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A fuzzy solution approach to supplier selection and order allocation in green supply chain considering the location-routing problem

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Abstract. In the field of supply chain, selecting a suitable green supplier could significantly help us decrease the cost and risks of the operations and increase the quality of green supply. This paper develops an integrated two-stage approach based on Fuzzy Analytic Hierarchy Process (FAHP) and multi-objective mixed-integer linear programming to select suppliers and allocate order in the green supply chain. In the first stage, suppliers are evaluated using FAHP method and in the second stage, a multi-product multi-period supply chain is developed considering green location-routing problem, discounting, and time window under uncertainty. Then, a fuzzy solution approach is applied to solve the proposed model using the data of a pharmaceutical chain in Iran. Results will verify the efficiency of the proposed model.

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1. Introduction

Deteriorating effect of excessive exploitation of natural resources on the environment is one of the obvious results of growing world population. For instance, over the last few years, on average, 30000 million tons of carbon dioxide has been produced [1]. Designing a green supply chain is one of the principal approaches to alleviating the mentioned destructive effect. A green supply chain protects the environment while increasing the competitiveness of organizations through integration of financial information and logistics [2,3]. A while after the proposition of green supply chain, many organizations have prioritized environmental issues and modified their operations accordingly [3]. The first step to this end is to purchase an environmentally-friendly raw material [4]. For manufacturing companies, approximately 70% of the cost of a product is related to its raw material [5]. Therefore, pursuing purchasing strategies in green supply chain management is vital and significant.

More specifically, the concurrent selection of appropriate suppliers and satisfaction of multiple criteria such as price, quality, delivery, risk, innovation, flexibility, green, etc. have turned the purchasing procedure into a critical challenge [6].

Decision-making literature shows that considering multiple criteria that oppose each other will yield a Multiple-Criteria Decision-Making (MCDM) problem [7–10]. It is called MCDM because of the many competing criteria in the supplier selection

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problem [11,12]. Moreover, this complexity increases upon adding environmental concerns to this already complicated problem. There are numerous studies in the literature that use MCDM methods for green supplier selection and order allocation [3,13–16].

MCDM process is divided into two parts: Multiple Attribute Decision-Making (MADM) and Multiple Objective Decision-Making (MODM). In most of the studies, the MADM approach is used for supplier evaluation (with qualitative criteria) and MODM approach is used to assign order allocation and other quantitative decisions [17]. One of the widely applied MADM methods in supplier evaluations is Analytic Hierarchy Process (AHP) [18,19].

The Analytic Network Process (ANP) [20,21], the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) [22,23], Visekriterijumska Optimizacija I Kompromisno Resenje (VIKOR) [24–26], the Decision-Making Trial and Evaluation Laboratory (DEMATEL) [27,28] and the Best-Worst Method (BWM) [3] are other MADM methods adopted in the suppliers evaluation process. Also, Linear Programming (LP) [29], Mixed Integer Linear Programming (MILP) [30,31], Fuzzy Multi-Objective Linear Programming (FMOLP) [3], Multi-Objective Mixed Integer Linear Programming (MOMILP) [32], Multi-Objective Mixed Integer Non-Linear Programming (MOMINLP) [16,33], and goal programming [34] are common MODM methods. These methods have been used in the field of supplier selection and order allocation. The more we know about these methods and on how they could be combined for a specific problem, the better we conduct research in this area.

A review of the related literature shows that many studies have investigated supplier selection so far. Some of these studies have focused only on supplier selection (strategic approach), while some others have considered order allocation and supplier selection (strategic and operational approaches). Hence, this paper develops a hybrid two-stage approach based on Fuzzy Analytic Hierarchy Process (FAHP) and MOMILP for supplier selection and order allocation in green supply chain considering the location-routing problem under demand uncertainty. Therefore, the proposed model will be considered in this study in which such assumptions as multi-period, multi-product, multi-depot, capacitated and green location-routing problems, discounting on purchase, storage, shortage, and other common assumptions are included. To the best of our knowledge, it is notable that these assumptions concerning supplier selection and order allocation problem have not been simultaneously considered in any other studies so far.

In the following, Sections 2 and 3 introduce the literature review and the proposed approach, respectively. Section 4 is dedicated to the application of the proposed model to the company under study. Section 5 presents sensitivity analysis. The final section is allocated to the conclusion.

2. Literature review

The challenging competitions and globalization of today's markets have converted supplier selection to one of the most significant decisions made by decision-makers [35]. Supplier selection problem has been an enticing theme for research since 1960 [5]. There has been a wealth of review papers in this domain such as De Boer et al. [36], Aissaoui et al. [37], Ho et al. [38], Ware et al. [39], Chai et al. [40], Igarashi et al. [41], Govindan et al. [42], Zimmer et al. [43], and Keshavarz Ghorabaee et al. [44].

Studies in the field of supplier selection can be mainly divided into three categories: supplier evaluation and selection, order allocation, and combination of both [3]. In this research, the papers on the green supplier selection and order allocation are reviewed.

Mafakheri et al. [45] employed the AHP to determine criteria weights and scores for suppliers. They also used a bi-objective mathematical model and a solution approach based on dynamic programming for order allocation. The objective functions simultaneously minimize costs and maximize the purchase value. Four main criteria of price, delivery, quality, and environmental performance were defined for supplier evaluation.

Shaw et al. [46] employed a combined approach made up of FAHP and FMOLP for supplier selection and order allocation problem in order to minimize greenhouse gas emissions. They applied the model to a garment manufacturing company in India for model validation.

Kannan et al. [13] developed an integrated approach based on FAHP, Fuzzy TOPSIS (FTOPSIS), and MOLP for supplier selection and order allocation in green supply chain management. They measured the performance of each supplier based on the cost, quality, delivery, technology capability, and environmental competency criteria using a combination of FAHP and FTOPSIS methods. Then, the obtained scores were used as factors in the objective function of maximizing purchases from fitting suppliers. The other objective function was to minimize the total cost of purchasing.

Using three environmental criteria including environmental management system, pollution and greenhouse emissions, along with other criteria, Azadnia et al. [47] utilized the FAHP method to evaluate suppliers. They developed a multi-objective programming model for allocating orders to suppliers.

Govindan and Sivakumar [14] proposed an MOLP model for simultaneously minimizing costs, minimizing defective product purchases, minimizing delays in products delivery, minimizing recycling losses, and minimizing carbon emissions. They used fuzzy TOPSIS method to calculate the factors of each objective function.

An integrated approach as integration of FAHP, FTOPSIS, and multi-objective mathematical models was developed by Hamdan and Cheaitou [15]. They took into account the traditional and green criteria and quantity discount. The resulting multi-objective problem was solved using a weighted comprehensive criterion method and branch-and-cut algorithm. Similar to this approach, Hamdan and Cheaitou [48,49] integrated AHP, FTOPSIS, and multi-objective programming model approaches to solve supplier selection and order allocation problem, taking both traditional and green criteria into account.

Mohammed et al. [17] used a four-phased approach to sustainable supplier selection and order allocation. In the first phase, the weight of criteria was calculated using FAHP and in the second phase, FTOPSIS was used to calculate the scores assigned to suppliers. The third phase was devoted to the development of a multi-objective programming model and finally, in the fourth phase, the Pareto solutions were presented using the TOPSIS.

A hybrid approach based on BWM, FTOPSIS, and fuzzy multi-objective linear programming model was developed by Lo et al. [3] for selecting suppliers and allocating orders. Using BWM, they calculated the weight of the criteria and then, used FTOPSIS to rank suppliers. Finally, by using a FMOLP model, the orders were allocated to suppliers.

Babbar and Amin [50] employed an MOLP model by considering environmental issues in the supplier selection and order allocation problem. To this end, they used a novel fuzzy quality function development model to determine the weights of suppliers and then, developed a stochastic MOLP model for order allocation.

An integrated three-part approach to sustainable supplier selection and order allocation was presented by Gören [27] considering lost sales. In the first part of the proposed approach, the weights of the criteria were calculated by the fuzzy DEMATEL. The obtained weights were considered as input of the second part and the scores given for suppliers were calculated by Taguchi loss function. Finally, in the third section, the proposed order allocation method was proposed. Cheraghalipour and Farsad [30] presented a hybrid approach based on multi-criteria decision-making and the MILP model for sustainable supplier selection and order allocation. They investigated two types of discounts on purchases from suppliers and disruption risks. In their proposed approach, the economic, environmental, and social scores for each supplier were calculated using BWM and then, they were placed as purchasing objective function coefficients from sustained suppliers. In another objective function, the total cost was minimized.

3. Problem statement and proposed approach

Designing a supply chain network with regard to strategic and operational decisions is critically important. In this paper, a hybrid approach based on FAHP and MOMILP model is developed for designing a green supply chain network by considering supplier selection and order allocation problem. The proposed approach consists of two stages. In the first stage, due to the hierarchical relationship between factors and lack of interdependence among them, FAHP method is applied to the evaluation and selection of suppliers. In the next stage, an MOMILP model is developed in which such assumptions as multi-period, multi-product, multi-depot, capacitated and green location-routing problems, discounting on purchase, storage, and shortage under uncertainty are considered.

One of the benefits of the proposed approach is that the performance of each supplier affects the selection process and cost is the only factor that does not influence the selection of suppliers. One of the other benefits of the proposed approach is the possibility of designing a network from the highest level of supply chain (supplier) to the lowest level (customer) considering the real-world assumptions. This approach is explained in the following.

3.1. First stage: Supplier evaluation

At this stage, suppliers are analyzed and ranked such that the qualified suppliers can be selected. To this end, one FAHP is applied in the following manner:

Step 1: A comprehensive set of common and green criteria is derived from a review of the related literature and inclusion of experts' opinions to analyze the suppliers.

Step 2: FAHP has been used according to the experts' opinions and due to a very low degree of innerdependence between the criteria and sub-criteria and the hierarchical structure among them. Experts will conduct a pairwise comparison between factors based on the linguistic terms shown in Table 1. Once the questionnaire was filled out and the pairwise comparison matrix derived, the local weight of each factor would be calculated by a non-linear model, as explained in Eq. (1). This model was proposed by Dağdeviren and Yüksel [51].

$$\max \lambda$$

s.t.:

$$(m_{ij} - l_{ij}) \times \lambda \times w_j - w_i + l_{ij} \times w_j \leq 0,$$

Table 1. Linguistic scale for difficulty and importance.

Linguistic scales for difficulty	Linguistic scales for importance	Triangular fuzzy scale	Triangular fuzzy reciprocal scale
Just equal	Just equal	(1, 1, 1)	(1, 1, 1)
Equally difficult	Equally important	(1/2, 1, 3/2)	(2/3, 1, 2)
Weakly more difficult	Weakly more important	(1, 3/2, 2)	(1/2, 2/3, 1)
Strongly more difficult	Strongly more important	(3/2, 2, 5/2)	(2/5, 1/2, 2/3)
Very strongly more difficult	Very Strongly more important	(2, 5/2, 3)	(1/3, 2/5, 1/2)
Absolutely more difficult	Absolutely more important	(5/2, 3, 7/2)	(2/7, 1/3, 2/5)

Table 2. Linguistic values and mean of fuzzy numbers.

Linguistic values for positive sub-factors	Linguistic values for negative sub-factors	Triangular fuzzy numbers	The mean of fuzzy numbers
Very weak	Very strong	(0, 0, 0)	0
Weak	Strong	(0, 0.167, 0.333)	0.167
Weak-mid	Mid-strong	(0.167, 0.333, 0.5)	0.333
Mid	Mid	(0.333, 0.5, 0.667)	0.5
Mid-strong	Weak-mid	(0.5, 0.667, 0.833)	0.667
Strong	Weak	(0.667, 0.833, 1)	0.833
Very strong	Very weak	(1, 1, 1)	1

$$(u_{ij} - m_{ij}) \times \lambda \times w_j + w_i - u_{ij} \times w_j \leq 0,$$

$$\sum_{k=1}^{n} w_k = 1,$$

$$w_k \geq 0,$$

$$k = 1, 2, ..., n,$$

$$i = 1, 2, ..., n-1,$$

$$j = 2, 3, ..., n. \tag{1}$$

In the non-linear model, (l, m, u) represent the lowest, the most, and the largest possible values of triangular fuzzy numbers in pairwise comparisons, respectively, and w_k represents the kth criterion weight. The parameters i and j show the row and column of the pairwise comparison matrix, respectively, and n denotes the number of criteria.

The optimal value of λ may be equal to a positive or negative number. A positive λ shows consistency in the pairwise comparison matrix, whereas a negative λ shows inconsistency in pairwise comparison matrix; thereby, the experts should be warned to reconsider their judgments.

Based on the proposed model, the total weight of the criteria should be equal to 1 and the weight of each criterion should be a positive number. Also, to complete the comparison pairs matrix, only the top of the diameter should be completed, which will reduce the number of pair comparisons.

Once the model has been solved, the local weight of each of the criteria and sub-criteria can be achieved. Then, the local weight of criteria should be applied to the local weight of sub-criteria in order to determine the global weight of each sub-criterion.

Step 3: In this step, the score for each supplier in each factor needs to be determined. For this purpose, experts are asked to score the related factors in each supplier using the linguistic terms given in Table 2. The triangular fuzzy numbers equivalent to linguistic terms are used in this step, as presented in Table 2 [51].

In doing so, the average of experts' opinions is calculated for each supplier in terms of each sub-criterion. Therefore, those suppliers with acceptable scores will move on to the second stage as qualified suppliers.

3.2. Second stage: Supply chain network design

At this phase, the multi-echelon supply chain including supply, distribution, and demand is at play. To design a supply chain with maximum desirable performance, an integrated chain with a desirable performance has been decided to be designed while achieving optimal policies at a micro level, especially in the fields of supplier selection, transportation planning, location, purchase planning, etc. In addition, the optimal parameters of the mentioned system at a macro level were determined. Hence, the aim is to make a wide range of decisions including strategic policies from selecting suitable suppliers and finding suitable locations to making operational decisions such as routing of vehicles and transferred products. The assumptions about the proposed model are as follows:

Assumptions:

- The intended supply chain in this research includes supply, distribution, and demand levels;
- The supply chain considered is of multi-product and multi-period type;
- The location of distribution centers is determined by the model;
- Vehicles have been considered heterogeneous;
- The number and capacity of vehicles used for transportation are determined;
- The time needed for the movement of vehicles is absolutely predetermined;
- The storage has been considered in the model;
- The vehicles routing problem lies between distribution and demand levels;
- The routing problem has been considered to be multi-depot;
- Taking the purchasing discount from suppliers has been considered;
- The rate of demand has been considered to be fuzzy;
- Time windows constraint has been considered in the proposed model;
- It is possible to encounter shortages that are considered as lost demand.

The following is a description of the proposed model:

Indices:

i	Product $(1 \leq i \leq I)$
s	Supplier $(1 \leq s \leq S)$
d	Distribution center $(1 \leq d \leq D)$
$c, \hat{c}$	Customer $(1 \leq c \leq C)$
k	Price level $(1 \leq k \leq K)$
ν	Vehicle $(1 \leq v \leq V)$
t	Time period $(1 \leq t \leq T)$

Parameters:

cp_{pat}^{sup}	Capacity of supplier a for product p in time period t
cp_{pbt}^{dst}	Capacity of distribution center b for product p in time period t
$cp_{m}^{\nu h}$	Capacity of vehicle ν
flw_{pab}	Maximum shipment flow of product p from supplier a to distribution center b
ds_{ij}^{cs}	Location distance of customer i from customer j
tm_{mij}^{cs}	Time distance of customer i from customer j by vehicle m
ds_{bj}	Location distance of distribution center b from customer j
tm_{mbj}	Time distance of distribution center b from customer j by vehicle m
cst_{b}^{dst}	Setup cost of distribution center b
cst_{m}^{vh}	Supply cost of vehicle m
cst_{padt}^{trn}	Transportation cost of each unit of product p from supplier a to distribution center b in time period t
dm_{pjt}	Demand of customer j for product p in time period t
hld_{pt}	Holding cost of each unit of product p in time period t
f_m	Fuel consumption of vehicle m per unit of distance
w_a	Weight (green score) of supplier a (achieved from FAHP)
prc_{plat}	Purchase price per unit of product p from supplier a at price level l in time period t
ord_{at}	Ordering cost to supplier a in time period t
A_{plat}	The upper bound volume of purchased product p from supplier a in time period t at price level l
φ	Time window
c^{fuel}	Price per unit of fuel
$bigm \sim \infty$	Big number

Variables:

$$x_b^{dst} \begin{cases} 1 & \text{If distribution center } b \text{ is launched} \\ 0 & \text{Otherwise} \end{cases}$$

$$x_m^{\nu h} \begin{cases} 1 & \text{If vehicle } m \text{ is supplied} \\ 0 & \text{Otherwise} \end{cases}$$

$$x_{mijt}\begin{cases}1 & \text{If vehicle } m \text{ moves from customer}\\ & \text{to customer } j \text{ in time period } t\\ 0 & \text{Otherwise}\end{cases}$$

$$y_{mb}\begin{cases}1 & \text{If vehicle } \nu \text{ is allocated to}\\ & \text{distribution center } d \text{ in time period } t\\ 0 & \text{Otherwise}\end{cases}$$

$$x^{sup}_{plat}\begin{cases}1 & \text{If product } p \text{ supplied from supplier}\\ & a \text{ at price level } l \text{ in time period } t\\ 0 & \text{Otherwise}\end{cases}$$

at_{mjt} Arrival time of vehicle m to location of customer j in time period t (Positive)

$invtry^{p}_{pjt}$ The number of products p available in the stock of customer j in time period t (Positive)

$invtry^{n}_{pjt}$ The amount of shortage of product p for customer j in time period t (Positive)

$invtry_{pjt}$ Inventory (Free)

z_{pmbjt} The number of products p transferred from distribution center b by vehicle m to customer j in time period t (Positive)

θ_{plabt} The number of products p purchased from supplier a by distribution center b at the price level l in time period t (Positive)

Mathematical model

Objective function

$$\begin{aligned}\min Z^{cost} =& c^{fuel} \times f_m \times \Big(\sum_{m,i>1,j>1,t} x_{mijt} \times ds^{cs}_{ij} + \sum_{m,b,j,t} (x_{m1jt} + x_{mj1t})\\ &\times y_{mb} \times ds_{bj}\Big) + \sum_{p,l,a,b,t} \theta_{plabt} \times cst^{trn}_{padt}\\ &+ \sum_{m} x^{\nu h}_{m} \times cst^{\nu h}_{m} + \sum_{p,j,t} hld_{pt} \times invtry^{p}_{pjt} + \sum_{p,l,a,b,t} prc_{plat} \times \theta_{plabt}\\ &+ \sum_{p,l,a,t} ord_{at} \times x^{sup}_{plat} + \sum_{b} cst^{dst}_{b} \times x^{dst}_{b}. \quad (2)\end{aligned}$$

First objective function: Minimizing the total costs of chain. These costs include transportation cost, the cost of holding products in the customer's stock, product supply cost, and distribution center location cost.

$$\max Z^{purchase\,value} = \sum_{p,l,a,b,t} w_a \times \theta_{plabt}. \quad (3)$$

Second objective function: Maximizing the value of purchases from qualified suppliers.

Subjected to:

$$\sum_{l,b} \theta_{plabt} \leq cp^{sup}_{pat} \qquad \forall p, a, t, \quad (4)$$

$$\sum_{l,a} \theta_{plabt} \leq cp^{dst}_{pbt} \qquad \forall p, b, t, \quad (5)$$

$$\sum_{l,a,b} \theta_{plabt} \leq \sum_{a,b} flw_{pab} \qquad \forall p, t. \quad (6)$$

Non-exceedance of supplier capacity, distribution center capacity, and product flow capacity among them are represented in Constraints (4) to (6), respectively.

$$\sum_{p,j} z_{pmbjt} \leq cp^{\nu h}_{m} \qquad \forall m, b, t. \quad (7)$$

Constraint (7) states that the number of products delivered by a vehicle should not exceed the capacity.

$$\sum_{l,a} \theta_{plabt} \geq \sum_{m,j} z_{pmbjt} \qquad \forall p, b, t. \quad (8)$$

The total number of products delivered from suppliers to distribution centers in each period should not be less than that of the products delivered from centers to customers, as explained in Constraint (8).

$$\sum_{p,b,j} z_{pmbjt} \leq bigm \times \sum_{b} y_{mb} \qquad \forall m, t, \quad (9)$$

$$\sum_{b} y_{mb} \leq 1 \qquad \forall m. \quad (10)$$

According to Constraint (9), products are delivered to customers by vehicles provided that the vehicle is allocated to one distribution center. According to Constraint (10), each vehicle is allocated to only one distribution center.

$$\sum_{m} y_{mb} \leq bigm \times x^{dst}_{b} \qquad \forall b. \quad (11)$$

According to Constraint (11), a vehicle cannot be allocated to the distribution center unless the center has been located.

$$\sum_{m,i} x_{mijt} \leq 1 \qquad \forall j, t. \quad (12)$$

Each customer can be visited only by one vehicle, as shown in Constraint (12).

$$\sum_i x_{mijt} = \sum_i m_{mjit} \qquad \forall m, j, t. \tag{13}$$

According to Constraint (13), if we enter one customer location, we should exit.

$$at_{mjt} + bigm \times (1 - x_{mijt}) \geq (at_{mit} + tm^{cs}_{mij}) \qquad \forall m, i, j > 1, t, \tag{14}$$

$$\varphi + bigm \times (1 - x_{mj1t}) \geq at_{mjt} + \sum_b tm_{mbj} \times y_{mb} \qquad \forall m, j, t. \tag{15}$$

Sub-tour elimination constraint and arrival time to each customer location are calculated using Constraints (14) and (15). Also, Constraint (15) shows the non-exceedance of time window for perishable products.

$$\sum_{p,b} z_{pmbjt} \leq bigm \times \sum_i x_{mijt} \qquad \forall m, j, t, \tag{16}$$

$$\sum_{p,b,j} z_{pmbjt} \leq bigm \times x^{\nu h}_m \qquad \forall m, t. \tag{17}$$

The product will be delivered to the customers if and only if the vehicle visits them and that the vehicle has already been supplied. This issue is justified in Constraints (16) and (17), respectively.

$$invtry_{pjt} = \sum_{m,b} z_{pmbjt} + invtry_{pj(t-1)} - dm_{pjt} \qquad \forall p, j, t > 1, \tag{18}$$

$$invtry_{pjt} = \sum_{m,b} z_{pmbjt} - dm_{pjt} \qquad \forall p, j, t = 1. \tag{19}$$

Constraints (18) and (19) are related to stock balance in customers' warehouses.

$$invtry_{pjt} = invtry^p_{pjt} - invtry^n_{pjt} \qquad \forall p, j, t. \tag{20}$$

Determining inventory and dealing with shortages are done in Constraint (20).

$$\sum_{m,b,t} z_{pmbjt} = \sum_t dm_{pjt} \qquad \forall p, j. \tag{21}$$

Constraint (21) enforces the model to meet all demands from customers at the end of the final period. Hence, it does not allow a lost demand to occur.

$$\theta_{plabt} + bigm \times (1 - x^{sup}_{plat}) \geq A_{plat} \qquad \forall p, l, a, b, t, \tag{22}$$

$$\theta_{plabt} \leq A_{p(l+1)at} + bigm \times (1 - x^{sup}_{plat}) \qquad \forall p, l, a, b, t. \tag{23}$$

Constraints (22) and (23) are applied in the step pertaining to discount on purchasing products from suppliers.

$$\sum_l x^{sup}_{plat} \leq 1 \qquad \forall p, a, t. \tag{24}$$

Finally, Constraint (24) indicates that it is possible to purchase products from each supplier in each time period at only one price level.

3.2.1. Linearization process

In order to apply the linearization process, the following auxiliary variables are defined based on which the linear equivalents are presented for each nonlinear phrase [52]:

$$xy_{mbijt} \begin{cases} 1 \\ 0 \end{cases} \qquad \text{Binary}$$

Nonlinear equation:

$$\begin{aligned} \min \ Z^{cost} = & c^{fuel} \times f_m \times \Bigg(\sum_{m,i>1,j>1,t} x_{mijt} \times ds^{cs}_{ij} + \sum_{m,b,j,t} (x_{m1jt} + x_{mj1t}) \\ & \times y_{mb} \times ds_{bj} \Bigg) + \sum_{p,l,a,b,t} \theta_{plabt} \times cst^{trn}_{padt} \\ & + \sum_m x^{\nu h}_m \times cst^{\nu h}_m + \sum_{p,j,t} hld_{pt} \times invtry^p_{pjt} \\ & + \sum_{p,l,a,b,t} prc_{plat} \times \theta_{plabt} + \sum_{p,l,a,t} ord_{at} \\ & \times x^{sup}_{plat} + \sum_b cst^{dst}_b \times x^{dst}_b. \end{aligned} \tag{25}$$

Linear equation:

$$\begin{aligned} \min \ Z^{cost} = & c^{fuel} \times f_m \times \Bigg(\sum_{m,i>1,j>1,t} x_{mijt} \times ds^{cs}_{ij} \\ & + \sum_{m,b,j,t} (xy_{mb1jt} + xy_{mbj1t}) \times ds_{bj} \Bigg) \\ & + \sum_{p,l,a,b,t} \theta_{plabt} \times cst^{trn}_{padt} + \sum_m x^{\nu h}_m \end{aligned}$$

$$\times cst_m^{\nu h} + \sum_{p,j,t} hld_{pt} \times invtry_{pjt}^p + \sum_{p,l,a,b,t} prc_{plat} \times \theta_{plabt} + \sum_{p,l,a,t} ord_{at} \times x_{plat}^{sup} + \sum_b cst_b^{dst} \times x_b^{dst}, \tag{26}$$

$$xy_{mbijt} \leq y_{mb} + (1 - x_{mijt}) \times bigm, \tag{27}$$

$$xy_{mbijt} \leq x_{mijt} + (1 - y_{mb}) \times bigm, \tag{28}$$

$$xy_{mbijt} \geq 1 + (x_{mijt} + y_{mb} - 2) \times bigm, \tag{29}$$

$$xy_{mbijt} \leq (x_{mijt} + y_{mb}) \times bigm. \tag{30}$$

3.3. Solution approach

Among different approaches used for dealing with uncertainty in optimization problems, Fuzzy Theory is the most popular method [53]. Depending on the specification of a given problem, different fuzzy approaches have been developed in literature [54–58]. The method which was developed by Zimmermann [54] and Lin [56] allows converting a multi-objective problem to a single-objective problem considering the uncertainty in the objective function and constraint. The solution approach is presented as follows:

$$\begin{aligned} &\max \alpha \\ &\text{S.t.}: \\ &\alpha \leq \mu_{z_k^{\min}}(x), \\ &\alpha \leq \mu_{z_r^{\max}}(x), \\ &\alpha \leq \mu_{g_l}(x). \end{aligned} \tag{31}$$

These membership functions are defined as follows:

$$\mu_{Z_k^{\min}}(x) = \begin{cases} 1 & z_k(x) > z_k^{\text{positive}} \\ 0 & z_k(x) < z_k^{\text{negative}} \\ f_{\mu_{Z_k^{\min}}} = \frac{z_k^{\text{positive}} - z_k(x)}{z_k^{\text{positive}} - z_k^{\text{negative}}}, & z_k^{\text{negative}} \leq z_k(x) \leq z_k^{\text{positive}} \end{cases}$$

$$\mu_{Z_l^{\min}}(x) = \begin{cases} 1 & z_l(x) > z_l^{\text{positive}} \\ 0 & z_l(x) < z_l^{\text{negative}} \\ f_{\mu_{Z_l^{\min}}} = \frac{z_l(x) - z_l^{\text{negative}}}{z_l^{\text{positive}} - z_l^{\text{negative}}}, & z_l^{\text{negative}} \leq z_l(x) \leq z_l^{\text{positive}} \end{cases}$$

$$\mu_{g_l}(x) = \begin{cases} 1 & g_l(x) > b_l \\ 0 & g_l(x) < b_l + d_l \\ f_{Z_l^{\max}} = \frac{1 - [g_l(x) - b_l]}{d_l}, & b_l \leq g_l(x) \leq b_l + d_l \end{cases}$$

where the value of the objective function $z_k(z_l)$ varies from the lower bound z_k^{negative} (z_l^{negative}) to upper bound z_k^{positive} (z_l^{positive}); $\mu_{z_k^{\min}}(x)$, $\mu_{z_r^{\max}}(x)$ and $\mu_{g_l}(x)$ represent the membership functions of maximum, minimum, and constraints, respectively. b_l and d_l are the lth crisp or fuzzy value and a tolerance value, respectively.

4. Case study

Pharmaceutical Distribution Companies are active in the areas of the supply and distribution of human pharmaceuticals, purchase and sale of human pharmaceuticals, medical equipment, import and export of human pharmaceuticals, investment in the manufacturing, distribution of human pharmaceuticals, etc. The main objectives of such companies are providing the required human pharmaceuticals both in Iran and the region, improving customers' and shareholders' satisfaction, promoting the distribution quality of pharmaceuticals, and increasing the company's share in the local provision and supply of human pharmaceuticals.

In this paper, the proposed model has been applied to assess the effectiveness and validation of a pharmaceutical company in the city of Tehran. The studied company produces and distributes more than 20 types of drugs. Three drugs are produced by the same production line and hence, hold similar data. Because of this similarity, these three drugs have been chosen for the study. Using expert opinion and the availability of the chain data under study, we implemented the model for 3 perishable goods, 6 suppliers, 3 distribution center locations, 3 vehicles, 4 price levels, and 6 time periods. The stages required for the implementation are as follows:

4.1. First stage: Supplier evaluation

4.1.1. Step 1:

In this step, the criteria and sub-criteria for supplier evaluation and selection were extracted based on a review of the related literature and experts' experiences in the chain under study. To this end, three criteria, namely greenness, quality, and delivery and service were selected. The sub-criteria under these three criteria are given in Table 3.

4.1.2. Step 2:

According to experts' opinions, given the low level of inner-dependence among the criteria, FAHP was

Table 3. Criteria and sub-criteria for supplier evaluation.

Criteria	Sub-criteria	References
Green	Environmental management system (G1)	Luthra et al. [59], Fallahpour et al. [60]
	Green packaging (G2)	Fallahpour et al. [60], Büyüközkan and Çifçi [61]
	Hazardous wastes (G3)	Kannan et al. [62]
	Green technology (G4)	Fallahpour et al. [60]
	Green design and purchasing (G5)	Luthra et al. [59]
	Air emission (G6)	Mina et al. [20], Noci [63], Humphreys et al. [64], Lee et al. [65]
	Eco-design (G7)	Fallahpour et al. [60], Handfield et al. [66]
Quality	Quality of product (Q1)	Luthra et al. [59]
	Capability of handling abnormal quality (Q2)	Lee et al. [65]
	Product rejection rate (Q3)	Feyziogğlu and Büyüközkan [67]
Delivery and service	On-time delivery (D1)	Mina et al. [20], Luthra et al. [59]
	Lead time flexibility (D2)	Fallahpour et al. [60], Yang and Wu [68]
	Time to solve the complaint (D3)	Fallahpour et al. [60], Yang and Wu [68]

Table 4. Pairwise comparison matrix among criteria.

Criteria	Green	Quality	Delivery and service
Green	(1, 1, 1)	(1/2, 2/3, 1)	(1/2, 2/3, 1)
Quality	(1, 3/2, 2)	(1, 1, 1)	(1, 1, 1)
Delivery and service	(1, 3/2, 2)	(1, 1, 1)	(1, 1, 1)

applied to determine their weights. Therefore, the local weights of all criteria and sub-criteria were determined using the proposed nonlinear model, as in the pairwise table filled out by experts with linguistic terms (Table 1).

The results obtained from the substitution of triangular fuzzy numbers for linguistic terms in pairwise comparisons are given in Tables 4 to 7.

In order to calculate the local weights of criteria and sub-criteria, the nonlinear model of Dağdeviren and Yüksel [51] and the pairwise comparison data are used as the parameters. For example, the nonlinear model is converted into the following form using the data given in Table 4. Thus, criteria weights are obtained by solving the model in GAMS24.1/CONOPT.

$$\max\ \lambda$$

$$s.t.:$$

$$\frac{1}{6}\times\lambda\times w_2-w_1+\frac{1}{2}\times w_2\leq 0,$$

$$\frac{1}{3}\times\lambda\times w_2+w_1-w_2\leq 0,$$

Table 5. Pairwise comparison matrix among green sub-criteria.

Green sub-criteria	G1	G2	G3	G4	G5	G6	G7
G1	(1,1,1)	(1,3/2,2)	(1,3/2,2)	(1/2,1,3/2)	(1/2,1,3/2)	(1,3/2,2)	(3/2,2,5/2)
G2	(1/2,2/3,1)	(1,1,1)	(1,3/2,2)	(1/2,2/3,1)	(1,3/2,2)	(1,3/2,2)	(3/2,2,5/2)
G3	(1/2,2/3,1)	(1/2,2/3,1)	(1,1,1)	(1/2,2/3,1)	(1/2,2/3,1)	(1,3/2,2)	(3/2,2,5/2)
G4	(2/3,1,2)	(1,3/2,2)	(1,3/2,2)	(1,1,1)	(1/2,2/3,1)	(1,3/2,2)	(3/2,2,5/2)
G5	(2/3,1,2)	(1/2,2/3,1)	(1,3/2,2)	(1,3/2,2)	(1,1,1)	(1,3/2,2)	(1,3/2,2)
G6	(1/2,2/3,1)	(1/2,2/3,1)	(1/2,2/3,1)	(1/2,2/3,1)	(1/2,2/3,1)	(1,1,1)	(1/2,1,3/2)
G7	(2/5,1/2,2/3)	(2/5,1/2,2/3)	(2/5,1/2,2/3)	(2/5,1/2,2/3)	(1/2,2/3,1)	(2/3,1,2)	(1,1,1)

Table 6. Pairwise comparison matrix among quality sub-criteria.

Quality sub-criteria	Q1	Q2	Q3
Q1	(1, 1, 1)	(2/3, 1, 2)	(1/2, 1, 3/2)
Q2	(1/2, 1, 3/2)	(1, 1, 1)	(1, 3/2, 2)
Q3	(2/3, 1, 2)	(1/2, 2/3, 1)	(1, 1, 1)

Table 7. Pairwise comparison matrix among delivery and service sub-criteria.

Delivery and service sub-criteria	D1	D2	D3
D1	(1, 1, 1)	(1, 3/2, 2)	(3/2, 2, 5/2)
D2	(1/2, 2/3, 1)	(1, 1, 1)	(2/3, 1, 2)
D3	(2/5, 1/2, 2/3)	(1/2, 1, 3/2)	(1, 1, 1)

Table 8. Local weights of criteria and sub-criteria and global weights of sub-criteria.

Criteria (local weight)	Sub-criteria	Local weight	Global weight
Green (0.25)	G1	0.204	0.051
	G2	0.148	0.037
	G3	0.14	0.035
	G4	0.148	0.037
	G5	0.148	0.037
	G6	0.123	0.03075
	G7	0.09	0.0225
Quality (0.375)	Q1	0.335	0.125625
	Q2	0.379	0.142125
	Q3	0.286	0.10725
Delivery and service (0.375)	D1	0.465	0.174375
	D2	0.291	0.109125
	D3	0.244	0.0915

$$\frac{1}{6} \times \lambda \times w_3 - w_1 + \frac{1}{2} \times w_3 \leq 0,$$

$$\frac{1}{3} \times \lambda \times w_3 + w_1 - w_3 \leq 0,$$

$$-w_2 + w_3 \leq 0, \qquad w_2 - w_3 \leq 0,$$

$$w_1 + w_2 + w_3 = 1.$$

Therefore, the local weights of all criteria and sub-criteria are calculated and the results are shown in Table 8. In order to obtain global weights of the sub-criteria, local weights of criteria are applied in local weights of their sub-criteria. The results are given in Table 8.

4.1.3. Step 3:

In this step, suppliers are individually evaluated in

Table 9. The final score of suppliers.

Supplier	**Supplier 1**	**Supplier 2**	**Supplier 3**	**Supplier 4**	**Supplier 5**	**Supplier 6**
Final score	0.608558	0.558433	0.516702	0.620516	0.474682	0.487581

Table 10. Customers demand per time period.

dm_{pjt}		$t=1$	$t=2$	$t=3$	$t=4$	$t=5$	$t=6$
$i=1$	$c=1$	300	300	500	300	800	400
$i=1$	$c=2$	700	300	800	600	700	700
$i=1$	$c=3$	600	500	400	900	400	500
$i=1$	$c=4$	400	900	500	300	700	400
$i=1$	$c=5$	600	400	400	80	400	300
$i=1$	$c=6$	800	800	800	900	500	300
$i=2$	$c=1$	800	400	400	900	700	300
$i=2$	$c=2$	600	600	700	400	500	600
$i=2$	$c=3$	800	400	500	300	900	500
$i=2$	$c=4$	500	900	600	800	800	900
$i=2$	$c=5$	900	700	300	500	400	700
$i=2$	$c=6$	700	800	400	600	400	600
$i=3$	$c=1$	700	300	400	900	700	800
$i=3$	$c=2$	500	400	700	700	500	300
$i=3$	$c=3$	900	800	900	500	500	900
$i=3$	$c=4$	500	900	900	400	300	300
$i=3$	$c=5$	700	900	400	300	600	500
$i=3$	$c=6$	300	800	500	900	500	400

terms of each sub-criterion. To this end, experts are asked to score each supplier on each sub-criterion by using linguistic terms of Table 2. The results of the final score are given in Table 9.

According to the experts' opinions, the supplier who obtains the least score of 0.5 should enter the second stage as a qualified supplier. Thus, suppliers 1, 2, 3, and 4 will be selected as qualified suppliers.

4.2. Second stage: Supply chain network design

This subsection consists of three parts. In the first part, data gathering will be dealt with and some of the most important parameters will be presented. In the second part, the proposed solution approach is applied and the single-objective fuzzy model is presented. The third part is dedicated to results and discussions.

4.2.1. Data gathering

In this part, some of the parameters corresponding to the case study are presented. Three perishable products, four selected suppliers, three potential distribution centers, four price levels, six customers, and six time periods are considered in validating the proposed model. Tables 10 to 12 show the most important parameters of the case study.

4.2.2. Applying the solution approach

In this section, by using the solution approach presented by Zimmermann [54] and Lin [56], the proposed model will be transformed into a single-objective model under uncertain demand. In doing so, the upper and lower bounds of each objective function are calculated as follows:

$$z_1^{\text{negative}} = 0,$$

$$z_2^{\text{negative}} = 0,$$

$$z_1^{\text{positive}} = 994703700,$$

$$z_2^{\text{positive}} = 2943.$$

Table 11. Transportation cost between suppliers and distribution centers.

$\boldsymbol{cst^{trn}_{padt}}$		$i=1$	$i=1$	$i=1$	$i=1$	$i=2$	$i=2$	$i=2$	$i=2$	$i=3$	$i=3$	$i=3$	$i=3$
		$s=1$	$s=2$	$s=3$	$s=4$	$s=1$	$s=2$	$s=3$	$s=4$	$s=1$	$s=2$	$s=3$	$s=4$
$d=1$	$t=1$	690	680	860	820	760	780	690	610	760	760	600	630
$d=1$	$t=2$	660	730	880	890	660	650	830	840	580	800	590	620
$d=1$	$t=3$	580	700	840	590	640	870	680	890	550	810	840	630
$d=1$	$t=4$	640	830	840	870	560	560	880	630	780	600	560	660
$d=1$	$t=5$	620	760	740	660	710	670	780	710	600	850	730	830
$d=1$	$t=6$	630	810	700	760	760	560	770	810	680	640	690	840
$d=2$	$t=1$	870	770	780	740	670	730	840	690	790	610	560	810
$d=2$	$t=2$	760	550	600	630	640	630	900	860	890	600	800	700
$d=2$	$t=3$	740	830	550	820	670	760	700	590	600	560	720	550
$d=2$	$t=4$	620	800	750	740	720	890	560	900	830	790	660	870
$d=2$	$t=5$	650	860	570	890	740	620	730	790	570	830	880	700
$d=2$	$t=6$	890	860	590	690	770	870	690	550	890	790	860	610
$d=3$	$t=1$	740	890	700	810	830	810	870	770	770	880	660	690
$d=3$	$t=2$	690	800	780	590	890	650	580	710	710	780	730	850
$d=3$	$t=3$	670	830	860	670	870	650	660	860	720	640	780	660
$d=3$	$t=4$	840	810	580	760	870	770	810	800	880	740	740	570
$d=3$	$t=5$	550	630	800	600	770	890	780	660	650	640	680	670
$d=3$	$t=6$	680	600	620	670	720	800	690	750	800	850	850	600

Table 12. Time distance between distribution centers and customers (minute).

$\boldsymbol{tm_{mbj}}$		$\boldsymbol{j=1}$	$\boldsymbol{j=2}$	$\boldsymbol{j=3}$	$\boldsymbol{j=4}$	$\boldsymbol{j=5}$	$\boldsymbol{j=6}$
$m=1$	$b=1$	0	36	41	30	33	43
$m=1$	$b=2$	0	38	45	31	36	40
$m=1$	$b=3$	0	34	39	30	32	39
$m=2$	$b=1$	0	25	38	26	32	24
$m=2$	$b=2$	0	19	42	25	31	27
$m=2$	$b=3$	0	25	33	19	28	22
$m=3$	$b=1$	0	23	19	27	22	34
$m=3$	$b=2$	0	23	42	31	35	27
$m=3$	$b=3$	0	31	45	33	37	41

Based on the upper and lower bounds of the objective functions, the membership functions of the first and second objective functions are calculated as follows:

$$\mu_{Z^{\text{cost}}} = \frac{994703700 - Z^{\text{cost}}}{994703700}, \tag{32}$$

$$\mu_{Z^{\text{purchase value}}} = \frac{Z^{\text{purchase value}}}{2943}. \tag{33}$$

Considering 10% of the violations for demand, the membership functions for Constraints (18), (19), and (21) are given as follows:

$$\mu^{+}_{18} = \frac{1.1 \times dm_{pjt} - \sum_{m,b} z_{pmbjt} - invtry_{pj(t-1)} + invtry_{pjt}}{0.1 \times dm_{pjt}} \quad \forall p, j, t > 1, \tag{34}$$

$$\mu^{-}_{18} = \frac{\sum_{m,b} z_{pmbjt} + invtry_{pj(t-1)} - invtry_{pjt} - 0.9 \times dm_{pjt}}{0.1 \times dm_{pjt}} \quad \forall p, j, t > 1, \tag{35}$$

$$\mu^{+}_{19} = \frac{1.1 \times dm_{pjt} - \sum_{m,b} z_{pmbjt} + invtry_{pjt}}{0.1 \times dm_{pjt}} \quad \forall p, j, t = 1, \tag{36}$$

$$\mu^{-}_{19} = \frac{\sum_{m,b} z_{pmbjt} - invtry_{pjt} - 0.9 \times dm_{pjt}}{0.1 \times dm_{pjt}}, \quad \forall p, j, t = 1 \tag{37}$$

$$\mu^{+}_{21} = \frac{1.1 \times \sum_{t} dm_{pjt} - \sum_{m,b,t} z_{pmbjt}}{0.1 \times \sum_{t} dm_{pjt}} \qquad \forall p, j, \tag{38}$$

$$\mu^{-}_{21} = \frac{\sum_{m,b,t} z_{pmbjt} - 0.9 \times \sum_{t} dm_{pjt}}{0.1 \times \sum_{t} dm_{pjt}} \qquad \forall p, j. \tag{39}$$

Thus, the fuzzy single-objective mathematical model is as follows:

Mathematical model:

Objective function

$$\max \alpha \tag{40}$$

s.t.:

$$\mu_{Z^{cost}} = \frac{994703700 - Z^{cost}}{994703700} \geq \alpha, \tag{41}$$

$$\mu_{Z^{purchase\ value}} = \frac{Z^{purchase\ value}}{2943} \geq \alpha, \tag{42}$$

$$\mu^{+}_{z_{dm}} = \frac{1.1 \times dm_{pjt} - \sum_{m,b} z_{pmbjt} - invtry_{pj(t-1)} + invtry_{pjt}}{0.1 \times dm_{pjt}} \geq \alpha \qquad \forall p, j, t > 1, \tag{43}$$

$$\mu^{-}_{z_{dm}} = \frac{\sum_{m,b} z_{pmbjt} + invtry_{pj(t-1)} - invtry_{pjt} - 0.9 \times dm_{pjt}}{0.1 \times dm_{pjt}} \geq \alpha \qquad \forall p, j, t > 1, \tag{44}$$

$$\mu^{+}_{z_{dm}} = \frac{1.1 \times dm_{pjt} - \sum_{m,b} z_{pmbjt} + invtry_{pjt}}{0.1 \times dm_{pjt}} \geq \alpha \quad \forall p, j, t = 1, \tag{45}$$

$$\mu^{-}_{z_{dm}} = \frac{\sum_{m,b} z_{pmbjt} - invtry_{pjt} - 0.9 \times dm_{pjt}}{0.1 \times dm_{pjt}} \geq \alpha \quad \forall p, j, t = 1, \tag{46}$$

$$\mu^{+}_{21} = \frac{1.1 \times \sum_{t} dm_{pjt} - \sum_{m,b,t} z_{pmbjt}}{0.1 \times \sum_{t} dm_{pjt}} \qquad \forall p, j, \tag{47}$$

$$\mu^{-}_{21} = \frac{\sum_{m,b,t} z_{pmbjt} - 0.9 \times \sum_{t} dm_{pjt}}{0.1 \times \sum_{t} dm_{pjt}} \qquad \forall p, j. \tag{48}$$

During these changes, the objective functions and Constraints (18), (19), and (21) are considered fuzzy and the other constraints are used without any change; of course, they have been excluded here to avoid duplication.

4.2.3. Results and discussion

A fuzzy single-objective model was applied to the described case study in GAMS software and CPLEX solver. Based on the obtained results, all four suppliers were chosen to purchase the products from; only the distribution center number 3 was established and then, vehicle 3 was purchased. The values of the objective functions and the maximum fuzzy membership function are reported in Table 13.

One of the operational decisions that makes a significant contribution to distribution of products, particularly perishable products, is the routing of vehicles taken for serving customers. As stated, the model only uses the vehicle number 3 to distribute its products. The route traveled by this vehicle in different

Table 13. Objective functions value.

α	Z^{cost}	$Z^{\text{purchasing value}}$
0.4444	553894500	1835.45

$at_{3,5,1} = 37$, $at_{3,4,1} = 83$, $at_{3,3,1} = 123$, $at_{3,2,1} = 161$, $at_{3,6,2} = 41$, $at_{3,4,2} = 65$, $at_{3,5,2} = 109$,
$at_{3,3,2} = 129$, $at_{3,2,2} = 167$, $at_{3,2,3} = 31$, $at_{3,3,3} = 68$, $at_{3,5,3} = 88$, $at_{3,6,3} = 116$, $at_{3,5,4} = 37$,
$at_{3,4,4} = 83$, $at_{3,6,4} = 128$, $at_{3,3,4} = 157$, $at_{3,2,4} = 195$, $at_{3,4,5} = 33$, $at_{3,6,5} = 80$, $at_{3,5,5} = 108$,
$at_{3,3,5} = 128$, $at_{3,2,5} = 166$, $at_{3,6,6} = 41$, $at_{3,5,6} = 48$, $at_{3,2,6} = 82$.

Box I

$\theta_{11235} = 300$, $\theta_{11336} = 350$, $\theta_{11435} = 400$, $\theta_{12133} = 600$, $\theta_{12236} = 500$, $\theta_{12331} = 500$,
$\theta_{12436} = 600$, $\theta_{13134} = 600$, $\theta_{13135} = 700$, $\theta_{13136} = 750$, $\theta_{13231} = 700$, $\theta_{13233} = 650$,
$\theta_{13234} = 600$, $\theta_{13332} = 550$, $\theta_{13333} = 700$, $\theta_{13431} = 750$, $\theta_{22133} = 600$, $\theta_{22236} = 400$,
$\theta_{22432} = 400$, $\theta_{22435} = 650$, $\theta_{23132} = 550$, $\theta_{23235} = 660$, $\theta_{23231} = 800$, $\theta_{23232} = 800$,
$\theta_{23333} = 700$, $\theta_{23332} = 700$, $\theta_{23335} = 800$, $\theta_{23431} = 750$, $\theta_{23434} = 800$, $\theta_{23432} = 700$,
$\theta_{23435} = 700$, $\theta_{23436} = 800$, $\theta_{33131} = 700$, $\theta_{33132} = 700$, $\theta_{33135} = 700$, $\theta_{33134} = 750$,
$\theta_{33231} = 800$, $\theta_{33233} = 650$, $\theta_{33235} = 700$, $\theta_{33332} = 700$, $\theta_{33333} = 700$, $\theta_{33335} = 800$,
$\theta_{33431} = 750$, $\theta_{33433} = 650$, $\theta_{33432} = 700$, $\theta_{33434} = 800$, $\theta_{33435} = 700$, $\theta_{33436} = 800$.

Box II

time periods is given below:

$$t = 1 \quad (\hat{c} \to c) : c_1 \to c_5 \to c_4 \to c_3 \to c_2 \to c_1,$$

$$t = 2 \quad (\hat{c} \to c) : c_1 \to c_6 \to c_4 \to c_5 \to c_3 \to c_2 \to c_1,$$

$$t = 3 \quad (\hat{c} \to c) : c_1 \to c_2 \to c_3 \to c_5 \to c_6 \to c_1,$$

$$t = 4 \quad (\hat{c} \to c) : c_1 \to c_5 \to c_4 \to c_6 \to c_3 \to c_2 \to c_1,$$

$$t = 5 \quad (\hat{c} \to c) : c_1 \to c_4 \to c_6 \to c_5 \to c_3 \to c_2 \to c_1,$$

$$t = 6 \quad (\hat{c} \to c) : c_1 \to c_6 \to c_5 \to c_2 \to c_1.$$

On the routes, the first customer (c_1) represents the established distribution center, which is the distribution center number 3. As it can be seen, the vehicle returns to distribution centers after visiting customers.

The arrival time of each vehicle to the customer's location in each time period is determined by using variable at_{mjt} as presented in Box I.

Other tactical decisions that have a significant impact on the greening of the network and the total cost reduction are the selection of suppliers and the number of orders in each time period. The results show that the purchase of products has been linked to each of the four suppliers, and the order quantity for each supplier of a product per time period is reported as follows. For example, it is shown that the first product purchased at the first price level from supplier 2 by the distribution center number 3 in the time period 5 is 300 units (Box II). The number of products delivered to customers by each vehicle in each time period from the located distribution center is another operational decision (z_{pmbjt}) (Box III).

Thus, by implementing the proposed model in GAMS software, the optimal values of objective functions and decision variables are calculated. In the network structure of the problem prior to mathematical model development, the distribution center 2 and Vehicles 1 and 3 were used. The total cost was 643927300 and the purchasing value of green suppliers was 1794.6. By implementing the proposed model, the total cost of the network decreased by more than 16% and the value of purchasing from green suppliers increased by more than 2%, which implies the suitable performance and effectiveness of the proposed model.

$z_{13313} = 1040$, $z_{13314} = 140$, $z_{13321} = 810$, $z_{13325} = 1400$, $z_{13331} = 570$, $z_{13351} = 570$,
$z_{13362} = 420$, $z_{13363} = 510$, $z_{13366} = 1850$, $z_{23313} = 1520$, $z_{23315} = 1050$, $z_{23321} = 30$,
$z_{23334} = 1910$, $z_{23341} = 470$, $z_{23352} = 1520$, $z_{23356} = 1000$, $z_{33311} = 660$, $z_{33321} = 480$,
$z_{33325} = 1900$, $z_{33331} = 440$, $z_{33333} = 770$, $z_{33341} = 470$, $z_{33344} = 2450$, $z_{33352} = 1520$,
$z_{33353} = 380$, $z_{33362} = 470$, $z_{33366} = 1650$.

Box III

Table 14. Obtained results from demand decrease scenarios.

Scenario	Number of demands	Z^{cost}	$Z^{\text{purchasing value}}$
1	0.70 × demands	435765200	1831.30
2	0.75 × demands	443216400	1813.25
3	0.80 × demands	456257100	1634.72
4	0.85 × demands	473571000	1787.58
5	0.90 × demands	499961500	1684.30
6	0.95 × demands	531682400	1673.87

Table 15. Obtained results from demand increase scenarios.

Scenario	Number of demands	Z^{cost}	$Z^{\text{purchasing value}}$
1	1.05× demands	572479800	1527.58
2	1.10× demands	610787000	1572.30
3	1.15× demands	673477200	1576.57
4	1.20× demands	714641100	1540.76
5	1.25× demands	751823800	1525.54
6	1.30× demands	784813900	1528.67

5. Sensitivity analysis

For the validation of the proposed model, its sensitivity to some parameters was measured. To this end, some scenarios should be defined. Applying each scenario, we examine to what extent our expectations of the model are consistent with the achieved results. For this purpose, two scenarios have been applied. The first set of scenarios is based on decreasing demands, while the second set is based on increasing demands.

5.1. Demand decrease scenario

In this section, scenarios are applied based on decreasing demands. If the demands decrease, the costs will not increase. However, the level of greenness would not increase, which is confirmed by the results of sensitivity analysis. Hence, one cannot express a decisive opinion about the greenness of the objective function. In other words, there is no way to prove a conflict between the green objective function and cost objective functions. In fact, the reason for incorporating this function in the model is only to satisfy the environmental needs, respect human rights, and obey the environmental rules and requirements. However, it is absolutely impossible to discuss greenness of the objective function. As a result, scenarios of decreasing demand and the achieved results are shown in Table 14 and Figures 1 and 2.

5.2. Demand increase scenario

The model is expected to bring about inverse results with demand decrease as a result of increasing the demands. Thus, the results obtained from the model implementation are illustrated in Table 15 and Figures 3 and 4.

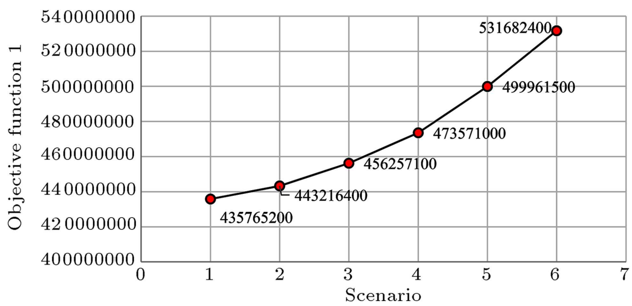

Figure 1. Results of demand decrease scenarios for objective function 1.

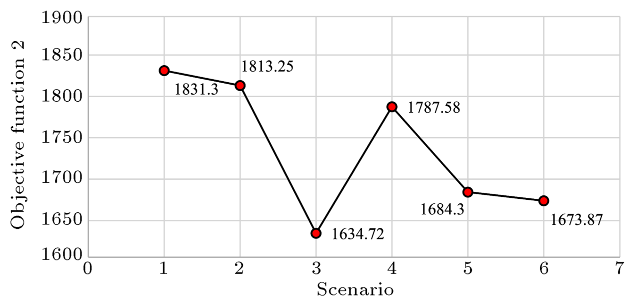

Figure 2. Results of demand decrease scenarios for objective function 2.

The results obtained from the sensitivity analysis of the model under two scenarios of demand decrease

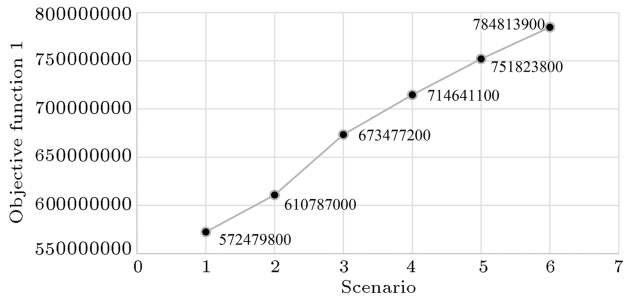

Figure 3. Results of demand increase scenarios for objective function 1.

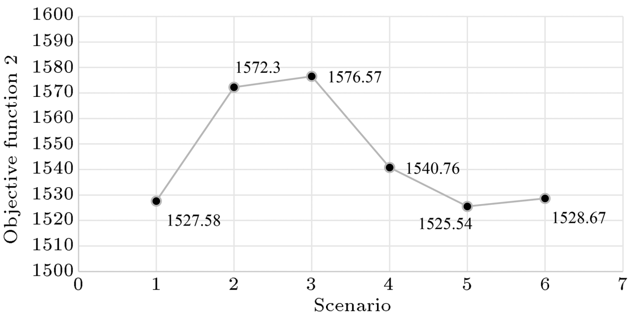

Figure 4. Results of demand increase scenarios for objective function 2.

and demand increase are consistent with our expectations of the model. Hence, it is possible to use these results to validate the model.

6. Conclusion

In today's competitive market, the purchasing process, especially supplier selection, is a very important challenge for companies to succeed. Since supplier is the first layer in a chain, any shortcoming in this layer will also affect other layers. In order to make a suitable decision regarding supplier selection and order allocation, this study developed a two-stage approach based on Fuzzy Analytic Hierarchy Process (FAHP) and Multi-Objective Mixed Integer Linear Programming (MOMILP) model under uncertainty.

The data from a pharmaceutical supply chain was used to evaluate the efficiency of the proposed approach and a fuzzy solution approach was employed to solve the bi-objective model with uncertain demands. Implementation of the proposed model resulted in a 16% reduction in total costs and a 2% increase in purchasing value of green suppliers. Also, the behavior of the proposed model for the scenarios caused by the sensitivity analysis of the demand parameter indicates the proper functionality of the proposed model.

As for future research, it is suggested that new Multiple Attribute Decision-Making (MADM) methods such as robust Best-Worst Method (BWM) and fuzzy BWM be used to evaluate suppliers, and because the model presented here is placed in the NP-hard issues category, it is recommended that large-scale algorithms be employed to solve large-scale problems.

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