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Research Article

Developing a Fuzzy Green Supply Chain Management Problem Considering Location Allocation Routing Problem: Hybrid Meta-Heuristic Approach

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Abstract

Nowadays, the internationalization of supply chains makes the management of operation affairs face a great challenge. On the other hand, vague parameters have challenged decision-makers to drive decision-making. To cope with these challenges, this study tries to model a green SCM (GSCM) model which considers fuzzy parameters. The objective function of our model is to minimize total fuzzy cost including fuzzy establishment costs of the plants and distribution centers, fuzzy transportation costs among the suppliers, facilities and customers, fuzzy hiring cost of the transportation facilities, and miscellaneous fuzzy environmental impact costs. The developed model also includes facilities location constraints, material flow constraints, open transportation routing from plants to customers and from distribution centers to customers. Also, determining alternative products for customers has not been addressed in the literature. Therefore, this paper tries to focus on the mentioned complex problem and develop a comprehensive model. Because of the level of complexity of the developed model, two empowered meta-heuristic approaches, named fuzzy hybrid genetic algorithm (FHGA) and fuzzy hybrid biogeography-based optimization algorithm (FHBBO), are implemented to solve the NP-hard developed problem. According to the best of our knowledge, the proposed FHGA is not addressed in the literature in this way. For instance, most of the fuzzy algorithms either are not hybrid or get out of the fuzzy environment in one of their complex evolution processes. However, our fuzzy hybrid algorithms follow a fuzzy environment from beginning test initialization to calculating the objective function and presenting the convergence plots and none of our parameters are defuzzied in all steps of these processes. Besides, miscellaneous Figures, illustrations and tables support the explanations of results.

Keywords: Green SCM; Fuzzy Theory; Green Transportation; Fuzzy Hybrid Meta-Heuristic Algorithms.

1. Introduction

Managers always encounter non-exact parameters in their decision-making process which includes vagueness. This vagueness, which is a dimension of uncertainty, is usually modeled by fuzzy theory. This research tries to address a green supply chain management (GSCM) model. The model includes suppliers, producers, distribution centers, and customer echelons. It assumes direct shipment between producers and customers under the objective function of fuzzy total costs minimization, which is consisted of the fuzzy establishment costs of the plants and distribution centers, fuzzy transportation costs among the suppliers, facilities and customers, and fuzzy hiring cost of the transportation facilities. The rest of the section reviews the literature and presents the chief gap being filled by the contributions of our work.

Tsai and Hung (2009) have developed a fuzzy goal programming (FGP) approach and evaluated the performance of a green SCM (GSCM) model. Büyüközkan and Çifçi (2012) have focused on green supplier selection (GSS) and implemented a hybrid multi-criteria decision making (MCDM) approach of fuzzy DEMATEL, fuzzy TOPSIS and fuzzy ANP models. Kannan et al. (2013) have also implemented an MCDM approach to select the best supplier considering economic, social, and environmental factors and investigated the allocation of orders to them in a GSC by applying AHP for supplier selection, fuzzy TOPSIS method for supplier evaluation, and multi-objective linear programming model for order quantity allocation. Wang and Chan (2013) have balanced economic and environmental conditions as well as the creation of competitive advantage in a GSC. They have used a hierarchical fuzzy TOPSIS method and provided managers with a process to identify the challenges involved in implementing different plans in GSCM and the requirements needed to implement them. Lin (2013) has analyzed the GSC risk and factors affecting the implementation of GSCM. They have used a fuzzy DEMATEL method and helped to solve the group decision problem in the fuzzy environment to obtain a good view of the impact of these factors by determining causal groups. Shen et al. (2013) have introduced a method based on the fuzzy set theory and fuzzy TOPSIS to evaluate the performance of green suppliers that provide managers with more market competition. Rostamzadeh et al. (2014) have investigated eco-design, green production, green shopping, green recycling, green transportation, and green warehousing as the elements of

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GSCM with a fuzzy VIKOR method. Mangla et al. (2014) have developed a flexible decision-making model based on fuzzy AHP and interpretive ranking process to provide a procedure for GSC risk assessment. Mangla et al. (2015) have also assessed the risk of GSC and provided six classifications of risks and 25 specific risks. They have used fuzzy AHP in their analysis. Govindan et al. (2015) have tried to find key points to improve the environmental and economic performance in a fuzzy GSCM. Wu et al. (2015) have developed a combination of fuzzy set theory and the decision-making trial and evaluation laboratory (DEMATEL) method to investigate the effects of each GSCP criterion. They have studied a case in Vietnam automotive industry. Kumar et al. (2016) have optimized the problem of order optimization and supplier selection in a sustainable supply chain, which includes three main economic, social, and environmental indicators for a sustainable supply chain. They have proposed a fuzzy multi-objective linear programming model and a fuzzy AHP for the sustainable supply chain. Dede and Uygun (2016) have studied the performance of GSCM of companies in the areas of green design, green purchasing, green transformation, green logistics, and reverse logistics by using a model based on fuzzy multi-criteria decision making (MCDM) methods including fuzzy Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) and fuzzy Analytic network process (ANP). Considering green criteria and using the fuzzy inference system (FIS) method, due to the uncertainty in the quality criteria, Shahin and Pourjavad (2017) have evaluated the performance of GSCM and reduced the uncertainty in management decisions in the GSCM performance evaluation process. They have also stated that the greatest impact on the performance of GSCM is related to green design and green production. Tseng et al. (2017) have investigated the problem of enhancing GSCM and its multi-criteria evaluation. They have used a combination of two methods of converged interval-valued triangular fuzzy and grey relation analysis to achieve this approach. Jiang and Deng (2019) have evaluated GSCM using an MCDM method called D number theory in a fuzzy environment. Kim and Noh (2019) have considered two levels of the supply chain including one producer and several retailers as distributors as well as the issue of greenhouse gas emissions in the production sector as a green factor; it has interacted with fuzzy GSCM. Tirkolaee et al. (2019) have implemented a fuzzy MCDM approach consisting of fuzzy ANP, fuzzy DEMATEL and fuzzy TOPSIS in a sustainable and reliable supplier selection in a two-echelon supplier-distributor SCM. Nayeri et al. (2020) have developed a mathematical model with the aim of optimizing the economic, environmental, and social sectors and considering the uncertainty in different sectors of the configuration. Puma and Giallanza (2020) have searched the problem of routing at three levels of supply, distribution, and customer from a food supply chain in a time horizon. They have considered fuzzy demand and using optimal routing as well as fuzzy set theory, they have helped to minimize the amount of transportation and reduce greenhouse gas emissions and total costs. Amiri et al. (2020) have presented a new approach for selecting a sustainable supplier in BMW SCM using the triangular fuzzy method and providing sustainability metrics. Since the numerical values in the multi-stage multi-objective fixed-charge solid transportation problem (MMFSTP) in a supply chain network are not accurate and fuzzy, Midya et al. (2020) have provided a creative study in the issue of transportation considering greenhouse gas emissions as an important subject in the field of environmental pollution at all levels of a GSC. As found from the literature review, a green perishable SCM considers fuzzy parameters and includes facility location constraints, material flow constraints, open transportation routing from plants to customers and distribution centers to customers. Moreover, determining alternative products for customers has not been considerably addressed in the literature. Therefore, this paper tries to focus on the mentioned complex problem and develop a comprehensive model. As mentioned, because of the level of complexity of the developed model, empowered meta-heuristic approaches are implemented.

Chapter 2 presents the mathematical model and fuzzy methodology of this research. Chapter 3 describes the development of fuzzy hybrid algorithms of FHGA and FHBBO for solving the developed uncertain model. It presents the solution structure and neighborhood structures, alongside the main flowcharts of the algorithms. Chapter 4 concentrates on the computational results of FHGA and FHBBO and provides various statistical and graphical analyses. Chapter 5 concludes the paper.

2. Mathematical Model and Assumptions

This research develops a GSCM model consisting of suppliers, producers, distribution centers, and customers, where direct shipment between producers and customers is also allowed. The objective function of the model is to minimize fuzzy total costs terms including fuzzy establishment costs of the plants and distribution centers, fuzzy transportation costs among the suppliers, facilities, and customers, fuzzy hiring cost of the transportation facilities, and miscellaneous fuzzy environmental impact costs. The constraints of the model include facility location constraints, material flow constraints, open transportation routing from plants to customers and distribution centers to customers, and determination of alternative products for customers according to their need. The assumptions of the model are as follows. In this model, there are a predetermined 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. Moreover, the number and location of the customers are also the model inputs. Each established facility has an employment rate and for each potential plant, a set of different manufacturing technologies is considered, that only one of them can be selected. Similarly, for each potential DC, a set of different capacities is considered, that only one of them can be selected. The model sufficiently considers enough available transportation devices with different capacities and costs and the tour of each transportation device is period and assumes only one DC for replenishing the demand of each customer. From the environmental point of view, the environmental impact of the established open. The problem is multi-product with a single planning

facilities and transportation activities are predetermined. Following notations are the implemented in the model.

Indexes Nomenclature

S	Set of suppliers	$s \in \{1,2,\dots,\vert S\vert\}$
M	Cumulative set of plants, distribution centers (DCs), and customers	$m = \{\mathrm{D} \cup \mathrm{P} \cup \mathrm{A}\}$
D	Set of potential plants	$d \in \{1,2,\dots,\vert D\vert\}$
P	Set of potential DCs	$p \in \{1,2,\dots,\vert P\vert\}$
X	Set of customers	$x \in \{1,2,\dots,\vert X\vert\}$
O	Dummy customer	$n \in \{N\}$
U^a	Set of transportation devices between suppliers and plants	$u^a \in \{1,2,\dots,\vert U^a\vert\}$
U^b	Set of transportation devices between plants and DCs	$u^b \in \{1,2,\dots,\vert U^b\vert\}$
U^c	Set of transportation devices between plants/DCs and customers	$u^c \in \{1,2,\dots,\vert U^c\vert\}$
F	Potential capacity levels for DCs	$f \in \{1,2,\dots,\vert F\vert\}$
H	Set of products	$h \in \{1,2,\dots,\vert H\vert\}$
Z	Set of raw materials	$z \in \{1,2,\dots,\vert Z\vert\}$
Y	Set of potential technologies for plants	$y \in \{1,2,\dots,\vert Y\vert\}$

Parameters Nomenclature

$C\widetilde{Raw}_{sz}$	Fuzzy price of raw material *z* bought from supplier *s*
$C\widetilde{Pro}_{hsy}$	Fuzzy price of producing a unit of product *h* at plant *j* by technology *y*
$C\widetilde{D\imath sD}_{hpf}$	Fuzzy price of processing a unit of product *h* at DC *p* with capacity *f*
$C\widetilde{D\imath sP}_{dh}$	Fuzzy holding cost of product *h* at plant *d* for direct shipment purpose
$C\widetilde{reent}_{u}$	Fuzzy hiring cost of device *u*
$C\widetilde{S2P}_{u}$	Fuzzy transportation cost of device *u* per unit of distance from a supplier to a plant
$C\widetilde{P2D}_{u}$	Fuzzy transportation cost of device *u* per unit of distance from a plant to a DC
$\tilde{C}_u^{CC}$	Fuzzy transportation cost of device *u* per unit of distance from a plant or DC to a customer
$\widetilde{CEV}S2P_u$	Fuzzy environmental cost of transportation by device *u* per unit of distance from a supplier to a plant
$\widetilde{CEV}P2D_u$	Fuzzy environmental cost of transportation by device *u* per unit of distance from a plant to a DC
$C\widetilde{EVC}_u$	Fuzzy environmental cost of transportation by device *u* to customers
$C\widetilde{EVP}_{dyh}$	Fuzzy environmental cost of producing a unit of product *g* at plant *j* with technology *e*
$\widetilde{CEV}_{dyh}^{P-E}$	Fuzzy environmental cost of establishing plant *d* with technology *y* for product *h*
$\widetilde{CEV}_{pfh}^{D-L}$	Fuzzy environmental cost of establishing DC *p* with capacity level *f* for product *h*
$\widetilde{PC}_{xhh'}$	Fuzzy cost of replacing product *h* by product *h'* for customer *x*
NOD_{hzy}	Required amount of raw material *z* for producing product *h* by technology *y*
DE_{xh}	Demand of customer *x* for product *h*
CP_{dyh}	Capacity of producing product *h* in plant *d* with technology *y*
CPS_{SZ}	Capacity of supplier *s* for raw material *z*
$CPS2P_{uz}$	Capacity of device *u* for transporting raw material *z*
$CPP2D_{uh}$	Capacity of device *u* for transporting product *h*
CPD_{pfh}	Capacity of DC *p* for product *h* at capacity level *f*
$C\widetilde{ActP}_{dyh}$	Fixed cost of establishing plant *d* with technology *y* for product *h*
$C\widetilde{ActD}_{pfh}$	Fixed cost of establishing DC *p* with capacity level *f* for product *h*
$Dist_{sd}^{S2P}$	Distance of supplier *s* and plant *d*
$Dist_{dp}^{P2D}$	Distance of plant *d* and DC *p*

$Dist^{CC}_{mm'}$	Distance of customers *m* and *m'* where $(m, m') \in M/\{D, P\}$
PX	Fixed penalty cost due to unfulfilled demands
E_h	Takes value of 1 if production of product *h* is possible, otherwise 0
$PF_{xhh'}$	Takes value of 1 if customers *x* product *h* can be replaced by product *h'*, otherwise 0
Big	A large positive value

Variable Nomenclature

Binary variables

k^{P-E}_{dyh}	Takes value of 1 if plant *d* is established with technology *y* for product *h*, otherwise 0
K^{D-L}_{pfh}	Takes value of 1 if DC *p* is established with capacity level *f* for product *h*, otherwise 0
$W_{mm'uh}$	Takes value of 1 if device *u* travels from node *m* to *m'*(where $(m, m') \in M$) for transporting product h, otherwise 0
$Rent_{uh}$	Takes value of 1 if device *u* is rented for transportation of product *h*
Q^{S-P}_{sduz}	Takes value of 1 if device *u* is used to transport raw material *z* from supplier *s* to plant *d*, otherwise 0
Q^{P-D}_{dpuh}	Takes value of 1 if device *u* is used to transport product *h* from plant *d* to DC *p*, otherwise 0
CN_{mxh}	Takes value of 1 if customer *x* is connected to plant or DC *b* for product *h*
$V_{xhh'}$	Takes value of 1 if product *h* is replaced by product *h'* for customer *x*

Integer variables

Fl^{S-P}_{sduz}	Amount of raw material *z* sent from supplier *s* to plant *d* by device *u*
Fl^{P-D}_{dpuh}	Amount of product *h* sent from plant *d* to DC *p* by device *u*
Fl^{P-C}_{dxuh}	Amount of product *h* sent from plant *d* to customer *x* by device *u*
Pd_{hdy}	Amount of product *h* produced by technology *y* at plant *d*
$Extra$	Excess/shortage production amount comparing to demand
ST_{myh}	Sub-tour elimination variable

The mathematical formulation of the problem is as follows:

$$
\begin{aligned}
Min\ \zeta = {} & \sum_{s\in S}\sum_{d\in d}\sum_{u\in U^a}\sum_{z\in Z}\widetilde{CRaw}_{sz}\times Fl^{S-P}_{sduz}+\sum_{s\in S}\sum_{d\in d}\sum_{u\in U^a}\sum_{z\in Z}Dist^{S2P}_{sd}\times \widetilde{CS}2P_u\times Q^{S-P}_{sduz}\\
&+\sum_{d\in D}\sum_{y\in Y}\sum_{h\in H}\widetilde{CPro}_{hsy}\times Pd_{hdy}+\sum_{d\in D}\sum_{u\in U^b}\sum_{p\in P}\sum_{h\in H}\widetilde{CP}2D_u\times Dist^{P2D}_{dp}\times Q^{P-D}_{dpuh}\\
&+\sum_{d\in D}\sum_{y\in Y}\sum_{h\in H}\widetilde{CActP}_{dyh}\times k^{P-E}_{dyh}+\sum_{u\in U^b}\sum_{f\in F}\sum_{p\in P}\sum_{h\in H}\sum_{d\in D}\widetilde{CDisD}_{hpf}\times Fl^{P-D}_{dpuh}\\
&+\sum_{u\in U^c}\sum_{x\in X}\sum_{h\in H}\sum_{d\in D}\widetilde{CDisP}_{dh}\times Fl^{P-C}_{dxuh}+\sum_{p\in P}\sum_{f\in F}\sum_{h\in H}\widetilde{CActD}_{pfh}\times K^{D-L}_{pfh}\\
&+\sum_{u\in U^c}\sum_{h\in H}\left(\widetilde{Creent}_u\times Rent_{uh}+\sum_{m\in M}\sum_{m'\in M}\tilde{C}^{CC}_u\times Dist^{CC}_{mm'}\times W_{mm'uh}\right)+PX\times Extra\\
&+\sum_{x\in X}\sum_{h\in H}\sum_{h'\in h}PC_{xhh'}\times V_{xhh'}+\sum_{s\in S}\sum_{d\in D}\sum_{u\in U^a}\sum_{z\in Z}\widetilde{CEV}S2P_u\times Dist^{S2P}_{sd}\times Q^{S-P}_{sduz}\\
&+\sum_{d\in D}\sum_{p\in P}\sum_{u\in U^b}\sum_{h\in H}\widetilde{CEV}P2D_u\times Dist^{P2D}_{dp}\times Q^{P-D}_{dpuh}\\
&+\sum_{m\in M}\sum_{m'\in x}\sum_{u\in U^c}\sum_{h\in H}\widetilde{CEV}C_u\times Dist^{CC}_{mm'}\times W_{mm'uh}+\sum_{d\in D}\sum_{y\in Y}\sum_{h\in H}\widetilde{CEV}^{P-E}_{dyh}\times k^{P-E}_{dyh}\\
&+\sum_{p\in P}\sum_{f\in F}\sum_{h\in H}\widetilde{CEV}^{D-L}_{pfh}\times K^{D-L}_{pfh}+\sum_{d\in D}\sum_{y\in Y}\sum_{h\in H}C\widetilde{EV}P_{dyh}\times Pd_{hdy}
\end{aligned}
\tag{1}
$$

The objective function (1) minimizes the total fuzzy cost of the network. The objective function of our model is to minimize total fuzzy cost including the fuzzy establishment costs of the plants and distribution centers, fuzzy transportation costs among the suppliers, facilities and customers, the fuzzy hiring cost of the transportation facilities, and miscellaneous fuzzy environmental impact costs.

$$\sum_{d\in D}\sum_{u\in U^a} Fl^{S-P}_{sduz} \le CPS_{SZ} \qquad \forall\, s\in S, z\in Z \qquad (2)$$

Constraint (2) respects the capacity of the suppliers.

$$\sum_{u\in U^a}\sum_{s\in S} Fl^{S-P}_{sduz} \ge \sum_{h\in H}\sum_{y\in Y} Pd_{hdy}\times NOD_{hzy} \qquad \forall\; d\in D, z\in Z \qquad (3)$$

Constraint (3) calculates the amount of raw material for production activities.

$$Fl^{S-P}_{sduz} \le CPS2P_{uz}\times Q^{S-P}_{sduz} \qquad \forall\; s\in S, d\in D, u\in U^a, z\in Z \qquad (4)$$

Constraint (4) applies the capacity limits of raw material given by the suppliers.

$$Pd_{hdy} \le CP_{dyh}\times k^{P-E}_{dyh} \qquad \forall\; d\in D, h\in H, y\in Y \qquad (5)$$

Constraint (5) ensures that only the established plants should have output.

$$\sum_{y\in Y} k^{P-E}_{dyh} \le 1 \qquad \forall\; d\in D, h\in H \qquad (6)$$

Constraint (6) ensures that in each plant for each product type, only one technology is used.

$$\sum_{y\in Y}\sum_{d\in D} k^{P-E}_{dyh} \le Big\times E_h \qquad \forall\, h\in H \qquad (7)$$

Constraint (7) ensures that a plant is established when the production of its products is possible.

$$\sum_{d\in D}\sum_{y\in Y} Pd_{hdy} \ge \sum_{x\in X} DE_{xh}\times E_h \qquad \forall\, h\in H, \qquad (8)$$

$$\sum_{d\in D}\sum_{y\in Y} Pd_{hdy} = \sum_{x\in X}(DE_{xh}+DE_{xh'}\times V_{xhh'}) \qquad \forall\, h\neq h'\in H, E_h=1, E_{h'}=0 \qquad (9)$$

Constraints (8)-(9) calculate the production amount of the products.

$$\sum_{d\in D}\sum_{u\in U^b} Fl^{P-D}_{dpuh} \le Big\times\sum_{f\in F} K^{D-L}_{pfh} \qquad \forall\, p\in P, h\in H \qquad (10)$$

$$\sum_{f\in F} K^{D-L}_{pfh} \le \sum_{d\in D}\sum_{u\in U^b} Fl^{P-D}_{dpuh} \qquad \forall\, p\in P, h\in H \qquad (11)$$

Constraints (10)-(11) guarantee that the product flow is between the established plants and DCs.

$$\sum_{p\in P}\sum_{u\in U^b} Fl^{P-D}_{dpuh} + \sum_{x\in X}\sum_{u\in U^c} Fl^{P-D}_{dpuh} = \sum_{y\in y} Pd_{hdy} \qquad \forall\, d\in D, h\in H \qquad (12)$$

Constraint (12) ensures that the products are delivered to the customers directly or indirectly.

$$Fl^{P-D}_{dpuh} \le CPP2D_{uh}\times Q^{P-D}_{dpuh} \qquad \forall\, d\in D, u\in U^b, h\in H, p\in P \qquad (13)$$

Constraint (13) determines the flow between the plants and DCs with respect to their capacities.

$$\sum_{d\in M/\{P,X\}}\sum_{u\in U^b} Fl^{P-D}_{dpuh} \le \sum_{f\in F} CPD_{pfh}\times K^{D-L}_{pfh} \qquad \forall\, p\in P, h\in H \qquad (14)$$

Constraint (14) respects the distribution capacities.

$$\sum_{u\in U^c} Fl_{dxuh}^{P-C} \leq BIG \times CN_{dxh} \qquad \forall\ d \in D, h \in H, x \in X \qquad (15)$$

Constrain (15) calculates the direct flow between the plants and the customers.

$$\sum_{x\in X} CN_{pxh} \leq Big \times \sum_{f\in F} K_{pfh}^{D-L} \qquad \forall\, p \in P, h \in H \qquad (16)$$

Constraints (16)-(17) assign the customers to the DCs.

$$\sum_{f\in F} K_{pfh}^{D-L} \leq Big \times \sum_{x\in X} CN_{pxh} \qquad \forall\, p \in P, h \in H \qquad (17)$$

$$\sum_{x\in X} CN_{pxh} \leq Big \times \sum_{y\in Y} k_{dyh}^{P-E} \qquad \forall\, d \in D, h \in H \qquad (18)$$

Constraint (18) assigns the customers to the plants.

$$\sum_{f\in F} K_{pfh}^{D-L} \leq 1 \qquad \forall\, p \in P, h \in H \qquad (19)$$

Constraint (19) considers only one capacity level for each established DC.

$$\sum_{m'\in M} W_{mm'uh} + \sum_{m'\in M/\{N\}} W_{m'xuh} - CN_{mxh} \leq 1 \qquad \forall\, m \in \{D \cup P\}, u \in U^c, h \in H, E_h = 1 \qquad (20)$$

Constraint (20) guarantees that the routing starts from the DCs or the plants who participate in direct shipment.

$$\sum_{m\in M} \sum_{u\in U^c} W_{mxuh} = 1 \qquad \forall\, x \in X/\{N\}, h \in H, E_h = 1 \qquad (21)$$

Constraint (21) guarantees that from the origin of each route, a route is started to the customers.

$$\sum_{m\in M} W_{mxuh} \leq 1 \qquad \forall\, x \in X/\{N\}, u \in U^c, h \in H, E_h = 1 \qquad (22)$$

Constraint (22) ensures that each transportation device can start only one route from each origin.

$$\sum_{x\in X} CN_{mxh} \leq Big \times \sum_{x\in X} \sum_{u\in U^c} W_{mxuh} \qquad \forall\, m \in \{D \cup P\}, h \in H, E_h = 1 \qquad (23)$$

$$\sum_{x\in X} CN_{mxh} \leq \sum_{u\in U^c} W_{mnuh} \qquad \forall\, m \in \{D \cup P\}, h \in H, E_h = 1, \forall\, n \in N \qquad (24)$$

Constraints (23)-(24) guarantee that each route starts from its determined origin.

$$\sum_{m'\in M} X_{m'muh} - \sum_{m'\in M} W_{mm'uh} = 0 \qquad \forall\, m \in M, u \in U^c, h \in H, E_h = 1 \qquad (25)$$

Constraint (25) guarantees that the traveled route of each device is continuous.

$$W_{mnuh} = 0 \qquad \forall\, m \in \{D \cup P\}, u \in U^c, h \in h, E_h = 1, \forall\, n \in N \qquad (26)$$

$$\sum_{x\in X/\{0\}} W_{xnuh} = 0 \qquad \forall\, u \in U^c, h \in H, E_h = 1, \forall\, n \in N \qquad (27)$$

Constraints (26)-(27) ensure that each route ends at the dummy customer.

$$ST_{myh} - ST_{x'uh} + |M| \times W_{mnuh} \leq |M| - 1 \qquad \forall\, m \in M, u \in U^c, h \in H, x \in X, E_h = 1, \forall\, n \in N \tag{28}$$

Constraint (28) eliminates sub-tours for each device.

$$\sum_{m \in M} \sum_{x \in X} W_{mnuh} \leq Big \times Rent_{uh} \qquad \forall u \in U^c, h \in H, \forall\, n \in N \tag{29}$$

$$Rent_{uh} \leq \sum_{m \in M} \sum_{x \in X} W_{mnuh} \qquad \forall u \in U^c, h \in H, \forall\, n \in N \tag{30}$$

Constraints (29)-(30) determine the transportation devices being hired.

$$\sum_{m \in \{D \cup P\}} W_{xmuh} = 0 \qquad \forall u \in U^c, x \in X/\{N\}, h \in H \tag{31}$$

Constraint (31) guarantees the concepts of open routing by forcing each route not being finished at the plants or DCs.

$$\sum_{d \in D} \sum_{y \in Y} Pd_{hdy} \leq Big \times E_h \qquad \forall h \in H \tag{32}$$

Constraint (32) ensures that a product can be produced only when it can be supplied in the network.

$$V_{xhh'} \leq CN_{xhh'} \qquad \forall h \neq h' \in H, x \in X \tag{33}$$

$$\sum_{h \in H, E_h = 1} V_{xhh'} \leq 1 \qquad \forall h' \in H, x \in X, E_{h'} = 0, \tag{34}$$

Constraints (33)-(34) allow replacing the products by their alternatives.

$$\sum_{h \in H} \left(\sum_{x \in X} DE_{xh} - \sum_{d \in D} \sum_{y \in Y} Pd_{hdy} \right) \leq Extra \tag{35}$$

Constraint (35) calculates the amount of shortage in the network.

$$k_{dyh}^{P-E}, \quad K_{pfh}^{D-L}, W_{mm'uh}, Rent_{uh}, Q_{sduz}^{S-P}, Q_{dpuh}^{P-D}, F_{mxh}, V_{xhh'} \in \{0,1\} \tag{36}$$

$$Fl_{sduz}^{S-P}, Fl_{dpuh}^{P-D}, Fl_{dxuh}^{P-C}, Pd_{hdy}, Extra, ST_{myh}, \geq 0 \tag{37}$$

Constraints (36)-(37) define the type and sign of variables.

3. Solution Methodology

In this section, we follow two steps to develop and solve our model. In Step.1, we introduced the fuzzy method used for making our fuzzy parameters and in Step.2, we presented our solution method consisting of meta-heuristic methods such as FHGA and FHBBO algorithms. According to the best of our knowledge, the proposed FHGA has not been addressed in the literature in this way. For instance, most of the fuzzy algorithms either are not hybrid or get out of the fuzzy environment in one of their complex evolution processes. However, our fuzzy hybrid algorithms follow a fuzzy environment, from beginning test initialization to calculating the objective function and presenting the convergence plots, and none of our parameters are defuzzied in all steps of these processes.

3.1. Fuzzy Estimation

In this section, two main operators called "summation" and "minimum or maximum" implemented in the research are explained. In other words, in the evolution process, the decoding process needs two main operations of fuzzy summation and fuzzy maximization and minimization. To do so, the fuzzy evolutionary algorithm implements the fuzzy summation (a1,a2,a3)+(b1,b2,b3)=(a1+b1,a2+b2,a3+b3) as Figure 1.

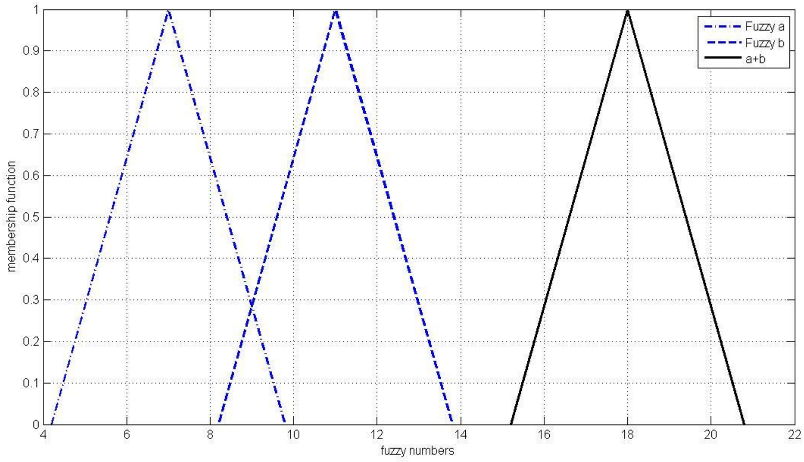
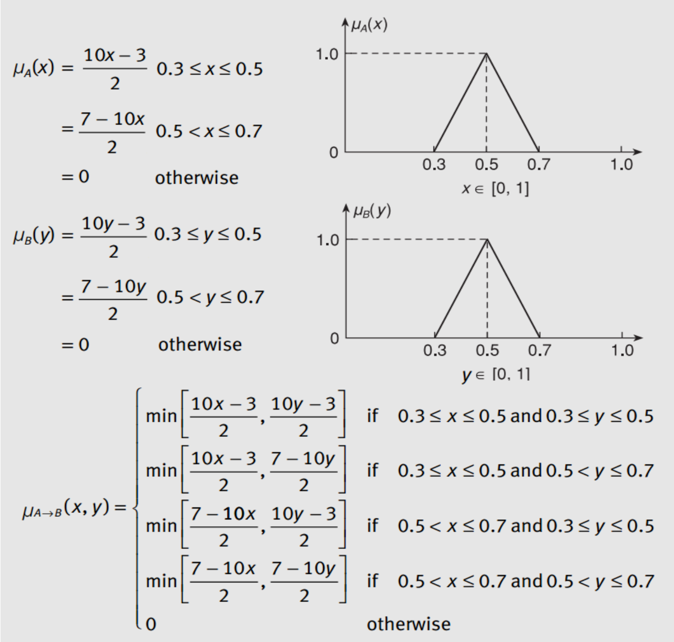


Fig. 1. The fuzzy operator.

Moreover, the fuzzy maximum and minimum follow the Mamdani approach as Figure 2.



$$\mu_A(x) = \frac{10x-3}{2} \quad 0.3 \le x \le 0.5$$
$$= \frac{7-10x}{2} \quad 0.5 < x \le 0.7$$
$$= 0 \quad \text{otherwise}$$

$$\mu_B(y) = \frac{10y-3}{2} \quad 0.3 \le y \le 0.5$$
$$= \frac{7-10y}{2} \quad 0.5 < y \le 0.7$$
$$= 0 \quad \text{otherwise}$$

$$\mu_{A\to B}(x,y) = \begin{cases} \min\left[\frac{10x-3}{2}, \frac{10y-3}{2}\right] & \text{if } 0.3 \le x \le 0.5 \text{ and } 0.3 \le y \le 0.5 \\ \min\left[\frac{10x-3}{2}, \frac{7-10y}{2}\right] & \text{if } 0.3 \le x \le 0.5 \text{ and } 0.5 < y \le 0.7 \\ \min\left[\frac{7-10x}{2}, \frac{10y-3}{2}\right] & \text{if } 0.5 < x \le 0.7 \text{ and } 0.3 \le y \le 0.5 \\ \min\left[\frac{7-10x}{2}, \frac{7-10y}{2}\right] & \text{if } 0.5 < x \le 0.7 \text{ and } 0.5 < y \le 0.7 \\ 0 & \text{otherwise} \end{cases}$$

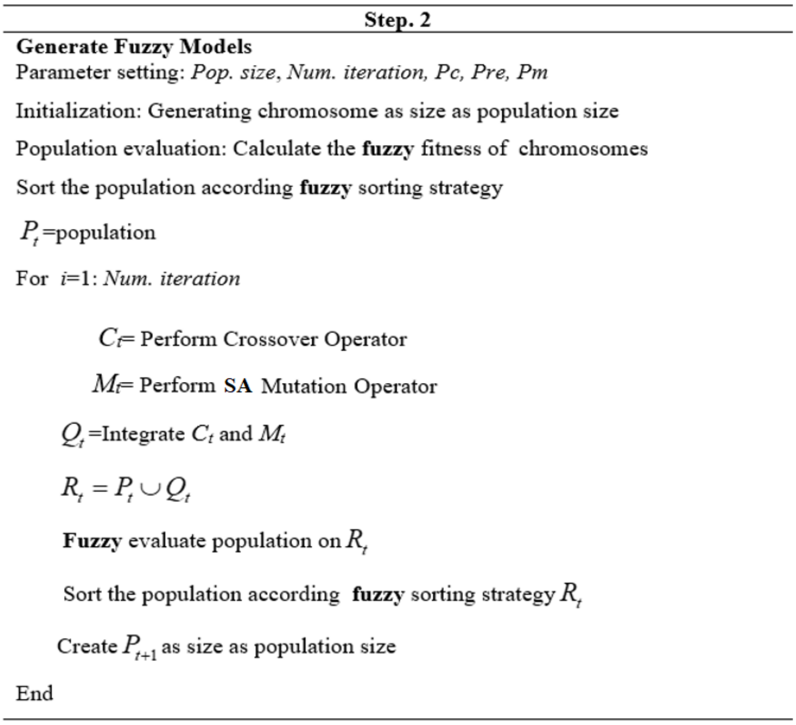
Fig. 2. The fuzzy operator scheme.

3.2. Suggested solution methods

This research used two met-heuristic algorithms of FHGA and FHBBO for optimizing the developed PSCM model. Figures 3 and 4 present the pseudo-codes of the FHGA and the FHBBO algorithm, respectively. In both hybrid algorithms, the mutation part is adjusted with simulated annealing (SA) algorithms. SA is a simple and effective meta-heuristic optimization algorithm to solve optimization problems in large search spaces. This algorithm is often used when the search space is discrete. For optimization problems, finding an approximate response for the overall optimal is more important than finding an accurate answer for the local optimal at a finite and specific time, so, SA may be preferable to other methods such as the descending gradient. In the SA method, each point s in the search space is like a state of a physical system and the entropy function to be minimized is like the internal energy of the system in that state. In this method, the goal is to move the system from the desired state to the state where the system has the least energy. As mentioned, in this research, SA is not implemented separately but it is used to empower the fuzzy GA and BBO algorithms.

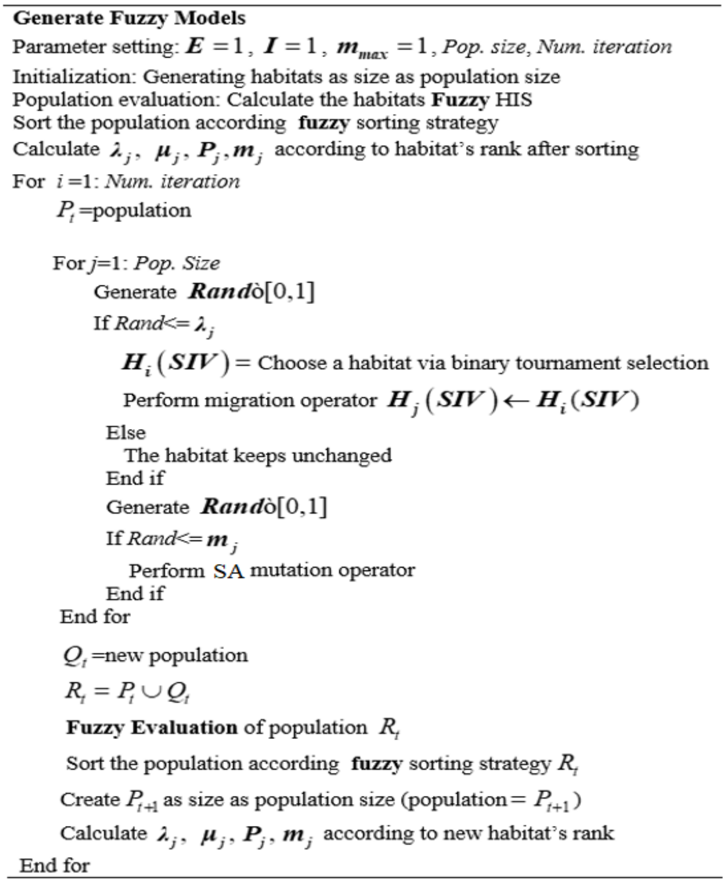
3.2.1 FHGA

GA is an effective meta-heuristic for solving combinatorial optimization problems. GA is a special type of evolutionary algorithm that uses evolutionary concepts such as inheritance, biological mutation, and Darwin's principles. The modeling of this algorithm is a programming technique that uses the genetic evolution process. The problem to be solved has inputs that are converted into solutions during a modeled process of genetic evolution, then the solutions are evaluated as candidates by the fitness function, and the algorithm terminates if the exit condition is met. In general, it is an iterative algorithm and most of its parts are selected as random processes. This algorithm is based on the population and each chromosome is known as a single chromosome and has its own level of fitness. The operators used include migration, mutation, and reproduction operators. A good solution is characterized by high fitness. In addition, GA operators can discard initial individuals during iterations (Rahmati and Zandieh, 2012).



```
Step. 2
Generate Fuzzy Models
Parameter setting: Pop. size, Num. iteration, Pc, Pre, Pm
Initialization: Generating chromosome as size as population size
Population evaluation: Calculate the fuzzy fitness of chromosomes
Sort the population according fuzzy sorting strategy
$P_t$=population
For i=1: Num. iteration
        $C_t$= Perform Crossover Operator
        $M_t$= Perform SA Mutation Operator
    $Q_t$=Integrate $C_t$ and $M_t$
    $R_t = P_t \cup Q_t$
    Fuzzy evaluate population on $R_t$
    Sort the population according fuzzy sorting strategy $R_t$
    Create $P_{t+1}$ as size as population size
End
```

Fig. 3. Pseudo-code of FHGA.



```
Generate Fuzzy Models
Parameter setting: $E = 1$, $I = 1$, $m_{max} = 1$, Pop. size, Num. iteration
Initialization: Generating habitats as size as population size
Population evaluation: Calculate the habitats Fuzzy HIS
Sort the population according fuzzy sorting strategy
Calculate $\lambda_j$, $\mu_j$, $P_j$, $m_j$ according to habitat's rank after sorting
For i =1: Num. iteration
    $P_t$=population

    For j=1: Pop. Size
        Generate $Rand$ò$[0,1]$
        If Rand<= $\lambda_j$
            $H_i(SIV)$ = Choose a habitat via binary tournament selection
            Perform migration operator $H_j(SIV) \leftarrow H_i(SIV)$
        Else
            The habitat keeps unchanged
        End if
        Generate $Rand$ò$[0,1]$
        If Rand<= $m_j$
            Perform SA mutation operator
        End if
    End for
    $Q_t$ =new population
    $R_t = P_t \cup Q_t$
    Fuzzy Evaluation of population $R_t$
    Sort the population according fuzzy sorting strategy $R_t$
    Create $P_{t+1}$ as size as population size (population = $P_{t+1}$)
    Calculate $\lambda_j$, $\mu_j$, $P_j$, $m_j$ according to new habitat's rank
End for
```

Fig. 4. Pseudo-code of FHBBO algorithm.

3.2.2 FHBBO algorithm

The BBO algorithm is another optimization method that is based on the concept of biogeography-based migration. Generally, biogeography studies the behavior of different biological species over time and space. The algorithm is population-based, and each habitat is identified as a single solution and has its own habitat suitability index (HSI). The operators used include migration and mutation operators. This algorithm does not have a reproduction operator but controls the exploitation operator by its own migration process. In this algorithm, the habitat or solution with higher HIS is more suitable. Moreover, the initial population is not discarded during iterations, but it is modified (Rahmati and Zandieh, 2012). Both algorithms start with a randomly generated initial population.

3.2.3 Solution Structure and Decoding

Figure 5 presents the solution structure implemented in the meta-heuristic approaches. All cells of this structure are filled by random key numbers. Each row also includes the size of the vector of the related solution structure.

Portion of demand of each customer for each product
$(D+P)\times X\times H$

0.227	**0.149**	**0.247**	**0.647**	**0.491**	**0.521**	**0.378**

Assign the value of raw material between the suppliers and the plants
$D\times P\times H$

0.748	**0.334**	**0.297**	**0.641**

Assign the value of product between the plants and the DCs
$S\times D\times Z$

0.967	**0.332**	**0.178**	**0.698**	**0.174**

Device used for transportation between the suppliers, the plants and the DCs
$U\times M/\{X\}\times(H,Z)$

1	**2**	**4**	**3**	**5**	**6**

Amount of raw material and products transported be the devices
$U\times M/\{X\}\times(H,Z)$

0.417	**0.227**	**0.374**	**0.974**	**0.371**	**0.166**

Capacity level of each DC for each product $P\times D\times F$

2	**1**	**2**	**1**

Technology level of each plant for each product $D\times H$

1	**2**	**1**	**3**	**2**

Fig. 5. The solution representation scheme used in the proposed meta-heuristic algorithms.

In this solution structure, the first row is a $(D+P)\times X\times H$ vector that determines the portion of demand of each customer for each product that is fulfilled by the plants and DCs. Figure 6 illustrates one customer, two products, two plants, and three DCs. In this figure, for example, if the demand of customer for product 1 is 1000, the amount of product 1 received from DC 1 is determined as$\left[\frac{0.227}{(0.227+0.149+0.247+0.647+0.491)}\times 1000\right]=129.$ The other rows' explanations are presented in the Figure. Finally, each device is routed according to the classical routing strategy presented in Figure 6. 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 the route because of the open routing policy considered in the problem of this study. Each solution generated by the proposed approach is evaluated easily using the objective functions (1) and the parameters of the problem.

First Vehicle			**Divider**	**Second Vehicle**			
4	**1**	**2**		**3**	**5**	**7**	**6**

Fig. 6. The routing strategy for each device.

4. Results

This chapter presents the results of the algorithms. It is noteworthy that in this study, two algorithms of FHGA and FHBBO are presented. It should be noted that the algorithm was implemented using an operating system with an Intel (R) Core (TM) i5-6200U CPU @ 2.30GHz and the algorithms were encoded in a MATLAB programming environment.

Table 1 presents the information on our implemented test problems. According to this table, eleven elements influence the size of our problem. It should be mentioned that even with a bit increase in these sizes of the problems, our best available computer processor went out of memory.

Table 1
The sizes of our implemented test problems

	S	D	P	X	Ua	Ub	Uc	F	H	Z	Y
1	2	2	2	2	2	2	2	2	2	3	2
2	2	2	2	3	3	3	1	2	2	3	2
3	2	3	2	8	3	3	7	2	3	4	2
4	2	3	3	11	3	3	11	3	3	4	2
5	2	3	4	11	5	4	9	5	3	4	2
6	3	3	4	13	5	5	10	6	3	4	5
7	3	3	4	13	6	5	9	6	3	4	5
8	3	4	5	14	6	6	11	6	4	5	5
9	4	4	5	15	6	6	12	6	4	5	6
10	4	5	6	15	6	6	14	6	5	6	6

Moreover, Table 2 illustrates the algorithm parameters. Since both FHGA and FHBBO implement SA algorithms, SA parameters are also introduced alongside the main algorithms.

Table 2
Parameters of the meta-heuristic algorithms

Algorithm Name	Parameter Name	Parameter Value
FHGA	Population Size	50
	Iteration Number	100
	Crossover Ratio	0.7
	Mutation Ratio	0.1
FHBBO	Population Size	50
	Iteration Number	100
	Habitat Keep Ratio	0.2
	Mutation Ratio	0.1
SA	Iteration Number	50
	Initial Temperature	1
	Reduction Ratio	0.9

Finally, Table 3 shows the fuzzy outputs of the algorithms on ten test problems. According to this table, FHGA and FHBBO have the almost similar manner in all test problems and do not considerably differ in all cases. Of course, this output is not a statistical claim since due to our fuzzy objective function values, statistical analysis is a challenge. This problem also appears in the parameter tuning of the fuzzy algorithms, which is not addressed in this research.

Table 3
Comparison of algorithms in total fuzzy cost

	FHGA			FHBBO		
1	1865580	1867447	1869314	1861559	1863422	1865285
2	2356951	2359310	2361669	2363678	2366044	2368410
3	8093134	8101235	8109336	8084624	8092717	8100810
4	11435447	11446894	11458341	11423228	11434663	11446098
5	11812973	11824798	11836623	11898927	11910838	11922749
6	14437684	14452136	14466588	14542492	14557049	14571606
7	14544555	14559114	14573673	14581041	14595637	14610233
8	31133204	31164368	31195532	30988895	31019915	31050935
9	33530404	33563968	33597532	33712011	33745757	33779503
10	37444060	37481542	37519024	37334243	37371615	37408987

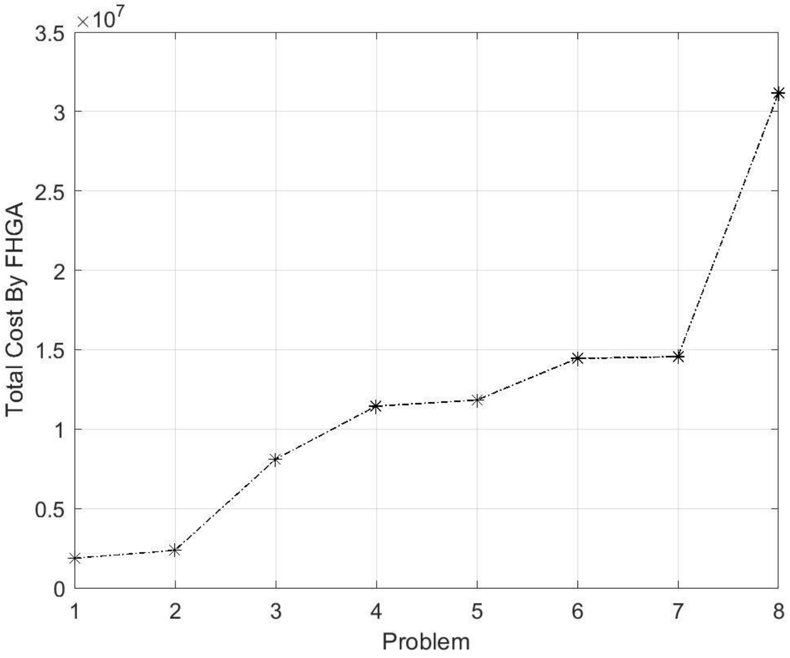


Fig. 7. Fuzzy results of the FHGA algorithm for ten problems.

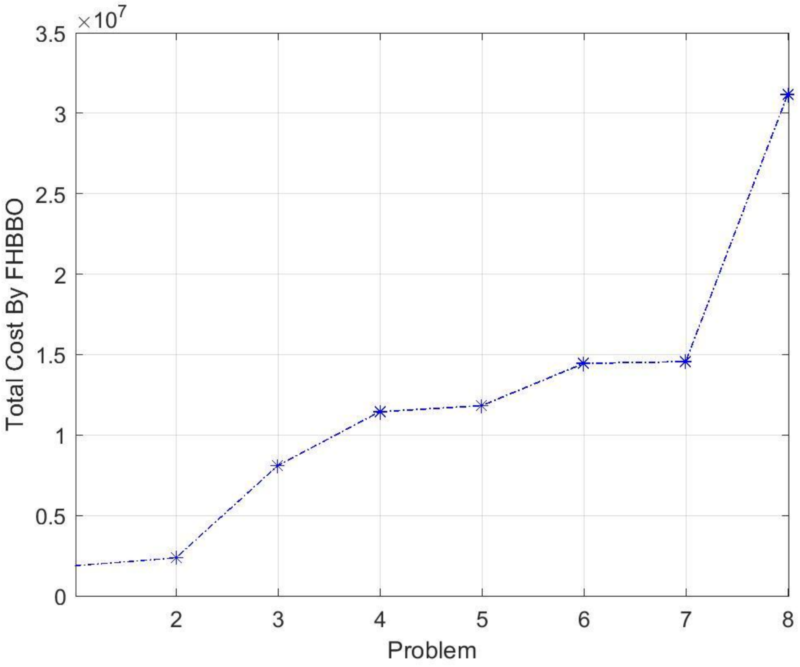


Fig. 8. Fuzzy results of the FHBBO algorithm for ten problems.

The illustrative outputs of the obtained fuzzy numbers are presented in Figure 7. They show that the algorithm considers all aspects of the model in a feasible manner. The algorithm includes the fuzzy establishment costs of the plants and distribution centers, fuzzy transportation costs among the suppliers, facilities and customers, the fuzzy hiring cost of the transportation facilities, and miscellaneous fuzzy environmental impact costs in the objective function, as well as facility location constraints, material flow constraints, open transportation routing from plants to customers and distribution centers to customers in the constraint part. Moreover, it determines alternative products for customers in the constraint part. As they show, increasing the problem size leads to the enhanced cost and time of the optimization, and the algorithms do not considerably differ in the manner.

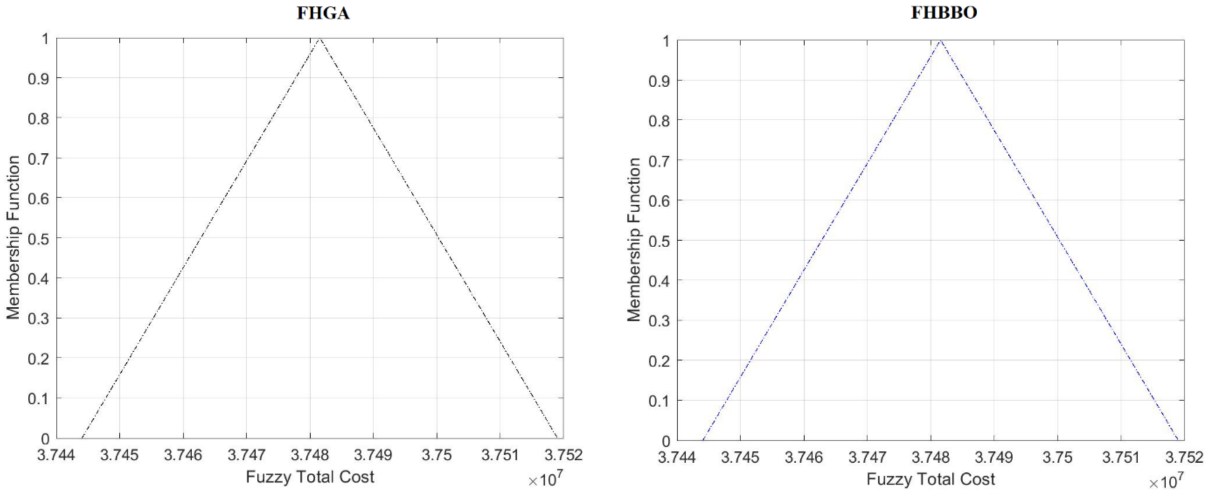


Fig. 9. Fuzzy number related to output cost function obtained from the algorithms on Problem 10.

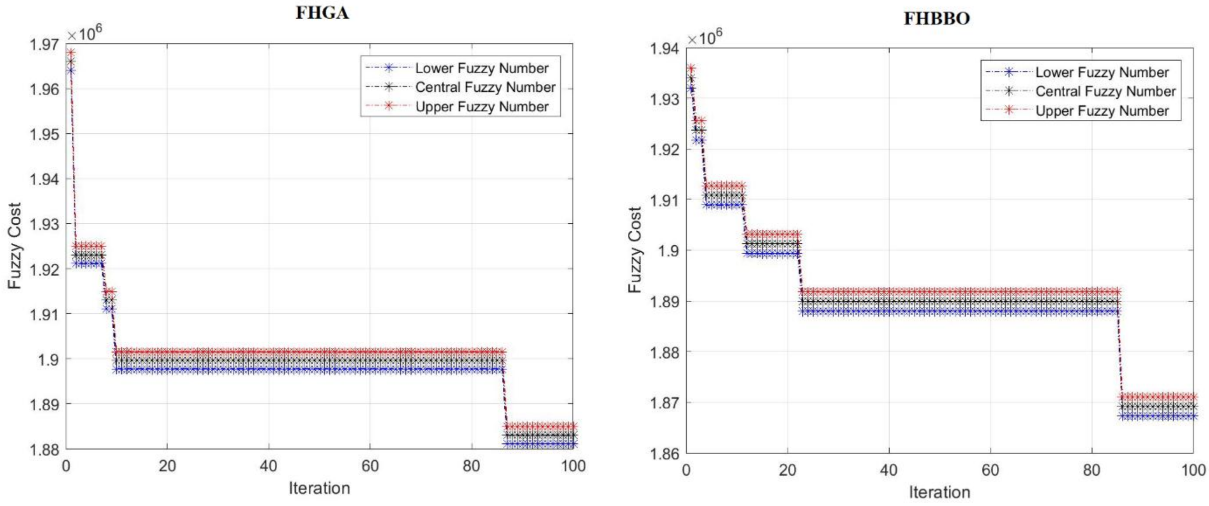


Fig. 10. The sample fuzzy convergence diagram of fuzzy hybrid algorithms on Problem 1.

As Table 3, Figures 7-9 illustrate that as the size of the test problems increases, the objective functions are increased, showing the impact of input elements. Moreover, as mentioned, even a small increase in the size of the problems causes our algorithms to go out of memory. However, as Figure 10 shows, the developed FHGA and FHBBO can entirely hold fuzzy assumption, from beginning test initialization to calculating objective function and presenting the convergence plots, and none of our parameters are defuzzied in all steps of these processes.

5. Conclusion

This study developed a GSCM model in an uncertain vague environment based on a triangular fuzzy approach. The objective function of our model was to minimize the total fuzzy cost including the fuzzy establishment costs of the plants and distribution centers, fuzzy transportation costs among the suppliers, facilities, and customers, the fuzzy hiring cost of the transportation facilities, and miscellaneous fuzzy environmental impact costs. The developed model also includes facility location constraints, material flow constraints, open transportation routing from plants to customers and distribution centers to customers, and determining alternative products for customers has not been addressed in the literature. The developed model was solved by two empowered algorithms of FHGA and FHBBO that control the fuzzy environment from beginning test initialization to calculating objective function and presenting the convergence plots, and none of our parameters are defuzzied in all steps of these processes. The results show that there is no significant difference between the used algorithms. Future work of this paper can focus on green logistics or SCM. Developing a Type-2 fuzzy model based on Buckley fuzzy numbers for PSCM control is also of interest. In the analysis part, developing and implementing the statistical process for comparisons and parameter tuning can also be suggested.

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