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FUZZY MULTI-OBJECTIVE NONLINEAR PROGRAMMING PROBLEMS UNDER VARİOUS MEMBERSHIP FUNCTIONS: A COMPARATİVE ANALYSIS

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Keywords
Green Supply Chain, Fuzzy Multi-objective Nonlinear Programming, Fuzzy Multi-objective Programming, Fuzzy Sets, Membership Functions, Zimmermann's Min-Max Approach.

Abstract
Fuzzy sets have been applied to various decision-making problems when there is uncertainty in real-life problems. In decision-making problems, objective functions and constraints sometimes cannot be expressed linearly. In such cases, the problems discussed are expressed by nonlinear programming models. Fuzzy multi-objective programming models are problems containing multiple objective functions, where objective functions and/or constraints include fuzzy parameters. Membership functions are crucial to obtain optimal solution of fuzzy multi-objective programming model. In this study, a green supply chain network model with fuzzy parameters is proposed. Proposed model with nonlinear constraints is a fuzzy multi-objective nonlinear programming model that minimizes both transportation costs and emissions generated by two vehicle types during transportation. The model is used in Zimmermann's Min-Max approach by considering triangular, hyperbolic and exponential membership functions and optimal solutions are obtained. When optimal solutions are compared, it is seen that optimal solution obtained using the hyperbolic membership function is better than the optimal solutions obtained from triangular and exponential ones. Maximum common satisfaction level calculated using hyperbolic membership function for proposed model is λ=0.97. Sensitivity analysis is also carried out by taking into account distances between suppliers, manufacturers, distribution centers and customers, as well as customer demands.

ÇEŞITLI ÜYELIK FONKSIYONLARI ALTINDA BULANIK ÇOK AMAÇLI DOĞRUSAL OLMAYAN PROGRAMLAMA PROBLEMLERİ: KARŞILAŞTIRMALI BIR ANALİZ

Anahtar Kelimeler
Yeşil Tedarik Zinciri, Bulanık Çok Amaçlı Doğrusal Olmayan Programlama, Bulanık Çok Amaçlı Programlama, Bulanık Kümeler, Üyelik Fonksiyonları, Zimmermann'ın Min-Max Yaklaşımı.

Öz
Bulanık kümeler, gerçek hayat problemlerinde belirsizlik olması durumunda çeşitli karar verme problemlerine uygulanmaktadır. Karar verme problemlerinde amaç fonksiyonları ve kısıtlar bazen doğrusal olarak ifade edilemez. Bu gibi durumlarda, ele alınan problemler doğrusal olmayan programlama modelleri ile ifade edilir. Bulanık çok amaçlı programlama modelleri, amaç fonksiyonları ve/veya kısıtların bulanık terimler içerdiği birden fazla amaç fonksiyonu olan problemlerdir. Bulanık çok amaçlı programlama modellerinin çözümünde kullanılan üyelik fonksiyonları, karar verme aşamasında çok önemlidir. Bu çalışmada, bulanık parametrelere sahip bir yeşil tedarik zinciri ağı modeli önerilmiştir. Doğrusal olmayan kısıtları olan model, hem taşıma maliyetlerini hem de taşıma esnasında iki araç tipi tarafından üretilen emisyonları en aza indiren bulanık çok amaçlı doğrusal olmayan programlama modelidir. Model, üçgensel, hiperbolik ve üstel üyelik fonksiyonları gözönüne alınarak Zimmermann'ın Min-Max yaklaşımında kullanılmış ve optimal çözümler elde edilmiştir. Optimal çözümler karşılaştırıldığında, hiperbolik üyelik fonksiyonu kullanılarak elde edilen optimal çözümün üçgensel ve üstel üyelik fonksiyonlarından elde edilen optimal çözümlerden daha iyi olduğu görülmüştür.

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Önerilen model için hiperbolik üyelik fonksiyonu kullanılarak hesaplanan maksimum ortak memnuniyet düzeyi λ=0.97'dir. Çalışmada, müşteri taleplerinin yanı sıra tedarikçiler, üreticiler, dağıtım merkezleri ve müşteriler arasındaki mesafeler dikkate alınarak duyarlılık analizi de yapılmıştır.

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FUZZY MULTI-OBJECTIVE NONLINEAR PROGRAMMING PROBLEMS UNDER VARİOUS MEMBERSHIP FUNCTIONS: A COMPARATİVE ANALYSIS

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Highlights

- A fuzzy multi-objective nonlinear programming (FMNOLP) model for a green supply chain network (GSCN) is proposed.
- The model includes linear constraints with fuzzy parameters, nonlinear constraints, and two objective functions.
- Both transportation costs and emissions generated by two vehicle types during transportation are minimized.
- The FMNOLP model is solved by Zimmermann's Min-Max approach under various membership functions.

Purpose and Scope

The aim of the study is to propose a fuzzy multi-objective nonlinear programming (FMNOLP) model for a green supply chain network (GSCN) model. The proposed model includes linear constraints with fuzzy parameters, nonlinear constraints, and two objective functions that minimize both transportation costs and emissions generated by two vehicle types during transportation.

Design/methodology/approach

The proposed FMNOLP model is solved by using Zimmermann's Min-Max approach under triangular, hyperbolic and exponential membership functions.

Findings

The optimal solution obtained for the FMNOLP model using the hyperbolic membership function is better than the optimal solutions obtained from the triangular and exponential membership functions.

Research limitations/implications

The limitation of the study is to consider a FMONLP model with two objective functions with linear and nonlinear constraints for a simple green supply chain network structure. In future studies, the proposed FMONLP model can be applied to more complicated GSCN models. Different nonlinear membership functions, different defuzzification techniques for fuzzy parameters or different linearization techniques can be handled. In addition, other solution methods in the literature proposed for FMOP problems can be applied under various linear and/or nonlinear membership functions.

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Originality

In the study, FMNOLP model which includes two objective functions as well as linear and nonlinear constraints is proposed. Linear constraints are dealt with demands of customers, fuzzy capacities of manufacturers, distribution centers and suppliers, and vehicle capacities. Nonlinear constraints are related to constraints on maximum capacity utilization for the manufacturers and distribution centers. In order to provide this, variability, i.e. standard deviation, must be minimum. The variability is the constant obtained by taking these two constraints as individual objective functions and solving them under the other constraints, and is added to these constraints as a right-hand side. Proposed FMNOLP model for green supply chain network is solved under various membership functions. A sensitivty analysis is also performed through capoacities and distances.

1. Introduction

Rapidly increased environmental problems adversely affect the world in various aspects such as health problems, costs, air pollution, environmental pollution, and the deterioration of the natural life cycle and pose a threat to future generations. In recent years, the effects of global warming and related climate change have reached serious levels, causing plenty of living creatures and even natural resources to face many dangers, especially destruction. Among the causes of climate change, the uses of greenhouse gases and insoluble raw materials in nature have a large share. These problems caused by people can still be prevented and compensated. For this purpose, many companies have created green supply chains by making some changes in supply chain management through environmentally friendly strategies and legal regulations.

Some real-life problems may include both fuzzy parameters and multiple objectives. For companies, cost is an important factor in the construct of green supply chain besides the amount of environmental damage. In some cases, high costs may be required due to the high technology used to prevent environmental pollution. In such cases, while trying to minimize the damage to the environment, the cost for the sustainability of the companies should be kept in mind and the problem should be considered as a fuzzy multi-objective programming model.
The Min-Max approach proposed by Zimmermann (1978) is a method that combines fuzzy set theory and multi-objective programming. In addition, Sakawa and Yano (1985), Bit et al. (1993), Kuwano (1996), Liang and Cheng (2009) and etc. contributed to the literature by developing some approaches and integrated algorithms to solve fuzzy multi-objective programming problems.

The multi-objective nonlinear programming problem involving fuzzy parameters was first introduced by Orlovski et al. (1984). Afterwards, Sakawa and Yano (1985) introduced a multi-objective nonlinear programming (MONLP) model with fuzzy objective functions. This model was discussed on a numerical example using triangular, exponential, hyperbolic, piecewise linear, and inverse hyperbolic membership functions. Zhao and Bose (2002) assessed different types of membership functions like triangular, trapezoidal, Gaussian, sigmoidal, and polynomial, in fuzzy control of an induction motor driver. At first, fuzzy controller sensitivity was analyzed and then comparisons between triangular membership functions and different membership functions were made. Bit (1993) aimed to obtain efficient and best compromise solutions for a fuzzy multi-objective transportation problem with capacity constraints by using hyperbolic membership function. In order to show the effectiveness of the methodology, solutions were obtained by fuzzy programming with linear and hyperbolic membership functions on a numerical example and a comparison was made.

In a fuzzy context, Wang and Liang (2004) proposed a fuzzy multi-objective linear programming (FMOLP) model to solve the multi-product aggregate production planning choice problem. For all objective functions, the problem was transformed into a linear programming problem using a piecewise linear membership function. In order to find solutions for integrated production/transport planning issues with fuzzy multiple objective functions, Liang (2007) proposed a fuzzy goal programming (FGP) approach. In the proposed approach, piecewise linear membership functions was considered for each of the fuzzy goals. Zangiabadi and Maleki (2007) proposed a fuzzy goal programming approach for the multi-objective transportation problem. They focused on minimization of the negative deviation variables from 1 to specify an optimal compromise solution assuming the objective functions have fuzzy goals. One of the nonlinear membership functions, hyperbolic, was used for each objective function in order to define all fuzzy goals.

Bodkhe et al. (2010) presented a fuzzy multi-objective programming method considering hyperbolic membership function for solving bi-objective transportation problem to compare with those obtained from the triangular membership function. Peidro and Vasant (2011) addressed the multi-objective problem of transportation planning decision (TPD) problem which has fuzzy goals, supplies and forecast demands. In order to solve considered problem in which fuzzy data is specified by modified S-curve membership functions, an interactive method was presented. In the proposed method, it was aimed to simultaneously minimize total production costs, transportation costs, and total delivery time by considering several constraints such as budget, available supply, machine capacities, forecasted demand, and warehouse space. Using the interactive fuzzy approach, the performance of the membership function types of S-curve and linear, are compared for solving the multi-objective TPD problem and a agreement solution is obtained.

Zangiabadi and Maleki (2013) carried out FGP to a linear multiobjective transportation problem. Nonlinear membership functions like hyperbolic and exponential were used to obtain an optimal compromise solution for multi-objective transportation problem and compare it with the solution obtained using the linear membership function. Singh and Yadav (2018) presented intuitionistic fuzzy multi-objective linear programming (ITFMOLP) problems which have mixed constraints. Triangular intuitionistic fuzzy numbers were considered for constraint functions, objective function coefficients, and right hand sides of constraints. The ITFMOLP problem was transformed into a multi- objective linear programming problem using the accuracy function, and then it was transformed into a fuzzy goal programming (FGP) model considering scalarization technique. Linear, parabolic and hyperbolic membership functions were used for solving the FGP problem to obtain optimal results. Medina-González et al. (2018) introduced a fuzzy multi-objective optimization model for sustainable design and planning related to water supply chains considering nonlinear membership functions. Linear membership functions are taken into account for economic profit and water consumption objectives, while a nonlinear membership function was handled for land usage objective.

Li et al.(2020), provides an optimal model for allocating agricultural water and soil resources under consideration. Heuristic fuzzy numbers, fuzzy reliability restricted programming, mixed integer nonlinear programming, and multi-objective programming are all part of the approach. For model solution, a nonlinear membership function and fuzzy programming approach are applied. Kara and Kocken (2021) presented a multi-objective solid transport problem model that takes into account to evaluate the performance of linear and nonlinear membership functions. The model was solved using both the hyperbolic and linear membership functions by a numerical example. From the results, it was seen that the hyperbolic membership function gives the best optimal solutions. Miah et al. (2022) addressed the multi-objective goal programming approach for the transportation problem. At the solution phase, the optimal solutions were compared through exponential and hyperbolic membership functions. Das (2022) handled a multi-objective inventory problem using several techniques such as geometric programming, fuzzy programming technique with hyperbolic membership function, and fuzzy nonlinear programming.

In this study, it is aimed to examine whether the selected membership functions make any difference for the solution of fuzzy multi-objective nonlinear supply chain problems involving uncertainty.

Remainder of this study is arranged as follows: Fuzzy multi-objective programming models, Zimmerman's Min-Max approach and various membership functions related to the approach are explained in Section 2. In Section 3, a fuzzy multi-objective nonlinear supply chain problem is considered as a numerical example. Comparative results according to sensitivity analysis considering various membership functions are given in Section 4. Future studies are given in Section 5.

2. Fuzzy Multi-Objective Programming Model

In real world decision-making problems, uncertainties have been existed due to decision makers may have not information regarding exact values of the coefficients or parameters related to the problem. Applying the fuzzy set theory proposed by Zadeh (1965), more efficient and more flexible solutions are provided for such problems. Bellman and Zadeh (1970), who carried out the first study in which fuzzy sets were applied to decision making problems, proposed a fuzzy decision model characterized by membership functions using minimum operators. Zimmermann (1978) extended the fuzzy linear programming approach to multi-objective linear programming (MOLP) problems and this method was called the Min-Max approach. In the study, the extended problem was transformed into a classical LP problem by defining each objective function with its corresponding membership function and using the minimum operator proposed by Bellman and Zadeh (1970).

Fares and Kaminska (1995) modelled a problem with fuzzy nonlinear objective function and fuzzy constraints using nonlinear membership functions. Verma et al. (1997) presented an optimal solution by using two nonlinear membership functions, hyperbolic and exponential, to solve the multi-objective transportation problem. Wang (2004) introduced a fuzzy multi-objective linear programming (FMOLP) model to obtain a solution for the multi-product aggregate production planning decision problem which contains fuzzy parameters. The model was solved by considering piecewise membership function for all objective functions. Liang (2006) presented an interactive-FMOLP method with piecewise linear membership function for solving transportation problems. Zeng et al. (2010) presented a FMOLP model with triangular fuzzy numbers. The model and its corresponding fuzzy goal programming problem were converted into to crisp ones. Hu (2017) introduced a multi-objective programming model for the printed circuit board (PCB) line assignment problem on the basis of the transportation problem and assignment problem. To obtain a solution for the presented model, the fuzzy goal programming method with nonlinear hyperbolic membership function was applied.

The fuzzy multi-objective programming (FMOP) model is given as follows:

$$\begin{gathered}\mathbf{Min}\ \mathbf{Z_i(x)} \cong \left(\mathbf{Z_1(x), Z_2(x), \dots, Z_k(x)}\right)^{\mathbf{T}} \\ \mathbf{g_j(x) \leq 0,\ j = 1, \dots, t}\end{gathered} \tag{1}$$

In Equation (1), $Z_i(x)$ denotes the objective function i $(i = 1, \dots, k)$, x indicates decision variables and $g_j(x)$ defines inequality constraint j $(j = 1, \dots, t)$.
The FMOP given in Equation (1) is called FMOLP in case of objective functions and constraints are all linear. On the other hand, it is called fuzzy multi-objective nonlinear programming (FMONLP) when at least one of the objective functions and/or constraints are nonlinear. Various methods have been introduced for solving the FMOP models.

In this study, a FMONLP model is introduced for green supply chain network. In the solution phase of this model, Zimmermann (1978)'s Min-Max approach is applied which is explained step by step below.
Step 1. The FMONLP model is constructed.
Step 2. $Z_i(x)'s, i = 1, \dots, k$ are solved individually under the same constraints.
Step 3. Using optimal solutions obtained from Step 2, corresponding values for each objective function is calculated at each optimal solution derived. Pay-off matrix is created using each optimal solution corresponding to each objective function.
Step 4. The lower value (Z_i^L) and the upper value (Z_i^U) of all objective functions are determined from the pay-off matrix given in Table 1.

Table 1. Pay-off matrix

Min	$Z_1(x)$	$Z_2(x)$	…	$Z_k(x)$
$Z_1(x)$	Z_{11}	Z_{12}	…	Z_{1k}
$Z_2(x)$	Z_{21}	Z_{22}	…	Z_{2k}
$\vdots$	$\vdots$	$\vdots$	$\ddots$	$\vdots$
$Z_k(x)$	Z_{k1}	Z_{k2}	…	Z_{kk}
Z_i^L	Z_1^L	Z_2^L	…	Z_k^L
Z_i^U	Z_1^U	Z_2^U	…	Z_k^U

Step 5. Membership function $\mu_i(Z_i(x))$ for each objective function is obtained by using the values of Z_i^L and Z_i^U given in Table 1.

Triangular, hyperbolic and exponential type membership functions for the objective function $Z_i(x)$ are defined in Equations (2), (3), and (4), respectively.

$$\mu_i^T(Z_i(x)) = \begin{cases} 1, & Z_i(x) \leq Z_i^L \\ \frac{Z_i^U - Z_i(x)}{Z_i^U - Z_i^L}, & Z_i^L \leq Z_i(x) \leq Z_i^U \\ 0, & Z_i(x) \geq Z_i^U \end{cases} \tag{2}$$

$$\mu_i^H(Z_i(x)) = \begin{cases} 1, & Z_i(x) \leq Z_i^L \\ \frac{1}{2}\tanh\left(\frac{Z_i^U + Z_i^L}{2} - Z_i\right)\alpha_i + \frac{1}{2}, & Z_i^L \leq Z_i(x) \leq Z_i^U \\ 0, & Z_i(x) \geq Z_i^U \end{cases} \tag{3}$$

$$\mu_i^E(Z_i(x)) = \begin{cases} 1, & Z_i(x) \leq Z_i^L \\ \frac{e^{-s\psi_i(x)} - e^{-s}}{1 - e^{-s}}, & Z_i^L \leq Z_i(x) \leq Z_i^U \\ 0, & Z_i(x) \geq Z_i^U \end{cases} \tag{4}$$

In Equations (3) and (4), $\alpha_i = \frac{6}{Z_i^U - Z_i^L}$, $\psi_i(x) = \frac{Z_i(x) - Z_i^L}{Z_i^U - Z_i^L}$, s is a non-zero parameter defined by desicion maker.

Step 6. The membership functions corresponding to each objective function are added to model given in Equation (1) as constraints. Thus, problem is converted into a single objective programming model by using variable λ which defines the common satisfaction level for all objective functions, as follows:

$$\begin{aligned} &\mathbf{Max}\ \boldsymbol{\lambda} \\ &\boldsymbol{\lambda} \le \boldsymbol{\mu}_{\mathbf{i}}(\mathbf{Z}_{\mathbf{i}}(\mathbf{x})), \mathbf{i} = \mathbf{1}, \mathbf{2}, \ldots, \mathbf{k} \\ &\mathbf{g}_{\mathbf{j}}(\mathbf{x}) \le \mathbf{0},\ \mathbf{j} = \mathbf{1}, \ldots, \mathbf{t} \\ &\mathbf{x} \ge \mathbf{0} \\ &\boldsymbol{\lambda} \in [\mathbf{0}, \mathbf{1}] \end{aligned} \tag{5}$$

The solution to the single-objective programming model given in Equation (5) provides an optimal solution for the FMONLP model.

3. Numerical Example

People and institutions have started to interest in environmental problems arising from logistics services since 1980s. The concept of green supply chain network (GSCN) has emerged with the development of modern logistics management and supply chain management Chunguang at al. (2008). The GSCN was introduced by the University of Michigan Research Society in 1996 to assess environmental impacts and resource use in the supply chain Zhang(2005). The GSCN aims to minimize or eliminate hazardous chemicals, emissions, energy, and solid wastes arising from supply chain processes Chin et al.(2015). Shaw et al. (2012) introduced a combined approach to the carbon emission problem by using FMOLP and fuzzy analytic hierarchy process to select most preferred supplier. Kannan et al. (2013) presented a FMOLP model for GSCN problem using fuzzy AHP, TOPSIS and Zimmermann's Min-Max approaches. Mohammed and Wang (2017) introduced a fuzzy multi-objective optimization model for a meat supply chain network under multiple uncertainties. In the model, the goal is to reduce total transportation costs, implementation costs, CO_2 emissions from transportation, product distribution time, and average delivery rate while satisfying product quantities. In the solution phase, methods of LP-metrics, goal programming, and ε-constraint were used to optimize the objective functions simultaneously.

3.1. Problem Description

This section deals with a green supply chain network (GSCN) model that minimizes both total transport costs and total CO_2 emissions between suppliers, manufacturers, distribution centres, and customers. This model includes two suppliers, three manufacturers, two distribution centers, three customer groups, and two different vehicle types, as illustrated in Figure 1. It is aimed to develop a FMONLP model for proposed GSCN that takes into account fuzzy capacities of suppliers, manufacturers, distribution centres, and demand of customers. Two objective functions are simultaneously minimized. The first one minimizes transport costs between suppliers, factories, distribution centers and customers. The second one minimizes the amount of CO_2 emissions for two different types of vehicles used during transportation. In order to determine the amount of product to be transported on which route with which vehicle type, the proposed FMONLP is solved under triangular membership function which is a linear membership function, as well as hyperbolic and exponential membership functions which are non-linear membership functions (Akarçay, 2019).

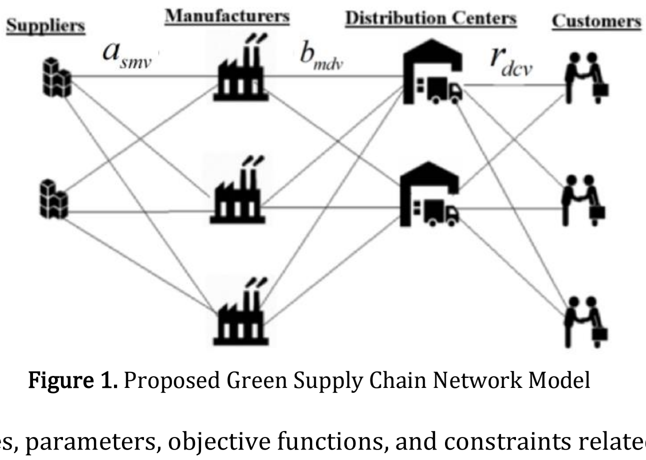

Figure 1. Proposed Green Supply Chain Network Model

The indices, decision variables, parameters, objective functions, and constraints related to the construction of the mathematical model of the proposed FMONLP problem are defined as follows:

Indices:
s: suppliers (s=1,2)
m: manufacturers (m=1,2,3)
d: distribution centers (d=1,2)
c: customers (c=1,2,3)
v: vehicle types (v=1,2)

Decision variables:
a_{smv}: quantity of the product transported from supplier s to manufacturer m with vehicle v
b_{mdv}: quantity of the product transported from manufacturer m to distribution center d with vehicle v
r_{dcv}: quantity of the product transported from distribution center d to customer c with vehicle v

$$y_{dcv} = \begin{cases} 1, & if\ distribution\ center\ d\ \ serves\ customer\ c\ with\ vehicle\ v \\ 0, & otherwise \end{cases}$$

Parameters:
h_v: transportation capacity of vehicle type v
d_{smv}: unit cost of product transportation from supplier s to manufacturer m with vehicle v
e_{mdv}: unit cost of product transportation from manufacturer m to distribution center d with vehicle v
f_{dcv}: unit cost of product transportation from distribution center d to customer c with vehicle v
CO_2: quantity of CO_2 produced by vehicles per km
p: demand of customers
$\tilde{G}(d)$: fuzzy capacity of distribution center d
$\tilde{H}(m)$: fuzzy capacity of manufacturer m
$\tilde{S}(s)$: fuzzy capacity of supplier s
dis_{sm}: distance between supplier s and manufacturer m
dis_{md}: distance between manufacturer m and distribution center d
dis_{dc}: distance between distribution center d and customer c

Objective Functions:

$$\mathrm{MinZ_1} = \sum_{s=1}^{2}\sum_{m=1}^{3}\sum_{v=1}^{2} d_{smv}a_{smv} + \sum_{m=1}^{3}\sum_{d=1}^{2}\sum_{v=1}^{2} e_{mcv}b_{mcv} + \sum_{d=1}^{2}\sum_{c=1}^{3}\sum_{v=1}^{2} f_{dcv}r_{dcv} \tag{6}$$

$$\mathrm{MinZ_2} = \sum_{s=1}^{2}\sum_{m=1}^{3}\sum_{v=1}^{2} \frac{a_{smv}}{h_v} CO_{2(smv)}dis_{sm} + \sum_{m=1}^{3}\sum_{d=1}^{2}\sum_{v=1}^{2} \frac{b_{mdv}}{h_v} CO_{2(mdv)}dis_{md} + \sum_{d=1}^{2}\sum_{c=1}^{3}\sum_{v=1}^{2} \frac{r_{dcv}}{h_v} CO_{2(dcv)}dis_{dc} \tag{7}$$

In Equation (6), Z_1 minimizes total transportation costs between suppliers and manufacturers, between manufacturers and distribution centers, and between distribution centers and customers. In Equation (7), Z_2 minimizes total amount of CO_2 emissions for two types of vehicles used in transportation.

Constraints:

$$\sum_{v=1}^{2}\sum_{c=1}^{3} y_{dcv} = 1, \forall d \tag{8}$$

$$\sum_{v=1}^{2}\sum_{m=1}^{3} b_{mdv} = \sum_{v=1}^{2}\sum_{c=1}^{3} r_{dcv}, \forall d \tag{9}$$

$$r_{dcv} = p \times y_{dcv}, \forall d, c, v \tag{10}$$

$$\sum_{d=1}^{2} b_{mdv} \le \tilde{H}(m), \forall m, v \tag{11}$$

$$\sum_{v=1}^{2}\sum_{d=1}^{2} y_{dcv} \times p \le \tilde{G}(d), \forall c \tag{12}$$

$$\sum_{m=1}^{3} a_{smv} \le \tilde{S}(s), \forall s, v \tag{13}$$

$$\sqrt{\sum_{m=1}^{3}\left(\sum_{d=1}^{2}\frac{b_{mdv}}{\tilde{H}(m)} - \frac{\sum_{d=1}^{2} b_{mdv}}{\sum_{j=1}^{3}\tilde{H}(m)}\right)^2} \le 0.7, \forall v \tag{14}$$

$$\sqrt{\sum_{d=1}^{2}\left(\sum_{c=1}^{3}\frac{r_{dcv}}{\tilde{G}(d)} - \frac{\sum_{c=1}^{3} c_{dcv}}{\sum_{d=1}^{2}\tilde{G}(d)}\right)^2} \le 0.7, \forall v \tag{15}$$

$$a_{smv} \le h_v, \forall s, m, v \tag{16}$$

$$b_{mdv} \le h_v, \forall m, d, v \tag{17}$$

$$r_{dcv} \le h_v, \forall d, c, v \tag{18}$$

$$a_{smv} \ge 0, \forall s, m, v \tag{19}$$

$$b_{mdv} \ge 0, \forall m, d, v \tag{20}$$

$$r_{dcv} \ge 0, \forall d, c, v \tag{21}$$

Equations (8)-(10) represent that the demands of each customer group are completely fulfilled. Equation (11) defines fuzzy capacity constraint for manufacturer production, Equation (12) describes fuzzy distribution center capacity constraint and Equation (13) represents fuzzy supplier capacity constraint. Constraints on maximum capacity utilization for the manufacturers and distribution centers are given in Equation (14) and Equation (15), respectively. In order to provide these constraints, variability, i.e. standard deviation, must be minimum. When these two constraints are taken as individual objective function and solved under other constraints, the minimum deviation is calculated as 0.7. Thus, the maximum utilization capacity ratio is determined as 0.7 and taken as the right-hand side constant. Constraints on the vehicle capacity for transported products are given in Equations (16)-(18). Non-negativity constraints on transported products are shown in Equations (19)-(21).

The fuzzy capacities of suppliers, manufacturers, distribution centers, and also the demand of customers are given in Table 2. Capacities and CO_2 emissions for two vehicle types are shown in Table 3. The product transportation costs per unit by two vehicle types from suppliers to manufacturers, from manufacturers to distribution centers and from distribution centers to customers are shown in Tables 4, 5 and 6.

Table 2. Fuzzy Capacities Of Suppliers, Manufacturers, Distribution Centers And Demand Of Customers

	Suppliers $\tilde{S}(i)$	Manufacturers $\tilde{H}(j)$	Distribution Centers $\tilde{G}(n)$	Customers (P)
1	(5500,6000)	(5500,6500)	(6200,7000)	2750
2	(5400,6000)	(920,1080)	(6100,7900)	2750
3	-	(2000,3000)	-	2750

Table 3. Capacities and emissions for two vehicle types

		Capacities (kg) (h_k)	Amounts of CO_2 (kg/km)
Vehicle Type	Van	3000	0.000263
	Truck	5000	0.000657

Table 4. Product Transportation Costs Per Unit From Suppliers To Manufacturers For Two Vehicle Types

d_{ijk}		Vehicle Type	Manufacturers 1	2	3
Suppliers	1	Van	0.7	0.4	0.6
		Truck	0.4	0.6	0.5
	2	Van	0.3	0.2	0.1
		Truck	0.5	0.7	0.3

Table 5. Product Transportation Costs Per Unit From Manufacturers To Distribution Centers For Two Vehicle Types

e_{jnk}		Vehicle Type	Distribution Centers 1	2
Manufacturers	1	Van	1.5	1.2
		Truck	1.2	1.6
	2	Van	1.3	1.6
		Truck	1.3	1.7
	3	Van	1.4	1.3
		Truck	1.4	1.5

Table 6. Product Transportation Costs Per Unit From Distribution Centers To Customers For Two Vehicle Types

f_{nmk}		Vehicle Type	Customers 1	2	3
Distribution Centers	1	Van	0.6	0.7	0.4
		Truck	0.3	0.4	0.6
	2	Van	0.5	0.3	0.6
		Truck	0.8	0.4	0.9

The quantity of CO_2 emission is proportional to the distance transported and the amount of weight carried. The distances between the suppliers, manufacturers, distribution centers, and customers in kilometers are shown in Figure 2.

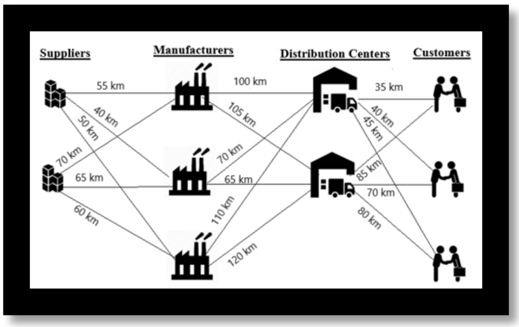

Figure 2. Distances Between The Suppliers, Manufacturers, Distribution Centers And, Customers

3.2. Solution of the Problem

In the solution phase, at first, fuzzy parameters are defuzzified using mean of maxima method to convert into crisp ones. Each objective function (Z_1,Z_2) is solved individually under the same constraints. The optimal values of the decision variables from solving the Z_1 are used to calculate the Z_2 value. On the other hand, the optimal values of the decision variables from solving the Z_2 are used to calculate the Z_1 value. Thus, pay-off matrix given in Table 7 is constituted by utilizing these objective function values.

Table 7. Pay-Off Matrix Of Problem

Min	$Z_1(x)$	$Z_2(x)$
$Z_1(x)$	16380	0.186
$Z_2(x)$	18617.408	0.152
Z_i^L	16380	0.152
Z_i^U	18617.408	0.186

The Min-Max approach of Zimmermann (1978) is implemented for the proposed FMONLP problem in order to obtain optimal solutions. For this aim, membership functions of triangular, hyperbolic and exponential are constructed by using the pay-off matrix in Table 7. Triangular membership functions related to objective functions Z_1 and Z_2, are defined as follows:

$$\mu_1^T(Z_1(x)) = \begin{cases} 1, & Z_1(x) \leq 16380 \\ \frac{18617.408 - Z_1(x)}{18617.408 - 16380}, & 16380 \leq Z_1(x) \leq 18617.408 \\ 0, & Z_1(x) \geq 18617.408 \end{cases} \tag{22}$$

$$\mu^T{}_2(Z_2) = \begin{cases} 1, & Z_2 < 0.152 \\ \frac{0.186 - Z_2}{0.186 - 0.152}, & 0.152 \leq Z_2 \leq 0.186 \\ 0, & Z_2 > 0.186 \end{cases} \tag{23}$$

For Z_1 and Z_2, hyperbolic membership functions are obtained as:

$$\mu_1^H(Z_1) = \begin{cases} 1, & Z_1 < 16380 \\ \frac{1}{2}\tanh\left(\frac{34997.408}{2} - Z_1\right)0.0026 + \frac{1}{2}, & 16380 \leq Z_1 \leq 18617.408 \\ 0, & Z_1 > 18617.408 \end{cases} \tag{24}$$

$$\mu_2^H(Z_2) = \begin{cases} 1, & Z_2 < 0.152 \\ \frac{1}{2}\tanh\left(\frac{0.338}{2} - Z_2\right)0.0026 + \frac{1}{2}, & 0.152 \leq Z_2 \leq 0.186 \\ 0\,, & Z_2 > 0.186 \end{cases} \tag{25}$$

For Z_1 and Z_2, exponential membership functions are constituted as follows:

$$\mu^E{}_1(Z_1) = \begin{cases} 1, & Z_1 < 16380 \\ \dfrac{e^{-\frac{Z_1-16380}{2237.408}} - e^{-1}}{1-e^{-1}}, & 16380 \le Z_1 \le 18617.408 \\ 0, & Z_1 > 18617.408 \end{cases} \quad (26)$$

$$\mu^E{}_2(Z_2) = \begin{cases} 1, & Z_2 < 0.152 \\ \dfrac{e^{-\frac{Z_2-0.152}{0.034}} - e^{-1}}{1-e^{-1}}, & 0.152 \le Z_2 \le 0.186 \\ 0, & Z_2 > 0.186 \end{cases} \quad (27)$$

where; s =1, $\psi_1 = \frac{Z_1-16380}{2237.408}$ and $\psi_2 = \frac{Z_2-0.152}{0.034}$

To convert the fuzzy single-objective nonlinear programming model, common satisfaction level and membership functions of the Z_1 and Z_2 are added to the presented FMONLP model as follows:

$$\begin{aligned} &Max\ \lambda \\ &\quad \lambda \le \mu_1(Z_1) \\ &\quad \lambda \le \mu_2(Z_2) \\ &\quad Equations\ (8)-(21) \end{aligned} \quad (28)$$

The model given in Equation (28) is solved under triangular, hyperbolic, and exponential membership functions for objective functions. Optimal solutions and common satisfaction levels are computed and given in Table 8. Additionally, optimal solutions obtained under triangular, hyperbolic and exponantial membership functions are illustrated in Figure 3, Figure 4, and Figure 5, respectively.

Table 8. Optimal Solutions

	Membership Function Types		
Objective Functions	**Triangular**	**Hyperbolic**	**Exponential**
$\boldsymbol{Z_1}$	16829.296	16812.158	16829.296
$\boldsymbol{Z_2}$	0.159	0.159	0.159
$\boldsymbol{\lambda}$	0.80	0.97	0.72
	Decision Variables		
$\boldsymbol{a_{111}}$	2260.741	2217.894	2260.741
$\boldsymbol{a_{121}}$	1000	1000	1000
$\boldsymbol{a_{211}}$	2489.259	2532.106	2489.259
$\boldsymbol{a_{231}}$	2500	2500	2500
$\boldsymbol{b_{111}}$	2000	2000	2000
$\boldsymbol{b_{121}}$	2750	2750	2750
$\boldsymbol{b_{211}}$	340.095	340.093	340.119
$\boldsymbol{b_{212}}$	659.905	659.907	659.881
$\boldsymbol{b_{311}}$	2378.895	2378.897	2378.880
$\boldsymbol{b_{312}}$	121.105	121.103	121.120
$\boldsymbol{r_{112}}$	2750	2750	2750
$\boldsymbol{r_{131}}$	2750	2750	2750
$\boldsymbol{r_{221}}$	2750	2750	2750

4. Sensitivity Analysis

In this section, a sensitivity analysis is carried out in order to show the accuracy of the proposed model. Different scenarios are created by making changes for customer demands and for distances between the suppliers, manufacturers, distribution centers and, customers. Then, the proposed model is solved under triangular, exponential and hyperbolic membership functions.

4.1. Sensitivity to Changes in Customer Demands

Two scenarios are created by decreasing the customer demands in the current model by 10% and increasing them by 10%. According to new parameters, the proposed model is solved under triangular, hyperbolic, and exponential membership functions and optimal solutions are given in Table 9.

Table 9. Optimal Solutions For Customer Demands

Customer Demands(-%10)				**Customer Demands (+%10)**			
Membership Function Types				**Membership Function Types**			
Objective Functions	**Triangular**	**Hyperbolic**	**Exponential**	**Objective Functions**	**Triangular**	Hyperbolic	Exponential
Z_1	14519.361	14539.673	14541.655	Z_1	18583.485	18604.373	18605.321
Z_2	0.143	0.143	0.143	Z_2	0.200	0.200	0.200
λ	0.74	0.94	0.64	λ	0.67	0.87	0.56
Decision Variables				**Decision Variables**			
a_{111}	664.536	665.575	672.185	a_{111}	187.586	190.458	193.370
a_{112}	60.464	259.425	252.815	a_{112}	2187.414	2384.542	2381.630
a_{121}	1000.000	1000.000	1000.000	a_{121}	1000.000	1000.000	1000.000
a_{211}	3200.000	3000.000	3000.000	a_{211}	3200.000	3000.000	3000.000
a_{231}	2500.000	2500.000	2500.000	a_{231}	2500.000	2500.000	2500.000
b_{111}	1450.000	1450.000	1450.000	b_{111}	1824.030	1824.118	1824.366
b_{121}	2475.000	2475.000	2475.000	b_{112}	750.970	750.882	750.634
b_{211}	716.687	716.687	716.687	b_{121}	3000.000	3000.000	3000.000
b_{212}	283.313	283.313	283.313	b_{211}	262.550	262.523	262.476
b_{311}	2500.000	2500.000	2500.000	b_{212}	737.450	737.477	737.524
r_{112}	2475	2475	2475	b_{311}	2227.941	2227.923	2227.853
r_{131}	2475	2475	2475	b_{312}	247.059	247.077	247.147
r_{221}	2475	2475	2475	b_{322}	25.000	25.000	25.000
				r_{112}	3025	3025	3025
				r_{132}	3025	3025	3025
				r_{222}	3025	3025	3025

4.2. Sensitivity to Changes in Distances

Six scenarios are created by decreasing the distances on the current model by 20% and increasing it by 20%. These changes are made for the distances between the supplier and the manufacturer, between the manufacturer and the distribution center, and between the distribution center and the customer. According to the new parameters, the model is solved according to the triangular, hyperbolic and, exponential membership functions. Comparison results are given in Tables 10, 11 and 12, respectively.

Table 10. Optimal Solutions For The Distance Between Supplier And Manufacturers

Change (-%20)				Change (+%20)			
Membership Function Types				Membership Function Types			
Objective Functions	**Triangular**	**Hyperbolic**	**Exponential**	**Objective Functions**	**Triangular**	**Hyperbolic**	**Exponential**
Z_1	16282.546	16288.043	16290.023	Z_1	16175.038	16197.326	16197.409
Z_2	0.157	0.157	0.157	Z_2	0.171	0.171	0.171
λ	0.68	0.90	0.58	λ	0.70	0.91	0.59
Decision Variables				**Decision Variables**			
a_{111}	657.152	626.809	633.409	a_{111}	706.257	714.608	715.894
a_{112}	874.848	1123.191	1116.591	a_{112}	843.743	1035.392	1034.106
a_{121}	1000.000	1000.000	1000.000	a_{121}	1000.000	1000.000	1000.000
a_{211}	3200.000	3000.000	3000.000	a_{211}	3200.000	3000.000	3000.000
a_{231}	2500.000	2500.000	2500.000	a_{231}	2500.000	2500.000	2500.000
b_{111}	2000.000	2000.000	2000.000	b_{111}	1610.536	1609.811	1608.804
b_{121}	2750.000	2750.000	2750.000	b_{112}	389.464	390.189	391.196
b_{211}	340.095	340.084	340.098	b_{121}	2750.000	2750.000	2750.000
b_{212}	659.905	659.916	659.902	b_{211}	396.562	396.928	397.435
b_{311}	2378.895	2378.902	2378.893	b_{212}	603.438	603.072	602.565
b_{312}	121.105	121.098	121.107	b_{311}	2500.000	2500.000	2500.000
r_{112}	2750	2750	2750	r_{112}	2750	2750	2750
r_{131}	2750	2750	2750	r_{131}	2750	2750	2750
r_{221}	2750	2750	2750	r_{221}	2750	2750	2750

Table 11. Optimal Solutions For The Distance Between Manufacturers And Distribution Centers

Change (-%20)				Change (+%20)			
Membership Function Types				Membership Function Types			
Objective Functions	**Triangular**	**Hyperbolic**	**Exponential**	**Objective Functions**	**Triangular**	Hyperbolic	Exponential
Z_1	16294.805	16317.354	16317.612	Z_1	16182.292	16227.828	16202.053
Z_2	0.146	0.146	0.146	Z_2	0.177	0.177	0.177
λ	0.66	0.87	0.55	λ	0.69	0.90	0.59
Decision Variables				**Decision Variables**			
a_{111}	1275.893	1281.953	1282.813	a_{111}	340.974	426.092	340.176
a_{112}	274.107	468.047	467.187	a_{112}	1209.026	1323.908	1409.824
a_{121}	1000.000	1000.000	1000.000	a_{121}	1000.000	1000.000	1000.000
a_{211}	3200.000	3000.000	3000.000	a_{211}	3200.000	3000.000	3000.000
a_{231}	2500.000	2500.000	2500.000	a_{231}	2500.000	2500.000	2500.000
b_{111}	1440.125	1442.560	1442.559	b_{111}	2000.000	2000.000	2000.000
b_{112}	559.875	557.440	557.441	b_{121}	2750.000	2750.000	2750.000
b_{121}	2750.000	2750.000	2750.000	b_{211}	336.782	336.782	336.783
b_{211}	470.771	469.843	469.843	b_{212}	663.218	663.218	663.217
b_{212}	529.229	530.157	530.157	b_{311}	2380.984	2380.984	2380.984
b_{311}	2500.000	2500.000	2500.000	b_{312}	119.016	119.016	119.016
r_{112}	2750	2750	2750	r_{112}	2750	2750	2750
r_{131}	2750	2750	2750	r_{131}	2750	2750	2750
r_{221}	2750	2750	2750	r_{221}	2750	2750	2750

Table 12. Optimal Solutions For The Distance Between Distribution Centers And Costumers

Change (-%20)				Change (+%20)			
Membership Function Types				**Membership Function Types**			
Objective Functions	**Triangular**	**Hyperbolic**	**Exponential**	**Objective Functions**	**Triangular**	**Hyperbolic**	**Exponential**
Z_1	16165.714	16215.788	16187.411	Z_1	16835.169	16798.550	16835.169
Z_2	0.154	0.154	0.154	Z_2	0.166	0.166	0.166
λ	0.70	0.90	0.60	λ	0.66	0.87	0.56
Decision Variables				**Decision Variables**			
a_{111}	514.370	615.792	521.328	a_{111}	2275.423	2183.874	2275.423
a_{112}	1035.630	1134.208	1228.672	a_{121}	1000.000	1000.000	1000.000
a_{121}	1000.000	1000.000	1000.000	a_{211}	2474.577	2566.126	2474.577
a_{211}	3200.000	3000.000	3000.000	a_{231}	2500.000	2500.000	2500.000
a_{231}	2500.000	2500.000	2500.000	b_{111}	2000.000	2000.000	2000.000
b_{111}	1771.344	1770.168	1770.042	b_{121}	2750.000	2750.000	2750.000
b_{112}	228.656	229.832	229.958	b_{211}	339.980	340.095	340.040
b_{121}	2750.000	2750.000	2750.000	b_{212}	660.020	659.905	659.960
b_{211}	349.355	349.365	349.398	b_{311}	2378.968	2378.895	2378.931
b_{212}	650.645	650.635	650.602	b_{312}	121.032	121.105	121.069
b_{311}	2469.560	2470.030	2470.059	r_{112}	2750	2750	2750
b_{321}	30.440	29.970	29.941	r_{131}	2750	2750	2750
r_{112}	2750	2750	2750	r_{221}	2750	2750	2750
r_{131}	2750	2750	2750				
r_{221}	2750	2750	2750				

According to the results of the sensitivity analysis, the hyperbolic membership function provides the highest level of satisfaction in all scenarios created by the changes made in the parameters. Therefore, it is suggested that the hyperbolic membership function can be used to obtain optimal solutions for the considered FMONLP problem.

5. Result and Discussion

In this study, a green supply chain network model on the basis of transportation problem is presented. This model is remarkable because of the nonlinear structure of its constraints and considering the environmental impact factor, especially CO_2 emissions. The model is examined as a FMONLP problem in which the total transportation costs and total CO_2 emissions generated by two different vehicles during transportation are minimized. In the presented FMONLP model, the most efficient membership function is tried to be determined and tested on a numerical example.

It is found that the maximum common satisfaction level is $\lambda = 0.97$ using the hyperbolic membership function. Total transportation cost is minimized in the first objective function Z_1. The total transportation cost calculated using both triangular and exponential membership functions are $Z_1 = 16829.296$, while it is calculated as $Z_1 = 16812.158$ using the hyperbolic membership function. In the second objective function Z_2, total amount of CO_2 emission is minimized. The total CO_2 emission calculated using triangular, exponential, and hyperbolic membership functions are equal, that is, $Z_2 = 0.159$ kg.

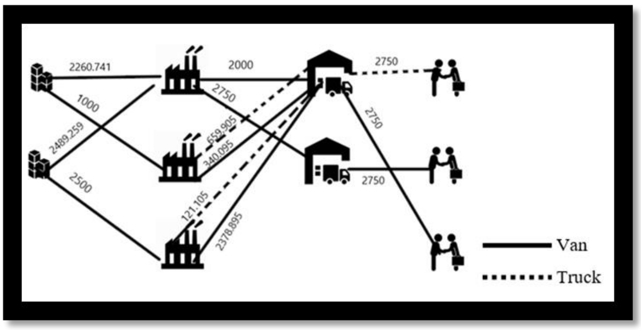

Figure 3. Optimal Distribution Network Under Triangular Membership Function

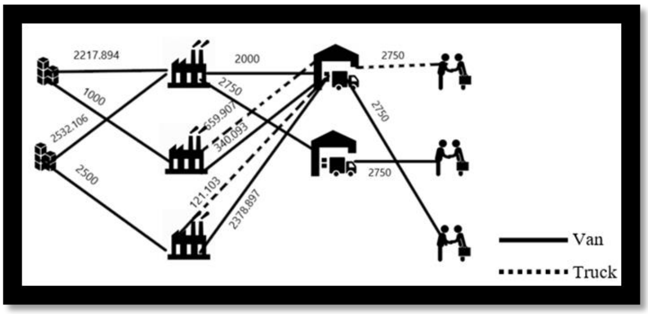

Figure 4. Optimal Distribution Network Under Hyperbolic Membership Function

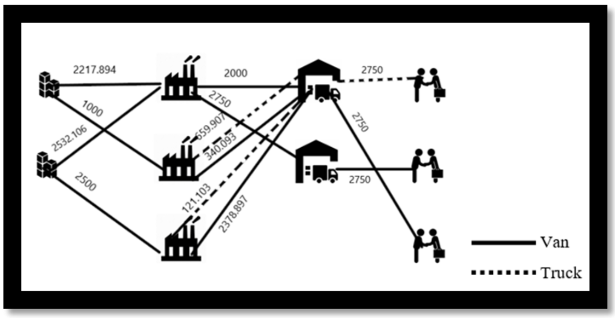

Figure 5. Optimal Distribution Network Under Exponential Membership Function

According to the results, the nonlinear hyperbolic membership function is provided a higher satisfaction level than the linear triangular membership function for the proposed FMONLP model. Sensitivity analyses are then carried out to measure the sensitivity of the model results for different parameter values for demand of customers and also distances between suppliers, manufacturers, distribution centers, and customers.
The increasing or decreasing demand of customers directly affects the satisfaction levels (λ) of the presented model. For instance, a 10% decrease in demand of customers results in 0.74, 0.94, and 0.64 for triangular, hyperbolic and exponential membership functions, respectively, while a 10% increase in demand of customers results in 0.67, 0.87, and 0.56.

On the other hand, the increasing or decreasing distances between suppliers, manufacturers, distribution centers, and customers have important effects on the satisfaction levels (λ) of the presented model. For example, a 20% decrease in distances results in 0.68, 0.90, and 0.58, for triangular, hyperbolic and exponential membership functions, respectively, while. a 20% increase in distances results in 0.70, 0.91, and 0.59. Similar results are obtained according to other changes in distances. Thus, the proposed FMONLP model with hyperbolic membership functions performs better than triangular and exponential in all of the scenarios. Although linear membership functions have been applied in real life problems due to their ease of implementation in most of the studies, it is seen that nonlinear membership functions also give good solutions.

In future studies, the proposed FMONLP model can be applied to more complicated GSCN models and it can be solved by adding various constraints and objective functions in linear or nonlinear form. FMONLP models can be compared under different nonlinear membership functions, different defuzzification techniques for fuzzy parameters or different linearization techniques. In addition, other solution methods in the literature proposed for FMOP problems can be carried out and comparisons can be made under various linear and/or nonlinear membership functions.

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Conflict of Interest

No conflict of interest was declared by the authors.

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