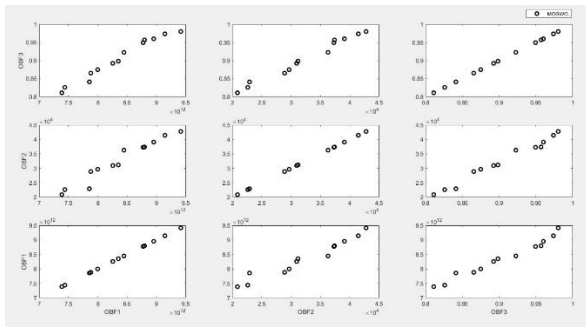
**TABLE 11.** Efficient solutions from the case study in Iranian engine oil industry

Efficient solutions	Objective function 1	Objective function 2	Objective function 3
1	7387708657310.84	20873	0.81
2	7439665190205.53	22619	0.83

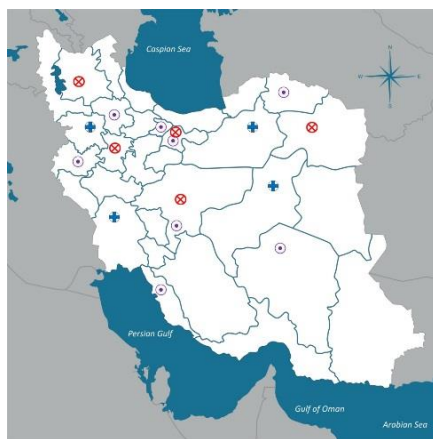
3	7857645842071.79	22921	0.84
4	7881325572261.93	28900	0.87
5	7999451000125.68	29678	0.87
6	8256810244200.38	30959	0.89
7	8351376182362.55	31184	0.90



8	8446676226610.35	36302	0.92
9	8773999647463.98	37314	0.95
10	8796633076821.11	37407	0.96
11	8953631688404.11	39097	0.96
12	9145413649915.65	41468	0.97
13	9415968260535.70	42790	0.98



**Figure 6.** Pareto front solutions from solving the problem in Iranian engine oil industry



⊗ Manufacturing centers  
⊕ Distribution centers  
⊕ Collection and destruction centers

**Figure 7.** Provincial centers selected for the case study of Iranian engine oil industry

Based on the obtained results, the implementation of such a network in Iran has a profit of 8362023479869.43, which can lead to job creation for 32424 people. Furthermore, the reliability of implementing such a system is equal to 90%. Figure 7 shows the provincial centers for selecting the manufacturing, distribution and collection centers.

## 6. CONCLUSIONS AND FURTHER RESEARCH IDEAS

Global economic conditions and environmental issues importance leads to excessive attention of governments

to the design of CLSC networks. In this paper, by presenting a mathematical model, an attempt was made to design a comprehensive network of supply, manufacturing, refining and supply of products to customers in which social, economic and environmental issues were observed. Due to the uncertainty of some parameters such as demand and cost factors, the robust fuzzy optimization method was used to tackle the existed uncertainty. The results showed an increase in total costs of the chain and decrease in reliability when the uncertainty rate increases. MOGWO and NSGA II algorithms were used to solve the problem. The results of solving the problem for larger sizes showed the performance of the MOGWO algorithm against the NSGA II algorithm. In order to compare the two algorithms, some indicators including means of objective functions, distance index, distance index from ideal point, maximum amplitude index, Pareto solution number index and computational time were applied.

As further research, it is suggested to consider a competitive chain for the problem under study. Other methods of uncertainty can also make the model closer to the real world situations. The results help the managers of the engine oil industry to analyze the results of the designed network for the most pessimistic and optimistic situations in product demand, and to be able to properly manage the construction of different facilities in the supply chain. Managers can also make good decisions about social and environmental issues which have become so much important in industries like engine oil from the viewpoint of international and national norms.

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### Persian Abstract

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#### چکیده

با توجه به اهمیت زنجیره تامین و مسائل زیست محیطی، این مقاله یک مدل ریاضی جدید برای شبکه زنجیره تامین حلقه بسته سبز با اهداف حداکثرسازی سود، حداکثر کردن تعداد مشاغل ایجاد شده و حداکثر کردن قابلیت اطمینان ارائه می دهد. به دلیل عدم قطعیت در برخی از پارامترها مانند تقاضا و هزینه حمل و نقل، از روش جدید مدل برنامه نویسی فازی استوار استفاده شده است. برای حل مسئله در سایزهای بزرگتر از الگوریتم های بهینه سازی گرگ خاکستری چندهدفه و الگوریتم ژنتیک مرتب سازی نامغلوب ۲ استفاده شده است. نتایج حاصل از مقایسه الگوریتم ها با در نظر گرفتن برخی معیارها از جمله میانگین توابع هدف، شاخص فاصله متریک، شاخص فاصله از نقطه ایده آل، بیشترین گسترش، تعداد جواب کارا و زمان محاسبه، همگرایی سریع و کارایی بالای الگوریتم بهینه سازی گرگ خاکستری چندهدفه را برای این مسئله نشان داد. در نهایت، پیاده سازی مدل برای مطالعه موردی واقعی در صنعت روغن موتور ایران، کارایی راه حل های به دست آمده را برای این شبکه نشان داد.

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