

Multi-Objective Location-Allocation-Routing Problem of Perishable Multi-Product Supply Chain With Direct Shipment and Open Routing Possibilities Under Sustainability

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Multi-objective location-allocation-routing problem of perishable multi-product supply chain with direct shipment and open routing possibilities under sustainability

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Abstract

In this study a multi-objective formulation is proposed for designing a supply chain of perishable products including suppliers, plants, distributors, and customers under sustainable development. In addition to the studies of the literature, direct shipment between producers and customers and also alternative products possibility are allowed. In this problem the objectives like facilities establishment costs, transportation costs, negative environmental impacts, and social impact (fixed and variable employment rates) are optimized simultaneously. As in real situations, most of the transportation activities of such supply chain are performed by hiring transportation devices, the open routing logic is applied to form the travelling path of each hired transportation device. Furthermore, the possibility of direct shipment from the plants to the customers is considered in order to increase profitability of the plants. Because of the NP-hard nature of the supply chain design problems, some meta-heuristic solution approaches of the literature are modified to multi-objective form and applied to solve the problem. Several test problems from small to large sizes are generated randomly to evaluate the meta-heuristic algorithms. As a result, among the proposed algorithms, the multi-objective grey wolf optimizer (MGWO) perform better than others by considering four well-known evaluation metrics. At the end, a case study from perishable products supply chain of Iran is solved and analyzed to show the applicability of the proposed problem.

Keywords: Perishable products; Supply chain; Multi-objective; Meta-heuristic algorithm; Open routing

1. Introduction

In general, supply chain management uses some effective strategies in order to integrate the flow of material and information among suppliers, producers, inventories, and shops for timely production and distribution of products (Simchi-Levi et al., 2008). In traditional supply chain networks, the products are assumed to be of endless life (Dai et al., 2018). But in reality, some of the products are perishable and lose whole or a part of their value after a while (Levina et al., 2010). Meat, vegetables, dairy products, human's blood, drugs, flowers, etc. are some examples for perishable products (Mirzaei and Seyfi, 2015). One of the most important parts of supply chain management is to design the supply chain network of perishable products. Due to short life cycle of these products (for example foods), the activities such as ordering, pricing, storing, etc. in the supply chain become very complex. Another difficulty of managing the supply chain of perishable products is that keeping high volume of them in inventories has three major negative effects e.g. (1) the cost of supply chain is increased if the products are perished, (2) the waste of perishable products have negative effects on environment, and (3) the quality of these products start to be decreased immediately after production.

Supply chain costs are approximately 30% of the total value of perishable products for a company. Therefore, managing such costs can increase competitive ability of the company (Diabat et al., 2019). On the other hand, other criteria such as environmental negative effects and social effects such as employment can improve sustainability of supply chain (Yakavenka et al., 2019). Therefore, these criteria should be considered in supply chain decision making. Generally, decision making in supply chain can be done in strategic, tactical, and operational levels (Shen and Qi, 2007). The strategic decisions are taken mainly

about number and locations of facilities e.g. plants, distribution centers, etc. (Ravindran and Warsing Jr, 2016). The tactical decisions are about material flow, information flow, amount of material and product in the facilities, etc. Finally, the operational decisions are taken about transportation activities and optimal transportation routing (Berman et al., 2012). Operations research (OR) is an optimization tool with many applications in supply chain decision making (Snyder et al., 2016). As of the most important applications of OR, design of distribution network in a multi-echelon network with location, allocation and routing decisions can be mentioned (Eiselt and Marianov, 2015). In addition, optimization algorithms (Rabbani et al., 2018) and multi-criteria decision making (Soltani et al., 2015) also are of such applications.

Some important studies of perishable products supply chain is reviewed here. Mohammed and Wang (2017) proposed a fuzzy multi-objective model for meat distribution planning. Diabat et al. (2019) presented a bi-objective robust model for designing the supply chain of perishable products. Rafie-Majd et al. (2018) studied a three-echelon supply chain of perishable products with stochastic demand. They used the lagrangean relaxation approach to solve the model. Dai et al. (2018) modeled a supply chain of perishable products in fuzzy environment with CO₂ emission and capacity constraints. Navazi et al. (2018) studied a supply chain of perishable products with objectives such as minimizing cost, CO₂, due date, and accident rate. Hamdan and Diabat (2019) presented a two-level stochastic programming for blood delivery supply chain. The details of the researches performed in this study area are represented by Table 1. These studies are detailed from problem type, structure, solution method, decision type, and sustainability points of view.

Table 1. The most recent studies in supply chain network design related to this study.

Study	Objectives		Logistics' structure				Solution method				Decisions			Sustainability		
	Single	Multiple	Single product	Multi-product	Direct Shipment	Alternative products	Exact	Heuristic	Meta-heuristic	Others	Location	Routing	Others	Economic	Environment	Social
Amiri et al. (2018)	<input type="checkbox"/>			<input type="checkbox"/>				<input type="checkbox"/>	<input type="checkbox"/>		<input type="checkbox"/>			<input type="checkbox"/>	<input type="checkbox"/>	
Tseng et al. (2018)		<input type="checkbox"/>	<input type="checkbox"/>						<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>			<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Eskandari-Khanghahi et al. (2018)		<input type="checkbox"/>	<input type="checkbox"/>					<input type="checkbox"/>		<input type="checkbox"/>	<input type="checkbox"/>			<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Asadi et al. (2018)		<input type="checkbox"/>	<input type="checkbox"/>					<input type="checkbox"/>		<input type="checkbox"/>	<input type="checkbox"/>			<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Jabbarzadeh et al. (2018)		<input type="checkbox"/>	<input type="checkbox"/>					<input type="checkbox"/>		<input type="checkbox"/>	<input type="checkbox"/>			<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Navazi et al. (2018)	<input type="checkbox"/>			<input type="checkbox"/>					<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>			<input type="checkbox"/>	<input type="checkbox"/>	
Tabrizi et al. (2018)		<input type="checkbox"/>		<input type="checkbox"/>					<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>			<input type="checkbox"/>	<input type="checkbox"/>	
Fatholohi-Fard et al. (2018)	<input type="checkbox"/>		<input type="checkbox"/>						<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>			<input type="checkbox"/>	<input type="checkbox"/>	
Fard and Hajaghaei-Keshteli (2018)	<input type="checkbox"/>			<input type="checkbox"/>					<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>			<input type="checkbox"/>	<input type="checkbox"/>	
Amirtaheri et al. (2018)	<input type="checkbox"/>			<input type="checkbox"/>					<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>			<input type="checkbox"/>	<input type="checkbox"/>	
Rad and Nahavandi (2018)		<input type="checkbox"/>		<input type="checkbox"/>			<input type="checkbox"/>						<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Ebrahimi (2018)		<input type="checkbox"/>		<input type="checkbox"/>			<input type="checkbox"/>				<input type="checkbox"/>		<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	
Khorasani and Almasifard (2018)		<input type="checkbox"/>		<input type="checkbox"/>						<input type="checkbox"/>			<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	
Lin et al. (2020)	<input type="checkbox"/>		<input type="checkbox"/>							<input type="checkbox"/>			<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Jin et al. (2018)	<input type="checkbox"/>		<input type="checkbox"/>							<input type="checkbox"/>			<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Ghomi-Avili et al. (2018)		<input type="checkbox"/>	<input type="checkbox"/>							<input type="checkbox"/>			<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	
Babazadeh and Torabi (2018)	<input type="checkbox"/>		<input type="checkbox"/>				<input type="checkbox"/>						<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	
Cao et al. (2018)		<input type="checkbox"/>	<input type="checkbox"/>						<input type="checkbox"/>				<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Chalmardi and Camacho-Vallejo (2019)	<input type="checkbox"/>			<input type="checkbox"/>					<input type="checkbox"/>				<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	
Mohammed et al. (2019)		<input type="checkbox"/>		<input type="checkbox"/>						<input type="checkbox"/>			<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Hassanpour et al. (2019)	<input type="checkbox"/>			<input type="checkbox"/>				<input type="checkbox"/>	<input type="checkbox"/>		<input type="checkbox"/>		<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	
Taleizadeh et al. (2019)	<input type="checkbox"/>		<input type="checkbox"/>				<input type="checkbox"/>						<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	

Jalil et al. (2019)		<input type="checkbox"/>	<input type="checkbox"/>				<input type="checkbox"/>						<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	
Hafezalkotob and Zamani (2019)	<input type="checkbox"/>		<input type="checkbox"/>						<input type="checkbox"/>				<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	
Karimi et al. (2019)		<input type="checkbox"/>	<input type="checkbox"/>						<input type="checkbox"/>				<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Cheraghalipour et al. (2019)	<input type="checkbox"/>		<input type="checkbox"/>						<input type="checkbox"/>				<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	
Rahmandoust and Soltani (2019)		<input type="checkbox"/>		<input type="checkbox"/>					<input type="checkbox"/>		<input type="checkbox"/>	<input type="checkbox"/>		<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Tosarkani and Amin (2019)	<input type="checkbox"/>			<input type="checkbox"/>					<input type="checkbox"/>		<input type="checkbox"/>	<input type="checkbox"/>		<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Dai et al. (2019)	<input type="checkbox"/>			<input type="checkbox"/>				<input type="checkbox"/>	<input type="checkbox"/>		<input type="checkbox"/>	<input type="checkbox"/>		<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Hadian et al. (2019)		<input type="checkbox"/>	<input type="checkbox"/>					<input type="checkbox"/>	<input type="checkbox"/>		<input type="checkbox"/>	<input type="checkbox"/>		<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Eskandarpour et al. (2019)		<input type="checkbox"/>	<input type="checkbox"/>					<input type="checkbox"/>	<input type="checkbox"/>		<input type="checkbox"/>	<input type="checkbox"/>		<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Zhou et al. (2019)		<input type="checkbox"/>		<input type="checkbox"/>					<input type="checkbox"/>		<input type="checkbox"/>	<input type="checkbox"/>		<input type="checkbox"/>	<input type="checkbox"/>	
This study		<input type="checkbox"/>		<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>		<input type="checkbox"/>	<input type="checkbox"/>		<input type="checkbox"/>	<input type="checkbox"/>		<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>

In this study a supply chain network design problem of perishable products is considered. This supply chain consists of suppliers, producers, distribution centers, and customers. In addition to the studies of the literature, direct shipment between producers and customers and also alternative products possibility are allowed. In order to cover more aspects of the problem, it is formulated as a multi-objective mathematical model. The objective functions of the model are (1) minimization of total costs, including establishment costs of the plants and distribution centers, all transportation costs among the suppliers, facilities and customers, and hiring cost of the transportation facilities, (2) minimization of the negative environmental impact of transportation activities, and (3) maximization of fixed and variable employment rate and minimization of the lost days. The constraints of the model include facilities location constraints, material flow constraints, open transportation routing from plants to customers and distribution centers to customers, and determining alternative products for customers according to their need. As the proposed formulation is generally from NP-hard class of optimization problems, we need to apply meta-heuristic algorithms to solve the medium and large sized instances of the problem. Therefore, some meta-heuristic solution approaches of the literature are modified to multi-objective form and applied to solve the problem. Several test problems from small to large sizes are generated randomly to evaluate the meta-heuristic algorithms. As a result, among the proposed algorithms, the multi-objective grey wolf optimizer (MGWO), perform better than others by considering four well-known evaluation metrics. At the end, a case study from perishable products supply chain of Iran is solved and analyzed to show the applicability of the proposed problem.

The remainder of this paper is organized in some other sections. Section 2 describes the problem of the study, presents its mathematical formulation, and discusses its computational complexity. Section 3 develops some classical and hybrid meta-heuristic algorithms to solve the proposed mathematical model. Section 4 performs a full computational study on the proposed meta-heuristic algorithms. Section 5 gives some conclusions for the study.

2. Problem description and formulation

In this study a problem of locating and open routing in a supply chain with four echelons such as suppliers, plants, distribution centers, and customers is modeled as a multi-objective problem with sustainability. The network of this problem is depicted by Figure 1.

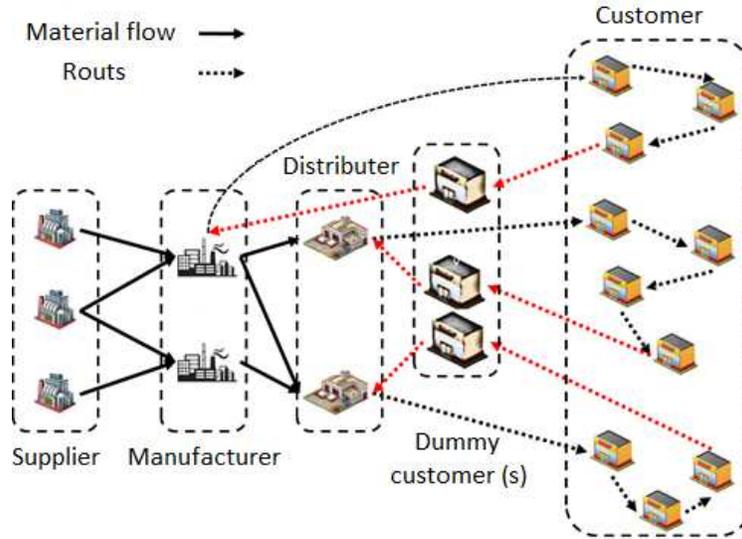


Figure 1. Network of the proposed problem.

In this problem direct transportation is considered between all echelons, while the routing is done between the established distribution centers (DCs) and the customers and also between the established plants and the customers. The flow of raw material is determined according to the amount of each raw material in final product. The transportation of final products is done in two ways by applying an open routing technique, first sending them to the established DCs and then transporting them to the customers, and second, direct transportation from the plants to the customers. Open routing is applied in this study as in real-world cases, many companies do not own transportation devices. Therefore, they hire some devices to send the products to the destinations. After that the device does not need to come back to the plant and leaves the system. This type of routing is called open routing. In the plants different manufacturing technologies can be used where they affect the cost, environmental impact, and social impact of an established plant. Selection of the technology of an established plant is done by the objective functions. On the other hand for the DCs different capacities are proposed where they affect the cost, environmental impact, and social impact of an established DC.

Mathematical model proposed for the problem consists of three objective functions. First objective function minimizes total cost of the network including establishment costs, transportation costs, hiring cost of transportation devices, raw material costs, and production costs. Second objective function minimizes negative environmental impacts of facilities establishment, production, and transportation activities. Third objective function maximizes positive social impacts including fixed and variable employment rates by establishing plants and DCs. In order to consider the concept of open routing in the proposed formulation, we use dummy nodes (customers) in the network of the problem (as shown by Figure 1). In the tour of each transportation device, a dummy customer is considered. The device after passing all customers enters the dummy customer. The distance and cost of this dummy customer to the other customers is zero, therefore, entering to this dummy customer has no cost for the network.

The assumptions used to model the problem is as follow,

- There are a set of potential plants, a set of potential DCs, and a set of potential suppliers. Some or all of them are to be established or used in the network.
- The number and place of the customers are known.
- There are enough available transportation devices with different capacities and costs.

- The problem is multi-product with a single planning period.
- The demand of each customer is fulfilled from only one DC.
- The environmental impact of the established facilities and transportation activities are known.
- Each established facility has an employment rate.
- For each potential plant a set of different manufacturing technologies is considered where only one of them can be selected.
- For each potential DC a set of different capacities is considered where only one of them can be selected.
- The tour of each transportation device is open.
- The products are sent to the customers from the DCs and directly from the plants.

The notations used to formulate the proposed formulation is given below,

Sets and indexes:

I	Set of suppliers	$i \in \{1,2, \dots, I \}$
M	Cumulative set of plants, distribution centers (DCs), and customers	$M = \{J \cup R \cup C\}$
J	Set of potential plants	$j \in \{1,2, \dots, J \}$
R	Set of potential DCs	$r \in \{1,2, \dots, R \}$
C	Set of customers	$c \in \{1,2, \dots, C \}$
O	Dummy customer	$o \in \{O\}$
V^a	Set of transportation devices between suppliers and plants	$v^a \in \{1,2, \dots, V^a \}$
V^b	Set of transportation devices between plants and DCs	$v^b \in \{1,2, \dots, V^b \}$
V^c	Set of transportation devices between plants/DCs and customers	$v^c \in \{1,2, \dots, V^c \}$
L	Potential capacity levels for DCs	$l \in \{1,2, \dots, L \}$
G	Set of products	$g \in \{1,2, \dots, G \}$
K	Set of raw materials	$k \in \{1,2, \dots, K \}$
E	Set of potential technologies for plants	$e \in \{1,2, \dots, E \}$

Parameters:

$Cost_{ik}^{raw}$	Price of raw material k bought from supplier i
$Cost_{gje}^{Pro}$	Cost of producing a unit of product g at plant j by technology e
$Cost_{grl}^{DisD}$	Cost of processing a unit of product g at DC r with capacity l
$Cost_{jg}^{DisP}$	Holding cost of product g at plant j for direct shipment purpose
$Cost_v^{rent}$	Hiring cost of device v
$Cost_v^{S2P}$	Transportation cost of device v per unit of distance from a supplier to a plant
$Cost_v^{P2D}$	Transportation cost of device v per unit of distance from a plant to a DC
$Cost_v^{CC}$	Transportation cost of device v per unit of distance from a plant or DC to a customer
$PCost_{cgg'}$	Cost of replacing product g by product g' for customer c
NED_{gke}	Required amount of raw material k for producing product g by technology e
$Demand_{cg}$	Demand of customer c for product g
Cap_{jeg}	Capacity of producing product g in plant j with technology e
CAP_{ik}^S	Capacity of supplier i for raw material k
CAP_{vk}^{S2P}	Capacity of device v for transporting raw material k
CAP_{vg}^{P2D}	Capacity of device v for transporting product g

CAP_{rlg}^D	Capacity of DC r for product g at capacity level l
$Cost_{jeg}^{ActP}$	Fixed cost of establishing plant j with technology e for product g
$Cost_{rlg}^{ActD}$	Fixed cost of establishing DC r with capacity level l for product g
$Dist_{ij}^{S2P}$	Distance of supplier i and plant j
$Dist_{jr}^{P2D}$	Distance of plant j and DC r
$Dist_{mm'}^{CC}$	Distance of customers m and m' where $(m, m') \in M/\{J, R\}$
ENV_v^{S2P}	Environmental impact of transportation by device v per unit of distance from a supplier to a plant
ENV_v^{P2D}	Environmental impact of transportation by device v per unit of distance from a plant to a DC
ENV_v^C	Environmental impact of transportation by device v to customers
ENV_{jeg}^P	Environmental impact of producing a unit of product g at plant j with technology e
ENV_{jeg}^{P-E}	Environmental impact of establishing plant j with technology e for product g
ENV_{rlg}^{D-L}	Environmental impact of establishing DC r with capacity level l for product g
Job_{jeg}^{P-E}	Fixed job positions created by establishing plant j with technology e for product g
Job_{rlg}^{D-L}	Fixed job positions created by establishing DC r with capacity level l for product g
$VJob_{jeg}^{P-E}$	Variable job positions created by establishing plant j with technology e for product g
$VJob_{rlg}^{D-L}$	Variable job positions created by establishing DC r with capacity level l for product g
$Lost_{jeg}^{P-E}$	Fixed lost job positions by establishing plant j with technology e for product g
$Lost_{rlg}^{D-L}$	Fixed lost job positions by establishing DC r with capacity level l for product g
$VLost_{jeg}^{P-E}$	Variable lost job positions by establishing plant j with technology e for product g
$VLost_{rlg}^{D-L}$	Variable lost job positions by establishing DC r with capacity level l for product g
PX	Fixed penalty cost due to unfulfilled demands
E_g	Takes value of 1 if production of product g is possible, otherwise 0
$PF_{cgg'}$	Takes value of 1 if product g can be replaced by product g' , otherwise 0
Big	A large positive value

Binary variables:

Y_{jeg}^{P-E}	Takes value of 1 if plant j is established with technology e for product g , otherwise 0
Y_{rlg}^{D-L}	Takes value of 1 if DC r is established with capacity level l for product g , otherwise 0
$X_{mm'vg}$	Takes value of 1 if device v travels from node m to m' (where $(m, m') \in M$) for transporting product g , otherwise 0
$Rent_{vg}$	Takes value of 1 if device v is rented for transportation of product g
Q_{ijvk}^{S-P}	Takes value of 1 if device v is used to transport raw material k from supplier i to plant j , otherwise 0
Q_{jrvg}^{P-D}	Takes value of 1 if device v is used to transport product g from plant j to DC r , otherwise 0
F_{mcg}	Takes value of 1 if customer c is connected to plant or DC m for product g
$U_{cgg'}$	Takes value of 1 if product g is replaced by product g' for customer c

Integer variables:

$Flow_{ijvk}^{S-P}$	Amount of raw material k sent from supplier i to plant j by device v
$Flow_{jrv}^{P-D}$	Amount of product g sent from plant j to DC r by device v
$Flow_{jcv}^{P-C}$	Amount of product g sent from plant j to customer c by device v
Pd_{gje}	Amount of product g produced by technology e at plant j
$Extra$	Excess/shortage production amount comparing to demand
$ST_{mv}g$	Sub-tour elimination variable

Mathematical formulation:

$$\begin{aligned}
Min \zeta = & \sum_{i \in I} \sum_{j \in J} \sum_{v \in V^a} \sum_{k \in K} Cost_{ik}^{raw} \times Flow_{ijvk}^{S-P} + \sum_{i \in I} \sum_{j \in J} \sum_{v \in V^a} \sum_{k \in K} Dist_{ij}^{S2P} \times Cost_v^{S2P} \times Q_{ijvk}^{S-P} \\
& + \sum_{j \in J} \sum_{e \in E} \sum_{g \in G} Cost_{gje}^{Pro} \times Pd_{gje} \\
& + \sum_{j \in J} \sum_{v \in V^b} \sum_{r \in R} \sum_{g \in G} Cost_v^{P2D} \times Dist_{jr}^{P2D} \times Q_{jrv}^{P-D} \\
& + \sum_{j \in J} \sum_{e \in E} \sum_{g \in G} Cost_{jeg}^{ActP} \times Y_{jeg}^{P-E} + \sum_{v \in V^b} \sum_{l \in L} \sum_{r \in R} \sum_{g \in G} \sum_{j \in J} Cost_{grl}^{DisD} \times Flow_{jrv}^{P-D} \\
& + \sum_{v \in V^c} \sum_{c \in C} \sum_{g \in G} \sum_{j \in J} Cost_{jg}^{DisP} \times Flow_{jcv}^{P-C} + \sum_{r \in R} \sum_{l \in L} \sum_{g \in G} Cost_{rlg}^{ActD} \times Y_{rlg}^{D-L} \\
& + \sum_{v \in V^c} \sum_{g \in G} \left(Cost_v^{rent} \times Rent_{vg} + \sum_{m \in M} \sum_{m' \in M} Cost_v^{CC} \times Dist_{mm'}^{CC} \times X_{mm'vh} \right) \\
& + PX \times Extra + \sum_{c \in C} \sum_{g \in G} \sum_{g' \in G} PCost_{cgg'} \times U_{cgg'}
\end{aligned} \tag{1}$$

$$\begin{aligned}
Min \xi = & \sum_{i \in I} \sum_{j \in J} \sum_{v \in V^a} \sum_{k \in K} ENV_v^{S2P} \times Dist_{ij}^{S2P} \times Q_{ijvk}^{S-P} \\
& + \sum_{j \in J} \sum_{r \in R} \sum_{v \in V^b} \sum_{g \in G} ENV_v^{P2D} \times Dist_{jr}^{P2D} \times Q_{jrv}^{P-D} \\
& + \sum_{m \in M} \sum_{m' \in C} \sum_{v \in V^c} \sum_{g \in G} ENV_v^C \times Dist_{mm'}^{C2C} \times X_{mm'vg} \\
& + \sum_{j \in J} \sum_{e \in E} \sum_{g \in G} ENV_{jeg}^{P-E} \times Y_{jeg}^{P-E} + \sum_{r \in R} \sum_{l \in L} \sum_{g \in G} ENV_{rlg}^{D-L} \times Y_{rlg}^{D-L} \\
& + \sum_{j \in J} \sum_{e \in E} \sum_{g \in G} ENV_{jeg}^P \times Pd_{gje}
\end{aligned} \tag{2}$$

$$\begin{aligned}
Max \psi = & \left(\sum_{j \in J} \sum_{e \in E} \sum_{g \in G} Job_{jeg}^{P-E} \times Y_{jeg}^{P-E} + \sum_{r \in R} \sum_{l \in L} \sum_{g \in G} Job_{rlg}^{D-L} \times Y_{rlg}^{D-L} \right. \\
& + \sum_{j \in J} \sum_{e \in E} \sum_{g \in G} VJob_{jeg}^{P-E} \times \left(\frac{Pd_{jeg}}{Cap_{jeg}} + \frac{\sum_{c \in M/\{J,R\}} \sum_{v \in V^c} Flow_{jcvg}^{P-C}}{\sum_{c \in M/\{J,R\}} Demand_{cg}} \right) \\
& + \sum_{j \in J} \sum_{l \in L} \sum_{g \in G} \sum_{r \in R} VJob_{rlg}^{D-L} \times \frac{\sum_{v \in V^b} Flow_{jrvg}^{P-D}}{CAP_{rlg}^D} \left. \right) \\
& - \left(\sum_{j \in J} \sum_{e \in E} \sum_{g \in G} Lost_{jeg}^{P-E} \times Y_{jeg}^{P-E} + \sum_{r \in R} \sum_{l \in L} \sum_{g \in G} Lost_{rlg}^{D-L} \times Y_{rlg}^{D-L} \right. \\
& + \sum_{j \in J} \sum_{e \in E} \sum_{g \in G} VLost_{jeg}^{P-E} \times \left(\frac{Pd_{jeg}}{Cap_{jeg}} + \frac{\sum_{c \in C} \sum_{v \in V^c} Flow_{jcvg}^{P-C}}{\sum_{c \in C} Demand_{cg}} \right) \\
& + \sum_{j \in J} \sum_{l \in L} \sum_{g \in G} VLost_{rlg}^{D-L} \times \frac{\sum_{v \in V^b} Flow_{jrvg}^{P-D}}{CAP_{rlg}^D} \left. \right)
\end{aligned} \tag{3}$$

Subject to

$$\sum_{j \in J} \sum_{v \in V^a} Flow_{ijvk}^{S-P} \leq CAP_{ik}^S \quad \forall i \in I, k \in K \tag{4}$$

$$\sum_{v \in V^a} \sum_{i \in I} Flow_{ijvk}^{S-P} \geq \sum_{g \in G} \sum_{e \in E} Pd_{gje} \times NED_{gke} \quad \forall j \in J, k \in K \tag{5}$$

$$Flow_{ijvk}^{S-P} \leq CAP_{vk}^{S2P} \times Q_{ijvk}^{S-P} \quad \forall i \in I, j \in J, v \in V^a, k \in K \tag{6}$$

$$Pd_{gje} \leq Cap_{jeg} \times Y_{jeg}^{P-E} \quad \forall j \in J, g \in G, e \in E \tag{7}$$

$$\sum_{e \in E} Y_{jeg}^{P-E} \leq 1 \quad \forall j \in J, g \in G \tag{8}$$

$$\sum_{e \in E} \sum_{j \in J} Y_{jeg}^{P-E} \leq Big \times E_g \quad \forall g \in G \tag{9}$$

$$\sum_{j \in J} \sum_{e \in E} Pd_{gje} \geq \sum_{c \in C} Demand_{cg} \times E_g \quad \forall g \in G, \tag{10}$$

$$\sum_{j \in J} \sum_{e \in E} Pd_{gje} = \sum_{c \in C} (Demand_{cg} + Demand_{cg'} \times U_{cgg'}) \quad \forall g \neq g' \in G, E_g = 1, E_{g'} = 0 \tag{11}$$

$$\sum_{j \in J} \sum_{v \in V^b} Flow_{jrvg}^{P-D} \leq Big \times \sum_{l \in L} Y_{rlg}^{D-L} \quad \forall r \in R, g \in G \tag{12}$$

$$\sum_{l \in L} Y_{rlg}^{D-L} \leq \sum_{j \in J} \sum_{v \in V^b} Flow_{jrvg}^{P-D} \quad \forall r \in R, g \in G \tag{13}$$

$$\sum_{r \in R} \sum_{v \in V^b} Flow_{jrvg}^{P-D} + \sum_{c \in C} \sum_{v \in V^c} Flow_{jcvg}^{P-C} = \sum_{e \in E} Pd_{gje} \quad \forall j \in J, g \in G \tag{14}$$

$$Flow_{jrvg}^{P-D} \leq CAP_{vg}^{P2D} \times Q_{jrvg}^{P-D} \quad \forall j \in J, v \in V^b, g \in G, r \in R \tag{15}$$

$$\sum_{j \in M/\{R,C\}} \sum_{v \in V^b} Flow_{jrvg}^{P-D} \leq \sum_{l \in L} CAP_{rlg}^D \times Y_{rlg}^{D-L} \quad \forall r \in R, g \in G \tag{16}$$

$$\sum_{v \in V^c} Flow_{jcvg}^{P-C} \leq BIG \times F_{jcg} \quad \forall j \in J, g \in G, c \in C \quad (17)$$

$$\sum_{c \in C} F_{rcg} \leq Big \times \sum_{l \in L} Y_{rlg}^{D-L} \quad \forall r \in R, g \in G \quad (18)$$

$$\sum_{l \in L} Y_{rlg}^{D-L} \leq BIG \times \sum_{c \in C} F_{rcg} \quad \forall r \in R, g \in G \quad (19)$$

$$\sum_{c \in C} F_{jcg} \leq Big \times \sum_{e \in E} Y_{jeg}^{P-E} \quad \forall j \in J, g \in G \quad (20)$$

$$\sum_{l \in L} Y_{rlg}^{D-L} \leq 1 \quad \forall r \in R, g \in G \quad (21)$$

$$\sum_{m' \in M} X_{mm'vg} + \sum_{m' \in M/\{O\}} X_{m'cvg} - F_{mcg} \leq 1 \quad \forall m \in \{J \cup R\}, v \in V^c, g \in G, E_g = 1 \quad (22)$$

$$\sum_{m \in M} \sum_{v \in V^c} X_{mcvg} = 1 \quad \forall c \in C/\{O\}, g \in G, E_g = 1 \quad (23)$$

$$\sum_{m \in M} X_{mcvg} \leq 1 \quad \forall c \in C/\{O\}, v \in V^c, g \in G, E_g = 1 \quad (24)$$

$$\sum_{c \in C} F_{mcg} \leq Big \times \sum_{c \in C} \sum_{v \in V^c} X_{mcvg} \quad \forall m \in \{J \cup R\}, g \in G, E_g = 1 \quad (25)$$

$$\sum_{c \in C} F_{mcg} \leq \sum_{v \in V^c} X_{movg} \quad \forall m \in \{J \cup R\}, g \in G, E_g = 1 \quad (26)$$

$$\sum_{m' \in M} X_{m'mvg} - \sum_{m' \in M} X_{mm'vg} = 0 \quad \forall m \in M, v \in V^c, g \in G, E_g = 1 \quad (27)$$

$$X_{movg} = 0 \quad \forall m \in \{J \cup R\}, v \in V^c, g \in G, E_g = 1 \quad (28)$$

$$\sum_{c \in C/\{O\}} X_{covg} = 0 \quad \forall v \in V^c, g \in G, E_g = 1 \quad (29)$$

$$ST_{mvg} - ST_{c'vg} + |M| \times X_{mcvg} \leq |M| - 1 \quad \forall m \in M, v \in V^c, g \in G, c \in C, E_g = 1 \quad (30)$$

$$\sum_{m \in M} \sum_{c \in C} X_{mcvg} \leq Big \times Rent_{vg} \quad \forall v \in V^c, g \in G \quad (31)$$

$$Rent_{vg} \leq \sum_{m \in M} \sum_{c \in C} X_{mcvg} \quad \forall v \in V^c, g \in G \quad (32)$$

$$\sum_{m \in \{J \cup R\}} X_{cmvg} = 0 \quad \forall v \in V^c, c \in C/\{O\}, g \in G \quad (33)$$

$$\sum_{j \in J} \sum_{e \in E} Pd_{gje} \leq Big \times E_g \quad \forall g \in G \quad (34)$$

$$U_{cgg'} \leq F_{cgg'} \quad \forall g \neq g' \in G, c \in C \quad (35)$$

$$\sum_{g \in G, E_g=1} U_{cgg'} \leq 1 \quad \forall g' \in G, c \in C, E_{g'} = 0, \quad (36)$$

$$\sum_{g \in G} \left(\sum_{c \in C} Demand_{cg} - \sum_{j \in J} \sum_{e \in E} Pd_{gje} \right) \leq Extra \quad (37)$$

$$Y_{jeg}^{P-E}, Y_{rlg}^{D-L}, X_{mm'vg}, Rent_{vg}, Q_{ijvk}^{S-P}, Q_{jrvg}^{P-D}, F_{mcg}, U_{cgg'} \in \{0, 1\} \quad (38)$$

$$Flow_{ijvk}^{S-P}, Flow_{jrvg}^{P-D}, Flow_{jcvg}^{P-C}, Pd_{gje}, Extra, ST_{mvg} \geq 0 \quad (39)$$

Objective function (1) minimizes total cost of the network. In this objective function, first term calculates the purchasing cost of raw material. Second term is the transportation cost from the suppliers to the plants. Third term calculates the manufacturing cost of the products at the plants. Fourth term is the transportation cost from the plants to the DCs. Fifth term calculates the establishment cost of the plants. Sixth term calculates the distribution cost of the DCs. Seventh term is the direct transportation cost from the plants to the DCs. Eighth term calculates the establishment cost of the DCs. Ninth term calculates the routing cost plus the transportation devices' hiring cost. Tenth term is the product shortage cost of the network. Eleventh term calculates the product replacement cost. Objective function (2) minimizes the environmental impacts of the network. In this objective function, first term calculates the environmental impact due to the transportation activities from the suppliers to the plants. Second term calculates the environmental impact due to the transportation activities from the plants to the DCs. Third term calculates the environmental impact due to the transportation activities from the plants and DCs to the customers. Fourth term is the environmental impact due to establishing the plants. Fifth term is the environmental impact due to establishing the DCs. Sixth term calculates the environmental impact of production activities at the plants. Objective function (3) maximizes the social impact of the network. In this objective function, first term calculates the fixed job positions created by establishing the plants. Second term calculates the fixed job positions created by establishing the DCs. Third term calculates the variable job positions created by establishing the plants. Fourth term calculates the variable job positions created by establishing the DCs. Fifth term calculates the lost working days at the plants. Sixth term calculates the lost working days at the DCs. Seventh and eighth terms are the cost of lost days at the plants and DCs respectively.

Constraints of the formulation (1)-(39) are explained here. Constraint (4) respects to the capacity of the suppliers. Constraint (5) calculates the amount of raw material for production activities. Constraint (6) applies the capacity limits of raw material given by the suppliers. Constraint (7) ensures that only the established plants should have output. Constraint (8) ensures that in each plant for each product type, only one technology is used. Constraint (9) a plant is established when the production of its products is possible. Constraints (10)-(11) calculate the production amount of the products. Constraints (12)-(13) guarantee that the product flow is between the established plants and DCs. Constraint (14) ensures that the products are delivered to the customers directly or indirectly. Constraint (15) determines the flow between the plants and DCs respecting to their capacities. Constraint (16) respects to the distribution capacities. Constraint (17) calculates the direct flow between the plants and the customers. Constraints (18)-(19) assign the customers to the DCs. Constraint (20) assigns the customers to the plants. Constraint (21) considers only one capacity level for each established DC. Constraint (22) guarantee that the routing starts from the DCs or from the plants that participate in direct shipment. Constraint (23) guarantee that from the origin of each route a route is started to the customers. Constraint (24) ensures that each transportation device can start only one route from each origin. Constraints (25)-(26) guarantee that each route starts from its determined origin. Constraint (27) guarantee that the traveled route of each device is continuous. Constraints (28)-(29) ensure that each route ends at the dummy customer. Constraint (30) eliminates sub-tours for each device. Constraints (31)-(32) determine the transportation devices being hired. Constraint (33) guarantee the concepts of open routing by forcing each route not being finished at the plants or DCs. Constraint (34) ensures that a product can be produced only when it can be supplied in the network. Constraints (35)-(36) allow to replace the products by their alternatives. Constraint (37) calculates the amount of shortage in the network. Constraints (38)-(39) define the type and sign of variables.

3. Meta-heuristic solution approaches

Generally supply chain network design problems are of NP-hard class of optimization problems (Akbari et al., 2020). Therefore, in order to obtain high quality solutions for such problems, use of meta-heuristic solution approaches are unavoidable. The problem introduced in previous section is a typical supply chain network design problem, so, in this section some meta-heuristic algorithms are introduced and applied to solve it effectively. Among the wide range of meta-heuristic algorithms of the literature, some population-based meta-heuristic solution approaches such as Grey Wolf Optimizer algorithm (GWOA) (proposed by Mirjalili et al., 2014), Ant Lion Optimizer algorithm (ALOA) (Mirjalili et al., 2017), and Dragonfly algorithm (DA) (Mirjalili, 2016) are selected and modified to be used for multi-objective formulation (1)-(39). The efficiency of these algorithms are proved in the literature of combinatorial optimization problems. Furthermore, the results obtained by these algorithms are compared by the NSGAI and SPEAI as two well-known and popular multi-objective meta-heuristic solution approaches of the literature. In the rest of this section, first a solution representation is developed to be used in all of the proposed algorithms, then the multi-objective form of the GWOA, ALOA, and DA approaches are explained in details, and then the comparison metrics used to evaluate the obtained multi-objective solutions are explained.

3.1. Solution representation

A matrix-like solution representation is proposed to generate any initial and neighborhood solutions in the meta-heuristic approaches of this study. All values in this solution representation are generated randomly. An example of this representation is given by Figure 2 and its description is given in the following of this sub-section. The length of each row in the matrix is written on the left side of the row in the figure.



Figure 2. The solution representation scheme used in the proposed meta-heuristic algorithms.

Row 1. This row determines the portion of demand of each customer for each product which is fulfilled by the plants and DCs. The length of this row is equal to $(J + R) \times C \times G$. The detailed representation of this row for one customer, two products, two plants, and three DCs is shown by Figure 3, where for example if the demand of customer for product 1 is 1000, the amount of product 1 received from DC 1 is determined as $\left\lceil \frac{0.227}{(0.227+0.149+0.247+0.647+0.491)} \times 1000 \right\rceil = 129$.

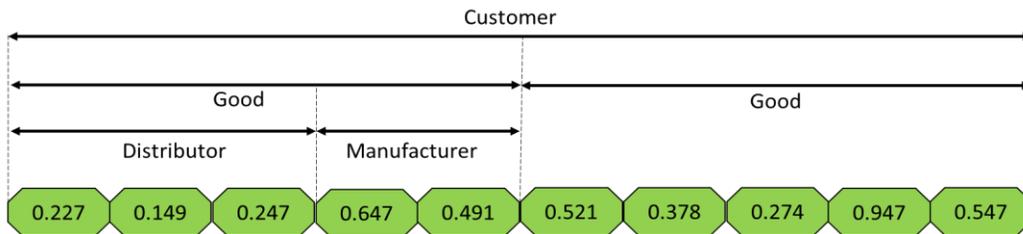


Figure 3. Demand assignment of the proposed solution representation.

Row 2. This row is used to assign the value of raw material between the suppliers and the plants. The assignment is done by similar logic used in Row 1.

Row 3. This row is used to assign the value of product between the plants and the DCs. The assignment is done by similar logic used in Row 1.

Row 4. The device used for transportation between the suppliers and the plants and then to the DCs are determined in this row randomly.

Row 5. The amount of raw material and products transported by the devices assigned in Row 4 is determined here. The logic of Row 1 is used here too.

Row 6. The capacity level of each DC for each product is determined in this row.

Row 7. The technology level of each plant for each product is determined in this row.

Finally, each device is routed according to the classical routing strategy presented by Figure 4. The destinations of each device are sequenced randomly and the transportation route is determined accordingly. The FC shows the dummy customer used for the end of route because of the open routing policy considered in the problem of this study.

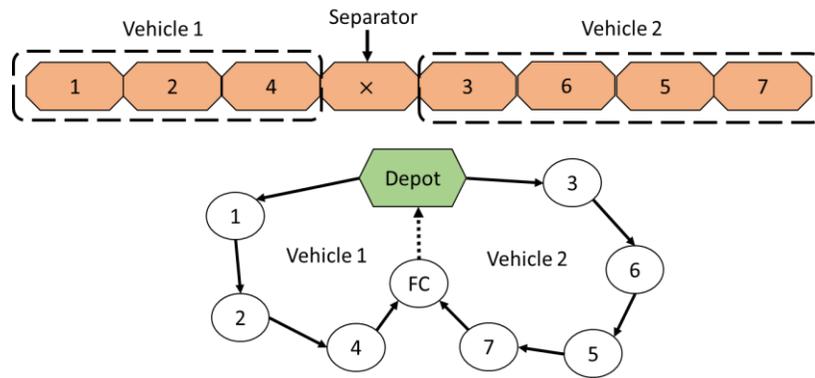


Figure 4. The routing strategy for each device.

Each solution generated by the proposed approach is evaluated easily using the objective functions (1)-(3) and the parameters of the problem.

3.2. Meta-heuristic solution approaches

3.2.1. Multi-objective grey wolf optimizer algorithm (MGWOA)

The grey wolf optimizer algorithm first was introduced by [Mirjalili et al. \(2014\)](#) and then was extended to multi-objective form by [Mirjalili et al. \(2016\)](#). This algorithm has been designed based on the social behavior of grey wolves and includes some operators e.g. social hierarchy, prey siege, hunting, hunting attack, prey search, etc. If \vec{X}_p be the vector of prey position and \vec{X} be the position of the grey wolf, then in this algorithm α is the best solution while the second and third best solutions are represented by β and δ and other solutions are represented by ω . In order to demonstrate the siege behavior in the algorithm, the following equations are proposed,

$$\vec{D} = |\vec{C} \cdot \vec{X}_p(t) - \vec{X}(t)| \quad (40)$$

$$\vec{X}(t+1) = \vec{X}_p(t) - \vec{A} \cdot \vec{D} \quad (41)$$

In these equations, t is iteration number, and \vec{A} and \vec{C} are the multipliers determined by the following equations,

$$\vec{A} = 2\vec{a} \cdot \vec{r}_1 - \vec{a} \quad (42)$$

$$\vec{C} = 2 \cdot \vec{r}_2 \quad (43)$$

The values of vector \vec{a} are linearly decreased from 2 to 0. The vectors \vec{r}_1 and \vec{r}_2 are randomly generated from the interval $[0, 1]$. In order to simulate the behavior of grey wolf, it is supposed that searching factors α , β , and δ have more information about the place of bait. Therefore, the best three solutions are always saved and other searching factors (like ω) will update their place according to the best place obtained by other factors. For this reason, the following equations are proposed.

$$\vec{D}_\alpha = |\vec{C}_1 \cdot \vec{X}_\alpha - \vec{X}|, \vec{D}_\beta = |\vec{C}_2 \cdot \vec{X}_\beta - \vec{X}|, \vec{D}_\delta = |\vec{C}_3 \cdot \vec{X}_\delta - \vec{X}| \quad (44)$$

$$\vec{X}_1 = \vec{X}_\alpha - \vec{A}_1 \cdot (\vec{D}_\alpha), \vec{X}_2 = \vec{X}_\beta - \vec{A}_2 \cdot (\vec{D}_\beta), \vec{X}_3 = \vec{X}_\delta - \vec{A}_3 \cdot (\vec{D}_\delta) \quad (45)$$

$$\vec{X}(t+1) = \frac{\vec{X}_1 + \vec{X}_2 + \vec{X}_3}{3} \quad (46)$$

Other operators of this algorithm are detailed in the study of [Mirjalili et al. \(2016\)](#). The pseudo code of this algorithm is given by Figure 5.

```

Initialize the grey wolf population
Initialize a, A, and C
Calculate the objective values for each search agent
Find the non-dominated solutions and initialize the archive with them
Xα = Select Leader (archive)
Exclude alpha from the archive temporarily to avoid selecting the same leader
Xβ = Select Leader (archive)
Exclude beta from the archive temporarily to avoid selecting the same leader
Xδ = Select Leader (archive)
Add back alpha and beta to the archive
t = 1
While (t < Max number of iterations)
  For each search agent
    Update the position of the current search agent
    Repair Solution using repair mechanism
  End
  Update a, A, and C
  Calculate the objective values of all search agents
  Find the non-dominated solutions
  Update the archive with respect to the obtained non-dominated solutions
  If the archive is full
    Run the grid mechanism to omit one of the current archive members
    Add the new solution to the archive
  End
  If any of the new added solutions to the archive is located outside the hypercube
    Update the grids to cover the new solution(s)
  End
Xα = Select Leader (archive)
Exclude alpha from the archive temporarily to avoid selecting the same leader
Xβ = Select Leader (archive)
Exclude beta from the archive temporarily to avoid selecting the same leader
Xδ = Select Leader (archive)
Add back alpha and beta to the archive

```

```

    t = t + 1
    End while
Return archive

```

Figure 5. The pseudo code of the MGWOA.

3.2.2. Multi-objective dragonfly algorithm (MDA)

In order to apply the MDA, an archive should be considered in the classical dragonfly algorithm in order to save the obtained Pareto solutions, but the food source is selected from the archive. The operators in the MDA is the same as the dragonfly algorithm. In order to find an extensive Pareto frontier, the food source is selected from the low density parts of the Pareto frontier. This is the same as the multi-objective PSO algorithm. The low density part of the Pareto frontier is obtained by dividing it into several sub-frontiers. This issue is done by considering the best and the worst Pareto solution, defining a hyper sphere for covering all of the Pareto solutions, and dividing the hyper sphere into some parts in each iteration. Then selecting the low density part of the Pareto frontier is done by a roulette wheel mechanism. The probability of each part is obtained by the following formula,

$$P_i = \frac{c}{N_i} \quad (47)$$

where, c is a constant being greater than 1 and N_i is number of parts in i -th Pareto frontier. According to this equation, the algorithm selects the food source from the low density parts of the Pareto frontier. Therefore, the dragonfly moves on the low density parts and distributes the solutions in the Pareto frontier uniformly. For being far from the enemies equation (47) is changed to the following equation.

$$P_i = \frac{N_i}{c} \quad (48)$$

In each iteration the archive is updated. In order to manage the Pareto frontier, the obtained non-dominated solutions are used to form it. If the archive is full, and still a new solution is generated, a solution from the high density parts is removed and the new solution is replaced. According to the study of [Mirjalili et al. \(2016\)](#), the overall structure of the MDA is depicted by the pseudo code of Figure 6.

```

Initialize the dragonflies population  $\vec{X}_1$ 
Initialize step vectors  $\Delta\vec{X}_1$ 
Define the maximum number of hyper spheres
Define the archive size
while the end condition is not satisfied
    Calculate the objective values of all dragonflies
    Find the non-dominated solutions
    Update the archive with respect to the obtained non-dominated solutions
    If the archive is full
        Run the archive maintenance mechanism to omit one of the current archive members
        Add the new solution to the archive
    end if
    If any of the new added solutions to the archive is located outside the hyper spheres
        Update and re-position all of the hyper spheres to cover the new solution(s)
    end if
    Select a food source from archive:  $\vec{X}_+ = \text{SelectFood}(\text{archive})$ 
    Select an enemy from archive:  $\vec{X}_- = \text{SelectEnemy}(\text{archive})$ 
    Update step vectors
    Update position vectors
    Check and correct the new positions based on the boundaries of variables

```

end while

Figure 6. The pseudo code of the MDA.

3.2.3. Multi-objective ant lion optimizer algorithm (MALOA)

In order to apply the MALOA, an archive should be considered in the classical ant lion optimizer algorithm in order to save the obtained non-dominated Pareto solutions. The convergence of the MALOA is similar to the classical ant lion optimizer algorithm. In order to modify the ant lion optimizer to obtain the MALOA, the structure of multi-objective PSO is used. In order to distribute the solutions of the archive adequately, two operators of leader selection strategy and archive controller are used. The dispersion of the solutions in the archive is measured by considering a radius around any of the solutions. The number of solutions in the area of the radius of any solution is considered as the dispersion criterion of the solution. Similar to the multi-objective PSO and the MDA, a solution from the low density and high density parts of the archive are selected by the following probabilities respectively.

$$P_i = \frac{c}{N_i} \quad (49)$$

$$P_i = \frac{N_i}{c} \quad (50)$$

According to the study of [Mirjalili et al. \(2017\)](#), the overall structure of the MALOA is depicted by the pseudo code of Figure 7.

```
while the end condition is not met
  for every ant
    Select a random antlion from the archive
    Select the elite using Roulette wheel from the archive
    Update c and d using equations
    Create a random walk and normalize it
    Update the position of ant
  end for
  Calculate the objective values of all ants
  Update the archive
  if the archive is full
    Delete some solutions using Roulette wheel from the archive
    to accommodate new solutions
  end
end while
return archive
```

Figure 7. The pseudo code of the MALOA.

3.3. Comparison metrics

As the multi-objective meta-heuristic solution approaches instead of considering a unique solution, consider a set of non-dominated solutions as a Pareto frontier, therefore, their comparison and evaluation become more difficult than single objective meta-heuristics. For this aim, according to the study of [Datta and Figueira \(2012\)](#), the following comparison metrics are considered to compare the solution approaches proposed in previous sub-section.

Number of Pareto solutions (NPS): It is the number of Pareto solutions found by a meta-heuristic algorithm. Its higher value shows better performance for an algorithm.

Diversity: It measures the diversity of the set of Pareto solutions by the following formula. Its higher value shows better performance for an algorithm.

$$D = \sqrt{\sum_{m=1}^M \left(\max_{i \in \{1:|Q|\}} f_m^i - \min_{i \in \{1:|Q|\}} f_m^i \right)^2} \quad (51)$$

where, M is the number of objective functions, $|Q|$ is the number of Pareto solutions (size of the archive), and f_m^i is the value of m -th objective function in i -th Pareto solution.

Spacing: This measure shows that how the Pareto solutions are spaced uniformly. The following formula is used for this measure. The less value of this criterion is favored.

$$S = \sqrt{\frac{1}{|Q|} \sum_{i=1}^{|Q|} (d_i - \bar{d})^2} \quad (52)$$

where, $d_i = \min_{k \in Q \wedge k \neq i} \sum_{m=1}^M |f_m^i - f_m^k|$ and $\bar{d} = \sum_{i=1}^{|Q|} \frac{d_i}{|Q|}$.

Mean ideal distance (MID): In this measure, the distance from optimal Pareto is calculated by the following formula, where its lower values are preferred.

$$MID = \frac{\sum_{i=1}^{|Q|} \sqrt{\sum_{m=1}^M (f_m^i - f_m^*)^2}}{|Q|} \quad (53)$$

where, f_m^* is the ideal objective function value for m -th objective function.

4. Computational study

In order to evaluate the proposed meta-heuristic algorithms, those are coded in MATLAB. A case study and some randomly generated test problems are solved by the cods on a PC with 3.2 GHz processor and 16 GB RAM. The details of the computational study are explained at the rest of this section.

4.1. Test problems

Three categories of small, medium, and large sizes are considered for test problems of this section. Totally 12 test problems are generated randomly. The parameters of these test problems are generated by Normal distribution. The characteristics of these test problems are detailed by Table 2.

Table 2. The characteristics of the generated test problems.

Size	Test problem <i>Prob (I,J,R,C,V^a,V^b,V^c,L,G,K,E)</i>	Range of the parameters		
Small	<i>Prob1 (2,3,5,15,2,2,3,2,5,3,2)</i>	$Cost_{ik}^{raw} \sim N(100,10)$	$CAP_{ik}^S \sim N(800,10)$	$ENV_{jeg}^P \sim N(10,10)$
	<i>Prob2 (3,3,7,20,3,3,3,3,5,3,2)</i>	$Cost_{gie}^{Pro} \sim N(40,10)$	$CAP_{vk}^{S2P} \sim N(500,10)$	$ENV_{jeg}^{P-E} \sim N(10,10)$
	<i>Prob3 (4,3,8,25,3,3,4,4,6,4,3)</i>	$Cost_{grl}^{DisD} \sim N(10,2)$	$CAP_{vg}^{P2D} \sim N(80,10)$	$ENV_{rlg}^{D-L} \sim N(10,10)$
	<i>Prob4 (4,4,8,30,3,3,4,4,6,4,3)</i>	$Cost_{ij}^{DisP} \sim N(8,2)$	$CAP_{rlg}^D \sim N(500,10)$	$Job_{jeg}^{P-E} \sim N(10,3)$
Medium	<i>Prob5 (10,8,10,60,5,5,8,4,10,5,5)</i>	$Cost_v^{rent} \sim N(8,2)$	$Cost_{jeg}^{ActP} \sim N(100,10)$	$Job_{rlg}^{D-L} \sim N(10,3)$
	<i>Prob6 (12,9,12,70,5,5,8,5,12,5,5)</i>	$Cost_v^{S2P} \sim N(3,3)$	$Cost_{rlg}^{ActD} \sim N(80,10)$	$VJob_{jeg}^{P-E} \sim N(30,5)$
	<i>Prob7 (12,10,14,80,8,8,10,5,15,6,7)</i>	$Cost_v^{P2D} \sim N(3,3)$	$Dist_{ij}^{S2P} \sim N(500,100)$	$VJob_{rlg}^{D-L} \sim N(30,5)$

	<i>Prob8</i> (14,10,16,80,8,8,10,5,18,6,7)	$Cost_v^{CC} \sim N(3,3)$	$Dist_{jr}^{P2D} \sim N(400,100)$	$Lost_{jeg}^{P-E} \sim N(20,5)$
Large	<i>Prob9</i> (20,15,22,120,10,10,15,7,25,8,8)	$PCost_{cgg'} \sim N(5,3)$	$Dist_{mm'}^{CC} \sim N(300,50)$	$Lost_{rlg}^{D-L} \sim N(20,3)$
	<i>Prob10</i> (25,18,25,140,10,10,15,7,25,8,8)	$NED_{gke} \sim N(10,3)$	$ENV_v^{S2P} \sim N(10,3)$	$VLost_{jeg}^{P-E} \sim N(30,5)$
	<i>Prob11</i> (30,20,28,150,10,10,20,8,30,10,10)	$Demand_{cg} \sim N(50,10)$	$ENV_v^{P2D} \sim N(10,3)$	$VLost_{rlg}^{D-L} \sim N(30,5)$
	<i>Prob12</i> (30,22,30,180,10,10,20,8,35,10,10)	$Cap_{jeg} \sim N(500,10)$	$ENV_v^C \sim N(10,3)$	

4.2. Parameter tuning

In any meta-heuristic algorithm, parameter tuning is done to obtain the best value for each of its controllable parameters for obtaining better performance according the given evaluation criteria. In order to tune the parameters of the proposed meta-heuristics of this study, a typical trial and error method is applied here. For this aim, the values of Table 3 is considered for the potential levels of the parameters of the proposed meta-heuristic algorithms.

Table 3. The potential levels considered for the parameters of the proposed meta-heuristic algorithms.

Parameter	Algorithm	Level 1	Level 2	Level 3
Iterations	MGWO, MALO, MDA, NSGAI, SPEAI	400	800	1200
Population size (to be multiplied by chromosome length)	MGWO, MALO, MDA, NSGAI, SPEAI	1.5	2	2.5
Mutation rate	NSGAI, SPEAI	0.5	0.7	0.9
Crossover rate	NSGAI, SPEAI	0.1	0.25	0.4

A medium size test problem (Prob7) is solved in some experiments. In each experiment all parameters are set to Level 2, except one of them that vary from Level 1 to Level 3. The NPS criterion is considered for evaluation purpose. The level with better NPS output is selected for the varying parameter. The best level for all parameters in all algorithms are obtained in this way. The obtained values are reported by Table 4.

Table 4. The best level for the parameters of the proposed meta-heuristic algorithms.

Parameter	Best obtained level				
	MGWO	MALO	MDA	NSGAI	SPEAI
Iterations	800	800	1200	1200	800
Population size (to be multiplied by chromosome length)	2.5	2.5	2.5	2.5	2.5
Mutation rate	-	-	-	0.7	0.9
Crossover rate	-	-	-	0.1	0.1

4.3. Final experiments on the test problems

In order to perform final experiments on the test problems generated in Section 4.1, the parameters of the proposed meta-heuristic algorithms are set to their best values obtained by parameter tuning stage explained by Section 4.2. Then each test problem is solved for 10 times by each meta-heuristic algorithm in order to obtain more reliable results. The obtained results are measured by the comparison metrics of Section 3.3 and the best obtained results for each algorithm is shown by Table 5, 6, and 7. The results of these tables are shown by Figures 8-13.

Table 5. The results obtained for small size test problems.

Test problem	Algorithm	CPU Time (sec)	Comparison metrics			
			NPS	MID	Diversity	Spacing

<i>Prob1</i>	MGWO	37	57	10292	6404	3180
	MALO	60	69	11589	5906	3562
	MDA	35	22	11657	4469	3903
	NSGAI	57	13	13494	5857	3260
	SPEAI	54	30	13852	3643	3625
<i>Prob2</i>	MGWO	49	69	13380	7173	3721
	MALO	74	78	12980	7265	4132
	MDA	40	28	13639	4916	4801
	NSGAI	67	17	16328	6443	3945
	SPEAI	60	35	17731	4627	4459
<i>Prob3</i>	MGWO	59	77	16190	7891	4801
	MALO	90	96	15706	8791	5124
	MDA	44	34	17186	6096	5330
	NSGAI	86	22	18288	8312	4932
	SPEAI	75	46	21100	5136	4995
<i>Prob4</i>	MGWO	71	85	20400	10022	6146
	MALO	104	117	19319	10286	6662
	MDA	52	44	20280	7803	5917
	NSGAI	97	25	23775	9975	6165
	SPEAI	86	52	25109	6523	5795

Table 6. The results obtained for medium size test problems.

Test problem	Algorithm	CPU Time (sec)	Comparison metrics			
			NPS	MID	Diversity	Spacing
<i>Prob5</i>	MGWO	280	56	69276	55704	20738
	MALO	558	33	82591	50088	30534
	MDA	232	26	107404	36593	22222
	NSGAI	520	23	110606	34550	22822
	SPEAI	384	12	100173	30201	24771
<i>Prob6</i>	MGWO	359	69	90059	62946	25508
	MALO	670	43	104891	59605	36641
	MDA	274	33	121367	45010	28000
	NSGAI	572	28	128303	38696	28756
	SPEAI	423	15	121210	37450	30717
<i>Prob7</i>	MGWO	435	77	115276	70500	30865
	MALO	744	56	124821	67950	42504
	MDA	332	38	150496	55813	35560
	NSGAI	704	34	144983	43727	33645
	SPEAI	500	20	157573	44566	35939
<i>Prob8</i>	MGWO	492	99	145248	87420	38582
	MALO	819	62	153530	87656	46755
	MDA	386	45	186616	66418	43739
	NSGAI	888	42	187029	55097	41384
	SPEAI	615	23	184361	57045	41330

Table 7. The results obtained for large size test problems.

Test problem	Algorithm	CPU Time (sec)	Comparison metrics			
			NPS	MID	Diversity	Spacing
<i>Prob9</i>	MGWO	1466	34	485995	347561	101333
	MALO	2514	21	613250	256615	152545

	MDA	1367	13	662418	229350	159495
	NSGAI	2800	16	587487	187454	162050
	SPEAI	2017	18	701607	155399	164572
<i>Prob10</i>	MGWO	1862	42	626934	448354	124640
	MALO	2766	25	705238	331034	180230
	MDA	1668	17	801526	279807	184321
	NSGAI	3528	20	669736	219322	189156
	SPEAI	2280	21	898057	180263	202563
<i>Prob11</i>	MGWO	2142	52	746052	538025	152061
	MALO	3513	33	853338	380690	210126
	MDA	1852	21	913740	349759	211855
	NSGAI	4128	24	770197	241255	223486
	SPEAI	2942	25	1149513	205500	241050
<i>Prob12</i>	MGWO	2635	65	843039	629490	188556
	MALO	4005	37	989873	483477	237278
	MDA	2315	27	1059939	419711	243747
	NSGAI	4872	31	939641	291919	252540
	SPEAI	3825	31	1436892	252765	310955

It can be seen easily from Table 5 that for the case of small size test problems, the MGWO, MALO, and MDA approaches perform better than the NSGAI and SPEAI approaches in all of the evaluation metrics. In most of the test problems 1 to 4, the MALO and MGWO approaches perform better than the MDA approach in approximately all metrics. According to the results presented by Table 6, for the case of medium size test problems, definitely the MGWO approach perform better than other algorithms in terms of all evaluation metrics. According to the results presented by Table 7, for the case of large size test problems, definitely the MGWO approach perform better than other algorithms in terms of all evaluation metrics.

According to the CPU running times reported by Tables 5-7, we can see that the lowest running time is recorded by the MDA approach while the slowest algorithms are the NSGAI and MALO approaches.

In general, according to the obtained results the MGWO has better performance comparing to other considered algorithms. The Pareto frontier for the Pareto solutions obtained by all algorithms for Prob9 is depicted by Figure 13. It can be seen easily that the MGWO dominates other approaches.

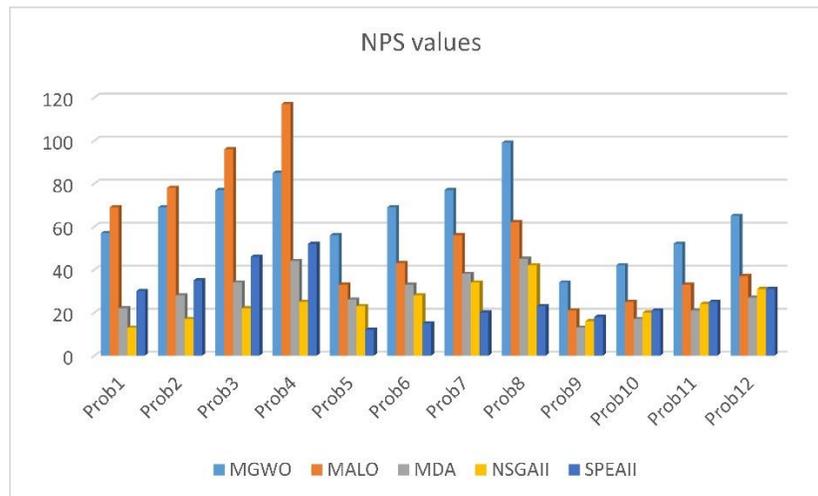


Figure 8. The obtained NPS measure values by the meta-heuristic approaches.

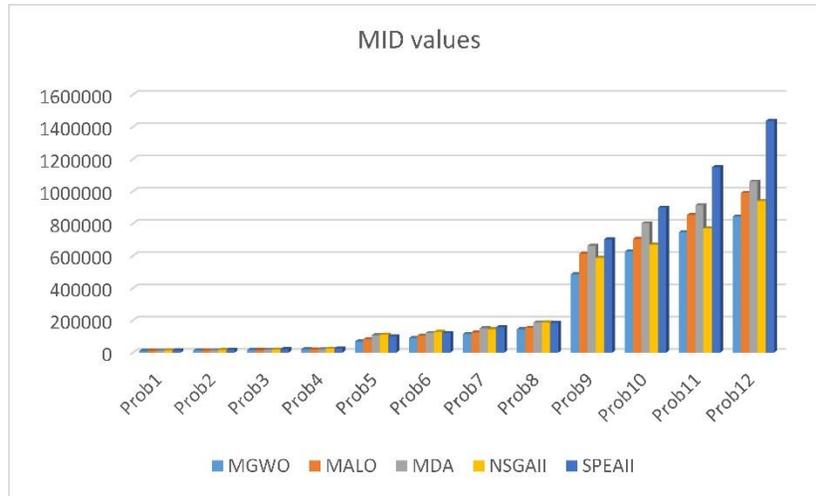


Figure 9. The obtained MID measure values by the meta-heuristic approaches.

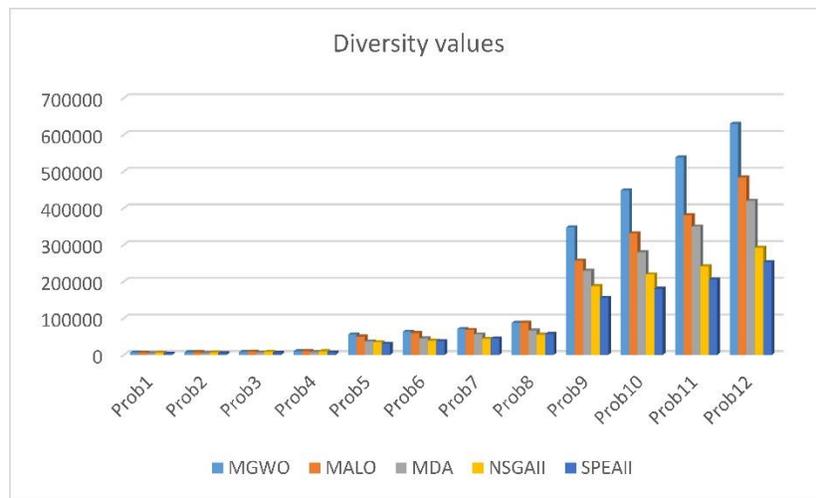


Figure 10. The obtained Diversity measure values by the meta-heuristic approaches.

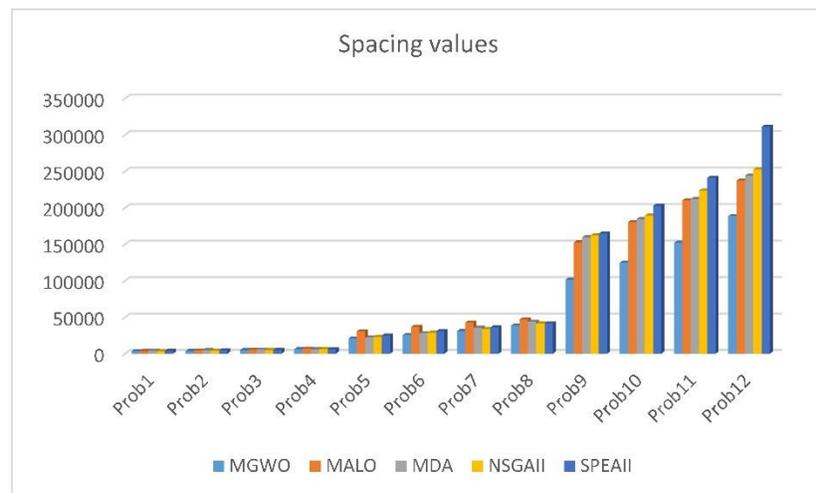


Figure 11. The obtained Spacing measure values by the meta-heuristic approaches.

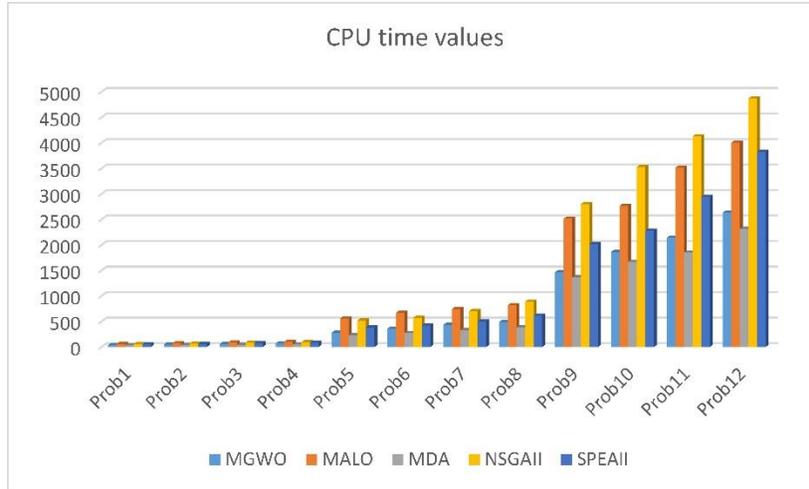


Figure 12. The CPU running times of the meta-heuristic approaches.

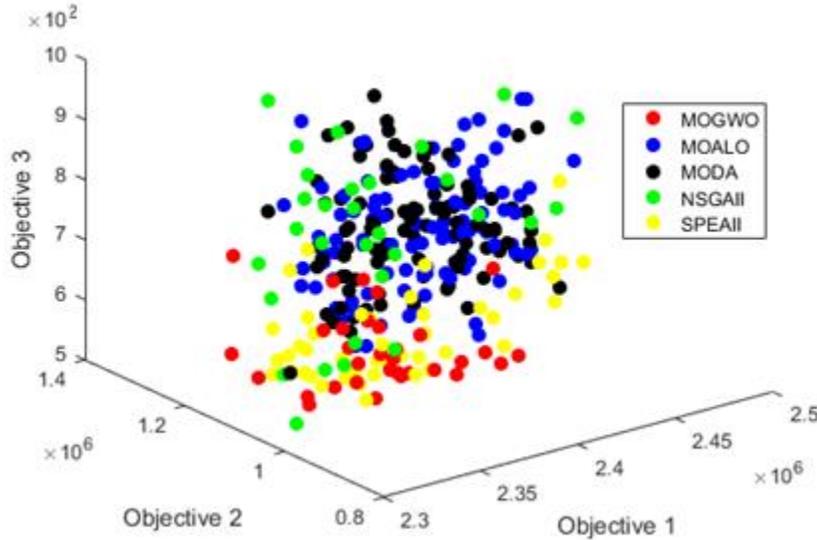


Figure 13. The Pareto frontier obtained for Prob9.

4.4. Case study

In order to show the applicability of this research a case study is presented and solved in this section. This case study considers the Somayyeh industrial group in Iran which produces food related products via establishing a chain consisting of suppliers, plants, distributors, and final customers. This chain has 4 suppliers, 10 potential plants, 31 potential distributors, and 378 customer zones. The raw material are carried from the suppliers to the plants by three types of transportation devices. The products are transported from the plants to the distributors by three types of transportation devices, while five types of device are used to transport the products from the distributors to the customers. All demand values for 15 types of perishable products are available, where, the cost and environmental parameters are valued according to the study of [Govindan et al. \(2014\)](#). The suppliers, potential plants, potential distributors, and customers are shown by Figure 13 and Figure 14.

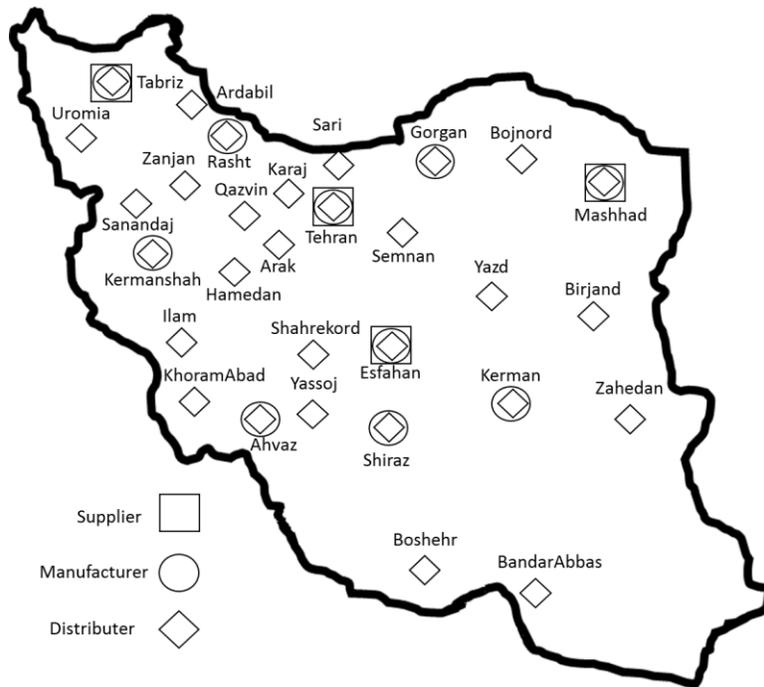


Figure 13. Geographical position of the potential places of the case study.



Figure 14. Geographical position of the customers of the case study.

The MGWO algorithm is used to solve the problem of this case study as this algorithm has shown the best performance comparing to other algorithms in experiments of Section 4.3. The Pareto frontier obtained by this approach is shown by Figure 15. Totally 30 Pareto solution is obtained for the case study. Each of them can be used by managers of the company to be implemented. Selecting any of them requires to consider the criteria which is important for the managers.

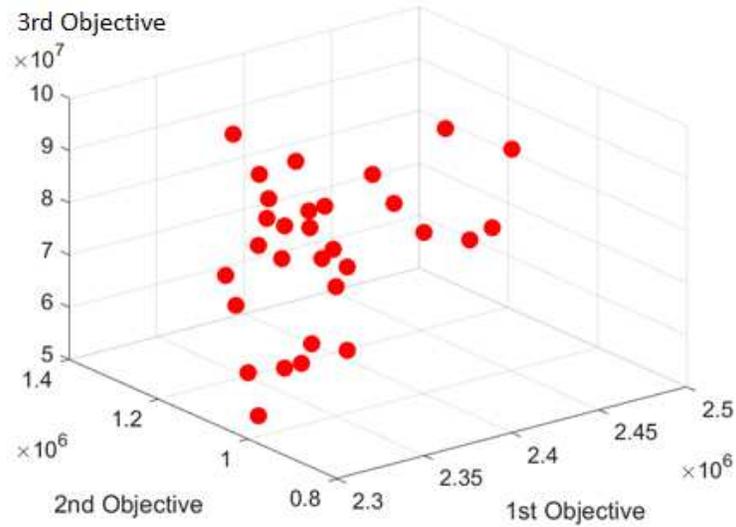


Figure 15. The Pareto frontier obtained for the case study by the MGWO algorithm.

For more analysis, one of the Pareto solutions is considered. In this solution 14 distributors are established in order to fulfill the demand received by the customers. In this solution a nice customer to distributor assignment structure is obtained which is shown by Figure 16.

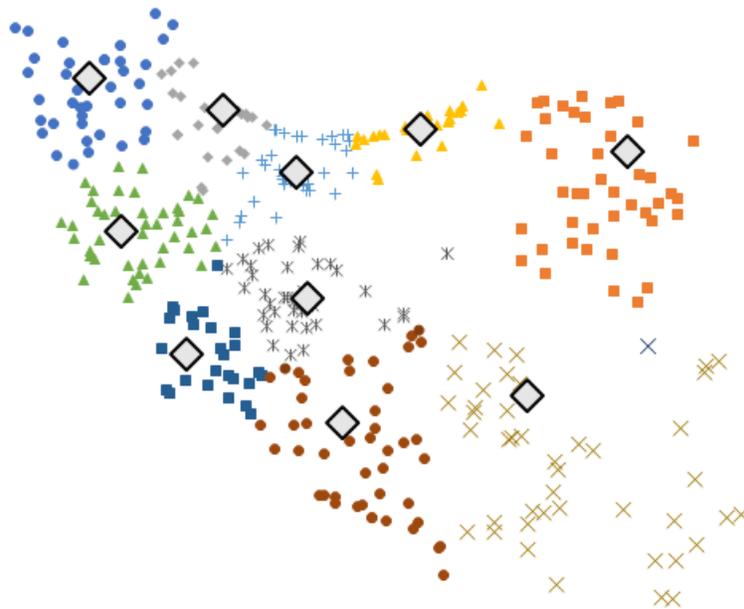


Figure 16. Customer to distributor assignment structure obtained for the case study in a sample Pareto solution.

In the considered Pareto solution the following locations are selected to be established,

- Three suppliers are selected to be included in the supply chain. These suppliers are in the cities Tehran, Mashhad, and Esfahan.
- Five plants are established at the cities Tehran, Rasht, Mashhad, Shiraz, and Kerman.

- Ten distributors are established at the cities Tehran, Tabriz, Rasht, Kermanshah, Gorgan, Mashhad, Esfahan, Ahvaz, Shiraz, and Kerman.

The flow between the suppliers, plants, and distributors are depicted by Figure 17, where the open routing concept can be seen in the obtained structure.

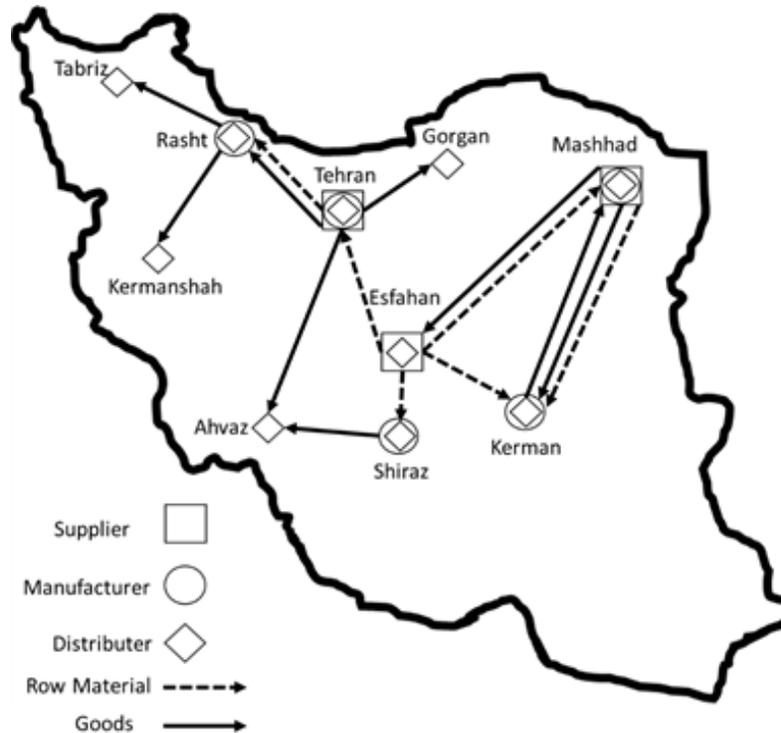


Figure 17. The obtained supply chain and its routing for the case study in a sample Pareto solution.

5. Concluding remarks

In this study a multi-objective formulation was proposed for designing a supply chain of perishable products including suppliers, plants, distributors, and customers under sustainable development. In this problem the objectives like facilities establishment costs, transportation costs, negative environmental impacts, and social impact (fixed and variable employment rates) should be optimized. As in real situations, most of the transportation activities of such supply chains are performed by hiring transportation devices, the open routing logic is applied to form the travelling path of each hired transportation device. Furthermore, the possibility of direct shipment from the plants to the customers is considered in order to increase profitability of the plants. Because of the NP-hard nature of the supply chain design problems, some meta-heuristic solution approaches of the literature were modified to multi-objective form and applied to solve the problem. Several test problems from small to large sizes were generated randomly to evaluate the meta-heuristic algorithms. As a result, among the proposed algorithms, the multi-objective grey wolf optimizer (MGWO) performed better than others by considering four well-known evaluation metrics. At the end, a case study from perishable products supply chain of Iran was solved and analyzed to show the applicability of the proposed problem.

Compliance with Ethical Standards

- **Funding:** This study was not funded by any organization.

- **Conflict of Interest:**
 - Author **Behzad Aghaei Fishani** declares that he has no conflict of interest.
 - Author **Ali Mahmoodirad** declares that he has no conflict of interest.
 - Author **Sadegh Niroomand** declares that he has no conflict of interest.
 - Author **Mohammad Fallah** declares that he has no conflict of interest.
- **Ethical approval:** This article does not contain any studies with human participants or animals performed by any of the authors.

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Figures

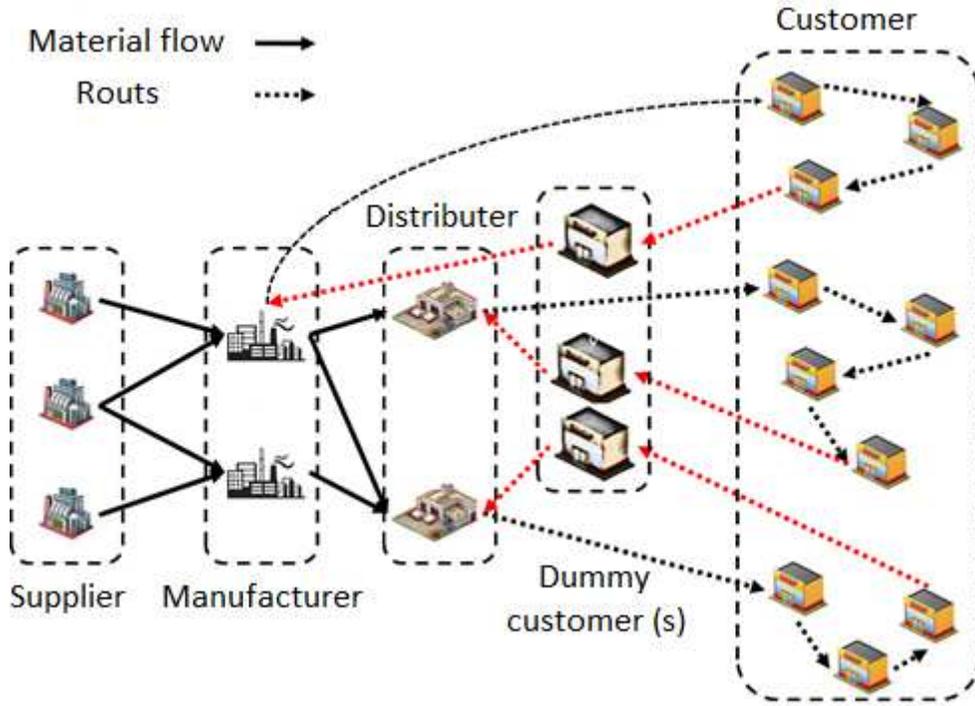


Figure 1

Network of the proposed problem.



Figure 2

The solution representation scheme used in the proposed meta-heuristic algorithms.

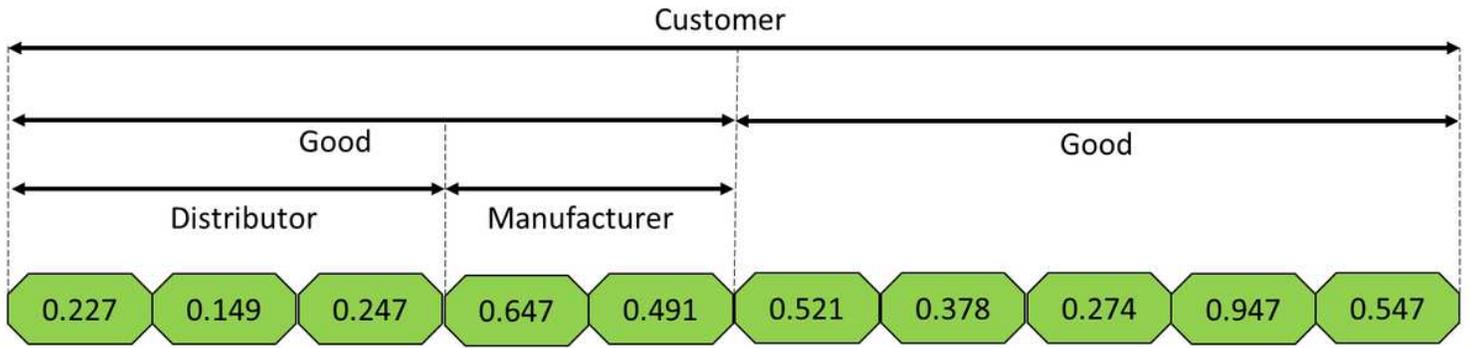


Figure 3

Demand assignment of the proposed solution representation.

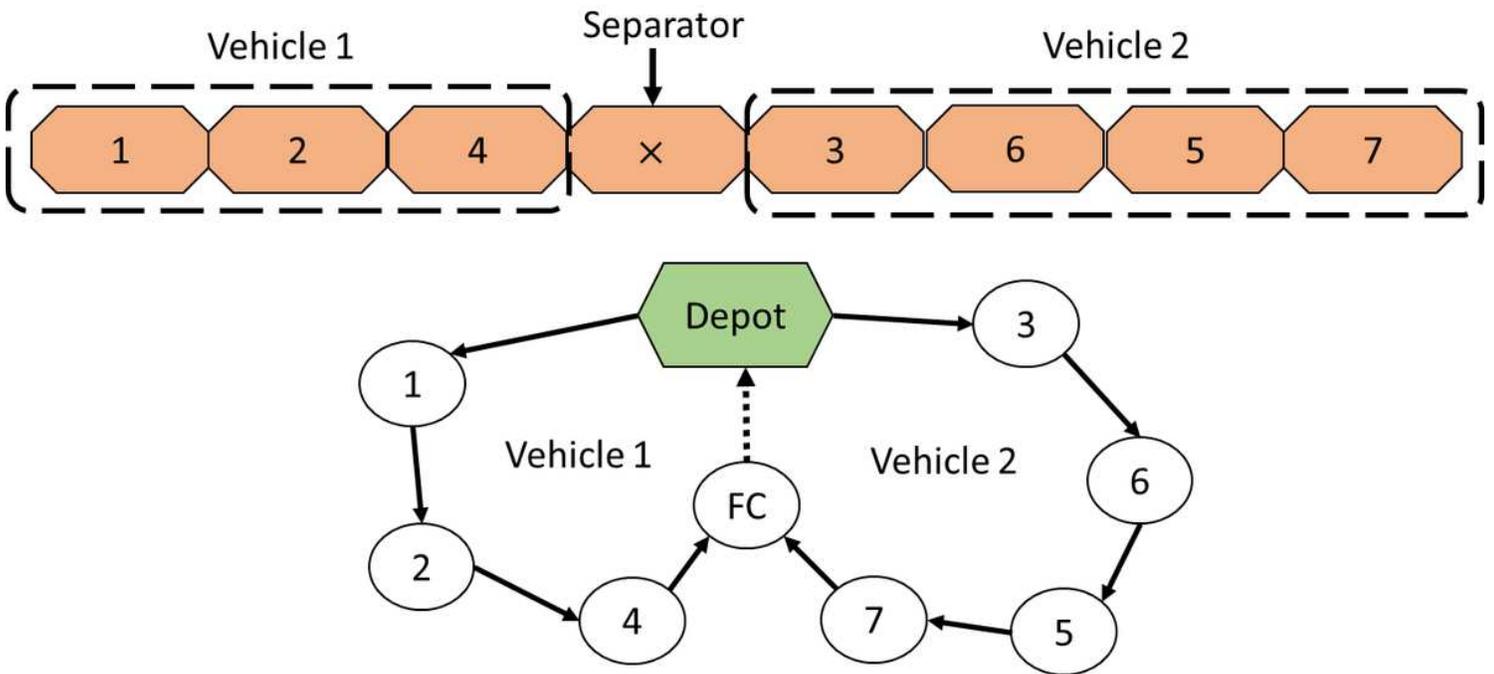


Figure 4

The routing strategy for each device.

```

Initialize the grey wolf population
Initialize a, A, and C
Calculate the objective values for each search agent
Find the non-dominated solutions and initialize the archive with them
 $X_\alpha$  = Select Leader (archive)
Exclude alpha from the archive temporarily to avoid selecting the same leader
 $X_\beta$  = Select Leader (archive)
Exclude beta from the archive temporarily to avoid selecting the same leader
 $X_\delta$  = Select Leader (archive)
Add back alpha and beta to the archive
t = 1
  While (t < Max number of iterations)
    For each search agent
      Update the position of the current search agent
      Repair Solution using repair mechanism
    End
    Update a, A, and C
    Calculate the objective values of all search agents
    Find the non-dominated solutions
    Update the archive with respect to the obtained non-dominated solutions
    If the archive is full
      Run the grid mechanism to omit one of the current archive members
      Add the new solution to the archive
    End
    If any of the new added solutions to the archive is located outside the hypercube
      Update the grids to cover the new solution(s)
    End
     $X_\alpha$  = Select Leader (archive)
    Exclude alpha from the archive temporarily to avoid selecting the same leader
     $X_\beta$  = Select Leader (archive)
    Exclude beta from the archive temporarily to avoid selecting the same leader
     $X_\delta$  = Select Leader (archive)
    Add back alpha and beta to the archive
    t = t + 1
  End while
Return archive

```

Figure 5

The pseudo code of the MGWOA.

```

Initialize the dragonflies population  $\vec{X}_i$ 
Initialize step vectors  $\Delta\vec{X}_i$ 
Define the maximum number of hyper spheres
Define the archive size
while the end condition is not satisfied
    Calculate the objective values of all dragonflies
    Find the non-dominated solutions
    Update the archive with respect to the obtained non-dominated solutions
    If the archive is full
        Run the archive maintenance mechanism to omit one of the current archive members
        Add the new solution to the archive
    end if
    If any of the new added solutions to the archive is located outside the hyper spheres
        Update and re-position all of the hyper spheres to cover the new solution(s)
    end if
    Select a food source from archive:  $\vec{X}_+ = \text{SelectFood}(\text{archive})$ 
    Select an enemy from archive:  $\vec{X}_- = \text{SelectEnemy}(\text{archive})$ 
    Update step vectors
    Update position vectors
    Check and correct the new positions based on the boundaries of variables
end while

```

Figure 6

The pseudo code of the MDA.

```

while the end condition is not met
    for every ant
        Select a random antlion from the archive
        Select the elite using Roulette wheel from the archive
        Update  $c$  and  $d$  using equations
        Create a random walk and normalize it
        Update the position of ant
    end for
    Calculate the objective values of all ants
    Update the archive
    if the archive is full
        Delete some solutions using Roulette wheel from the archive
        to accommodate new solutions
    end
end while
return archive

```

Figure 7

The pseudo code of the MALOA.

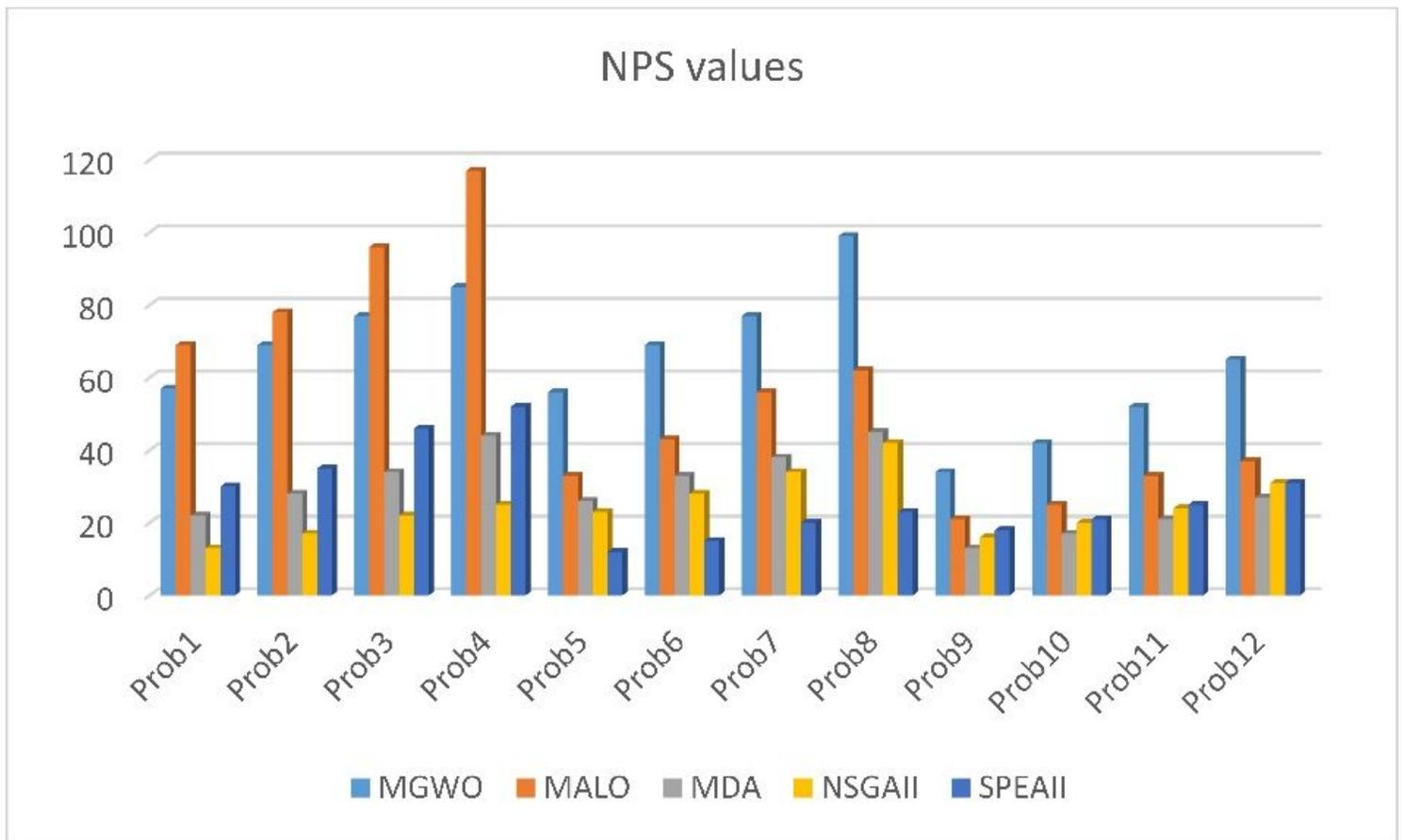


Figure 8

The obtained NPS measure values by the meta-heuristic approaches.

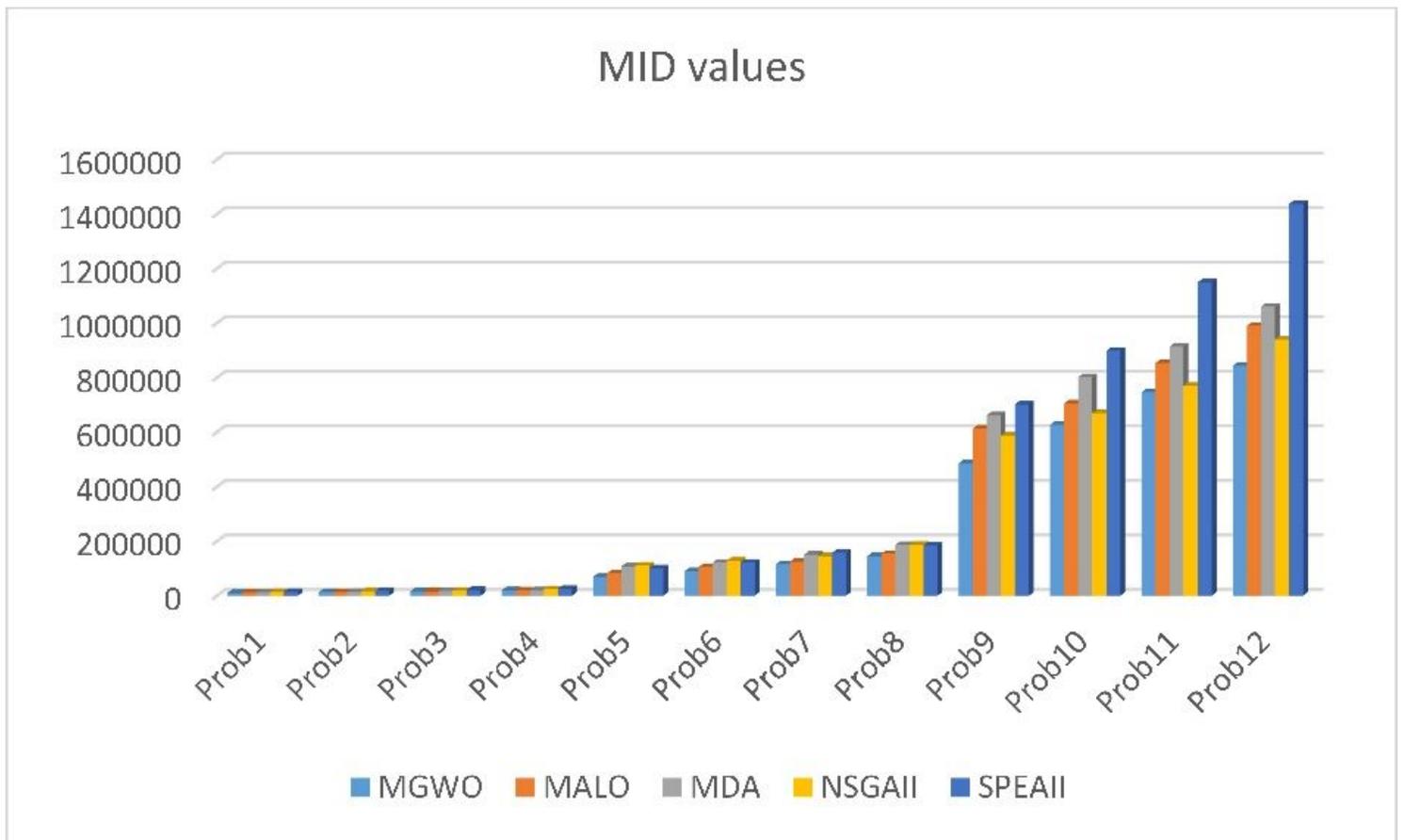


Figure 9

The obtained MID measure values by the meta-heuristic approaches.

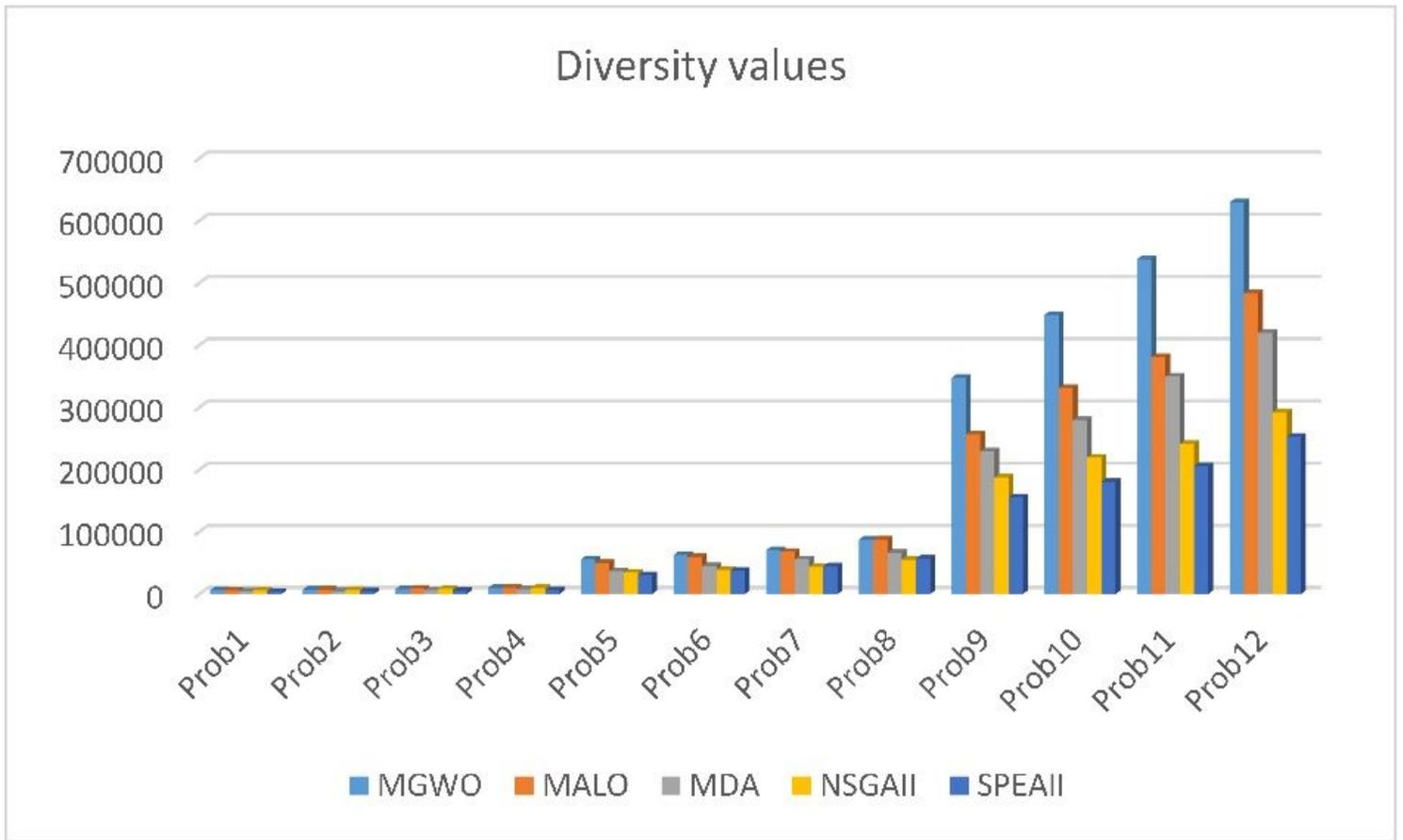


Figure 10

The obtained Diversity measure values by the meta-heuristic approaches.

Spacing values

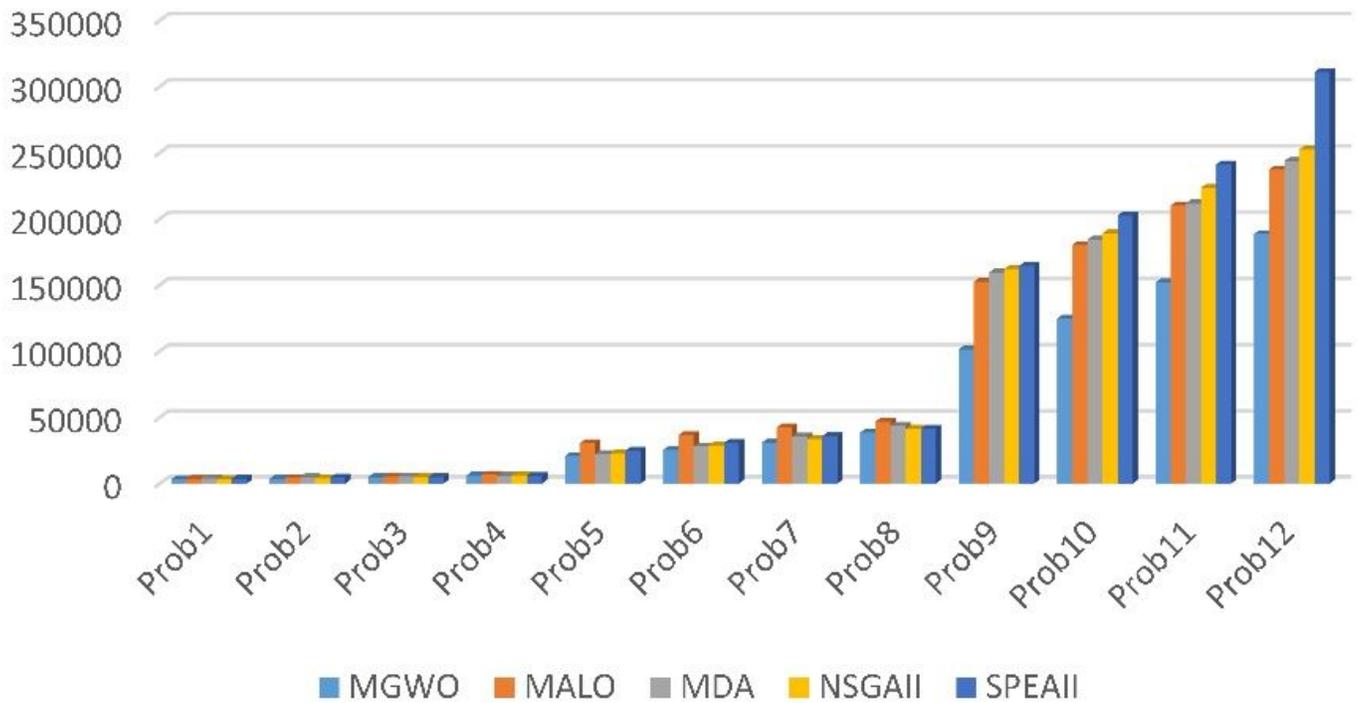


Figure 11

The obtained Spacing measure values by the meta-heuristic approaches.

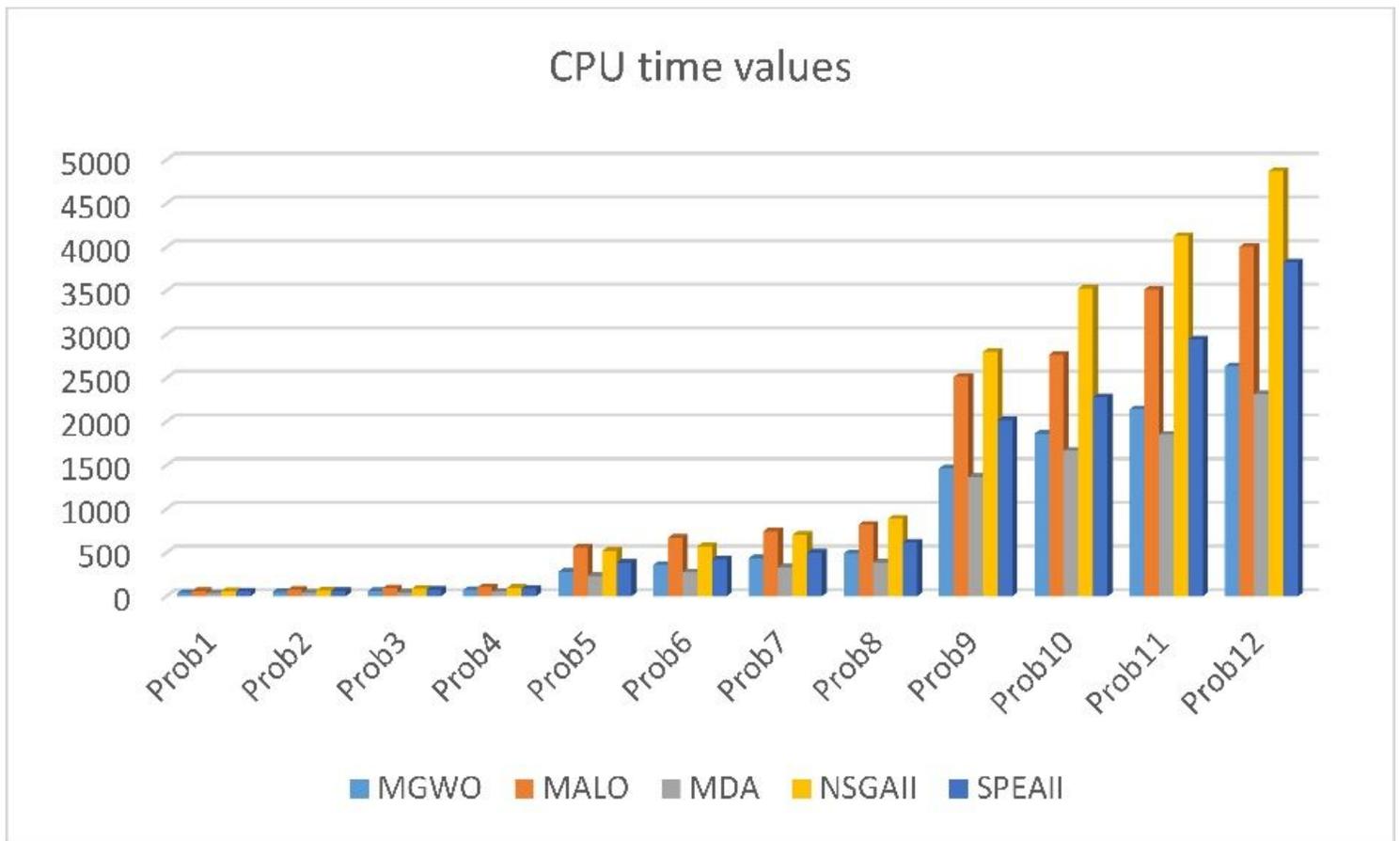


Figure 12

The CPU running times of the meta-heuristic approaches.

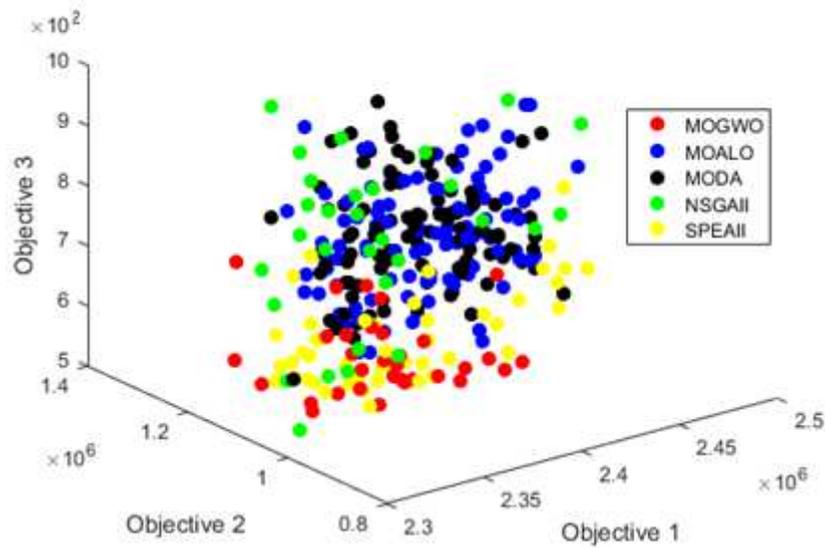


Figure 13

The Pareto frontier obtained for Prob9.

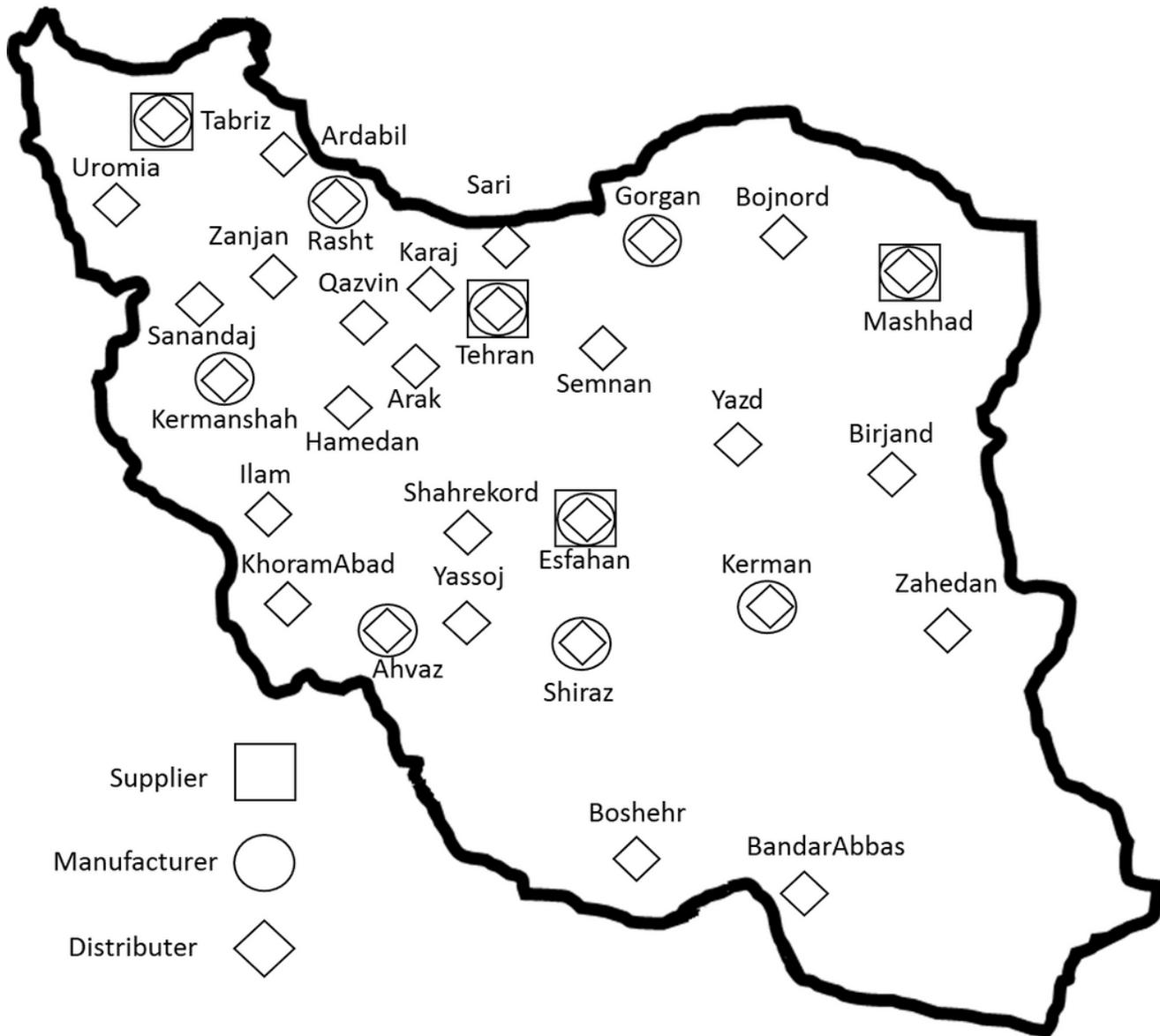


Figure 14

Geographical position of the potential places of the case study. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.



Figure 15

Geographical position of the customers of the case study. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

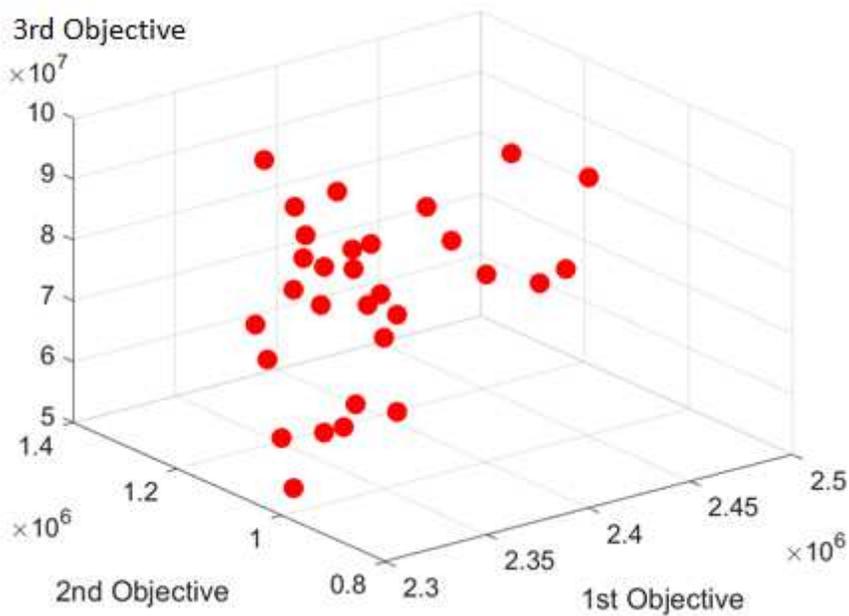


Figure 16

The Pareto frontier obtained for the case study by the MGWO algorithm.

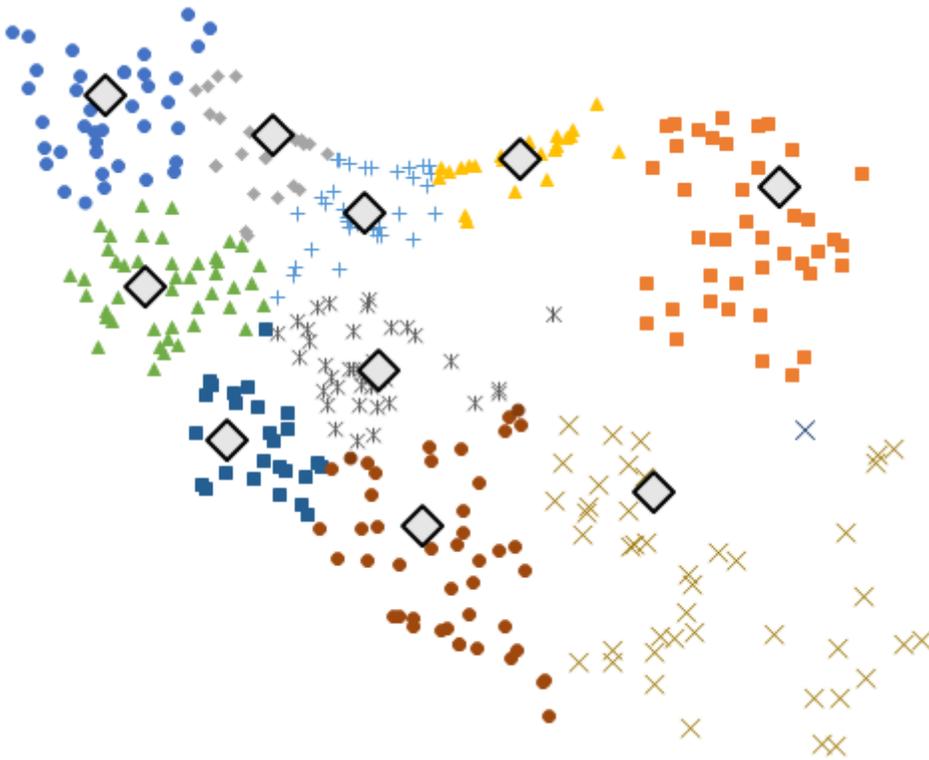


Figure 17

Customer to distributor assignment structure obtained for the case study in a sample Pareto solution.

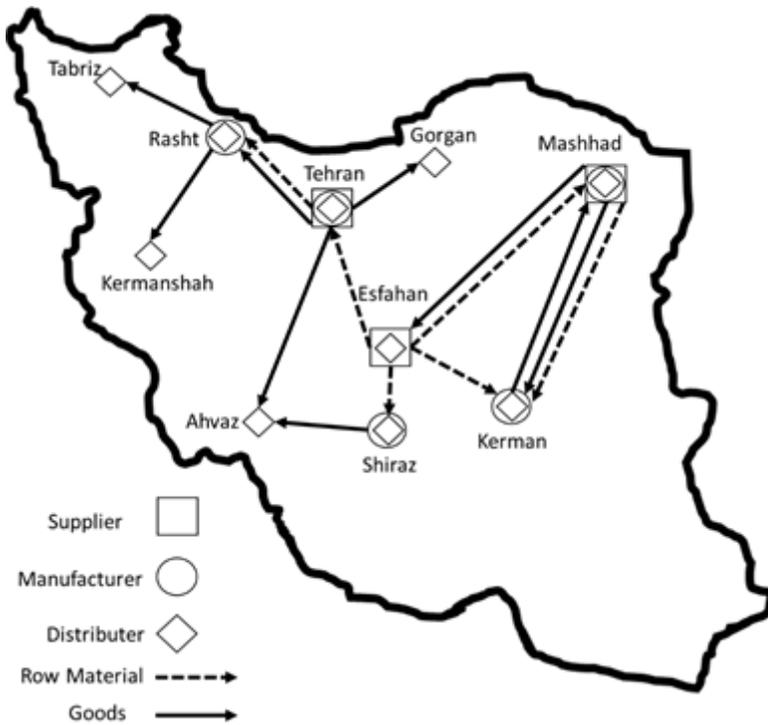


Figure 18

The obtained supply chain and its routing for the case study in a sample Pareto solution. Note: The designations employed and the presentation of the material on this map do not imply the expression of

any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.