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Huseyin Selcuk Kilic

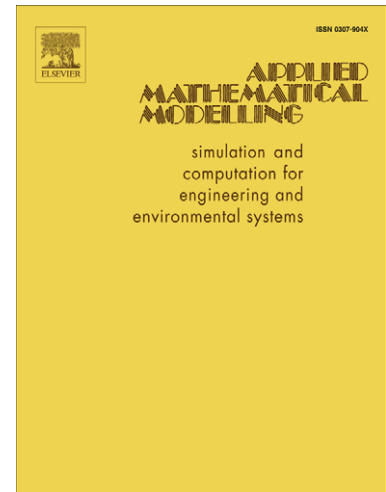
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AN INTEGRATED APPROACH FOR SUPPLIER SELECTION IN MULTI-ITEM/MULTI-SUPPLIER ENVIRONMENT

Huseyin Selcuk Kilic

Marmara University, Department of Industrial Engineering, 34722, Göztepe, İstanbul, Turkey

Tel: +90 (0216) 348 02 92, Fax: +90 (0216) 347 28 59

huseyin.kilic@marmara.edu.tr

Abstract

One of the important stages in supply chain management which regards all the activities from the purchasing of raw material to final delivery of the product is the supplier selection process. Since it is the first stage of the supply chain management, it is a critical process affecting the consecutive stages. It is simply desired to select the best supplier for a specific product. But since there are a lot of criteria and alternatives to be considered, numerous decision making models have been proposed to provide a solution to this problem. Within this study, an integrated approach including fuzzy Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) and a mixed integer linear programming model is developed to select the best supplier in a multi-item/multi-supplier environment. The importance value of each supplier with respect to each product is obtained via fuzzy TOPSIS in the first stage. Then in the second stage, these values are used as an input in the mathematical model which determines the suppliers and the quantities of products to be provided from the related suppliers. So as to validate the proposed methodology, an application is performed in air filter sector.

Keywords: Supplier selection, supply chain management, fuzzy TOPSIS, mixed integer linear programming.

1. Introduction

Supply chain management can be defined as the process including all the events related with the flow and transformation of goods and services from the source point to the usage point [1]. It aims to plan, implement and control the supply chain network operations efficiently [2]. The main objectives of supply chain management are to reduce supply chain risk, reduce production costs, maximize revenue, improve customer service, optimize inventory levels, business processes and cycle times and provide competitiveness, customer satisfaction and profitability [3].

One of the important activities of supply chain management is the supplier selection stage [4]. It is generally regarded as a complex process due to the involvement of many uncontrollable and unpredictable factors affecting the decisions [5]. Furthermore, it is considered as a complex multi-objective decision making problem since various and discordant criteria are taken into account and assessed during the process [6]. The way for determining the most suitable suppliers in the supply chain has been regarded as a key strategic consideration in recent years [7]. Quantitative and qualitative criteria are taken into account while making this decision.

Beginning from the study of Dickson [8], numerous studies have been performed considering different criteria and different methodologies for the selection of the best supplier. Dickson [8] determined 23 criteria and obtained the importance of them via a survey. According to the results of the survey, the first three criteria were quality, delivery and performance history. After Dickson [8], similar studies have been accomplished such as the study of Weber et al. [9]. According to their study, the most popular three criteria were net price, delivery and quality. Different from the study of Weber et al. [9], the most popular supplier selection criteria were obtained as quality, delivery and price in the study of Ho et al. [10]. As can be inferred from the related studies, the importance of selection criteria is not the same in all the studies.

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Similar to the variety in supplier selection criteria, various solution methodologies have been used for the supplier selection problem. Although most of them are used singly, a considerable amount of them are used with other techniques. That is, integrated methodologies are widely utilized. Some of the techniques used singly are; analytic hierarchy process (AHP), analytic network process (ANP), data envelopment analysis (DEA), mathematical programming, case-based reasoning, fuzzy set theory, simple multi-attribute rating technique and genetic algorithm. On the other hand, some of the integrated techniques are; integrated AHP approaches (integrated AHP and Bi-negotiation; integrated AHP and DEA; integrated AHP and goal programming (GP); integrated AHP and mixed integer non-linear programming and so on.), integrated fuzzy approaches (integrated fuzzy and AHP; integrated fuzzy AHP and cluster analysis; integrated fuzzy and genetic algorithm; integrated fuzzy and quality function deployment and so on.) and other integrated approaches. DEA, mathematical programming and AHP are the top three approaches used singly. Among the integrated approaches, the most widely used one is AHP-GP approach [10].

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There are mainly two kinds of supplier selection problems in the literature. In the first type, a supplier can fully provide the needs of a firm, whereas in the second type, a supplier is not enough to satisfy the needs by itself and the requirements can be satisfied partially by the suppliers [11]. These two problem types are also called “single sourcing” and “multiple sourcing” [12]. The proposed approach in this study can be regarded within “multiple sourcing” category since one supplier is not enough to satisfy all the needs. Furthermore, there are different types of products to be provided. So the problem investigated in this study can be defined as multi-item/multi-supplier problem. Moreover, as Ho et al. [10] state that since it is desired to provide long term partnership with fewer but reliable suppliers, this case is also regarded in the proposed approach by providing a constraint limiting the number of selected suppliers in the developed mathematical model.

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So as to find the best supplier in this multi-item/multi-supplier environment, a novel integrated approach including fuzzy TOPSIS and mixed integer linear programming model is proposed in this study differing from the other studies in the literature. For showing the validity of the proposed approach, an application was conducted in air filter sector.

The rest of the paper is organized as follows. Literature review is provided in part 2. Part 3 includes fuzzy TOPSIS method. The proposed methodology is provided in part 4. Application in air filter sector is given in part 5 and conclusion is presented in part 6 with the references following.

2. Literature review

Due to its popularity and applicability in various fields, numerous studies related with supplier selection have been performed since Dickson [8] who presented one of the first studies. Although, the main objective is simply to select the best supplier, the studies differ from each other mainly with respect to the applied methodologies, evaluation criteria, supplier and item properties and application areas. In addition to many research articles, a considerable amount of literature reviews were accomplished by various authors such as Weber et al. [9], Degraeve et al. [13], De Boer et al. [14] and Ho et al. [10]. The literature is overviewed briefly by providing some of the recent studies.

Amid et al. [4] proposed a fuzzy multi-objective linear model for supplier selection in a supply chain by using an asymmetric fuzzy decision making technique to provide the decision maker to allocate different weights to various criteria. Bevilacqua et al. [5] developed a fuzzy-quality function deployment (QFD) approach for supplier selection problem. The developed method was applied in a manufacturer of complete clutch couplings. Gencer and Gürpınar [15] used ANP for the supplier selection problem. For validating the model, they made an application in an electronic company. Liao and Rittscher [16] presented a multi-objective supplier selection model for the supplier selection problem under stochastic demands.

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Chou and Chang [17] used strategy aligned fuzzy simple multi-attribute technique (SMART) for the supplier selection problem by regarding the supply chain strategic management perspective. Demirtas and Üstün [11] proposed a two stage approach including ANP and multi objective mixed integer linear programming (MOMILP) for the supplier selection problem. Ha and Krishnan [18] developed a hybrid method including AHP, DEA and neural network (NN) enabling single sourcing and multiple sourcing via calculating a combined supplier score. The approach was applied in an auto company. Ng [19] presented a weighted linear program for the supplier selection problem by benefiting from the advantages of DEA. Boran et al. [3] used TOPSIS method including intuitionistic fuzzy set. Ebrahim et al. [20] developed mathematical models for multi-objective supplier selection problem with single item. Due to the complexity of the models developed, they presented a scatter search algorithm for solving the models. He et al. [21] dealt with a stochastic chance-constrained vendor selection problem and presented a solution methodology based on genetic algorithm. Kokangul and Susuz [22] developed a combined approach including AHP, non-linear integer and multi-objective programming for supplier selection problem. Both quantitative and qualitative data were taken into account via the developed approach. Lee [23] offered a supplier selection model based on fuzzy AHP regarding the benefits, opportunities, costs and risks. The offered approach was applied in a TFT-LCD manufacturing company. Önüt et al. [24] presented a hybrid model consisting of fuzzy ANP and fuzzy TOPSIS. In the presented model, criteria weights were obtained by fuzzy ANP and used in the fuzzy TOPSIS method. The model was applied in a telecommunication company. Razmi et al. [25] utilized fuzzy ANP for the supplier selection problem. Shu and Wu [26] used fuzzy set theory as a tool for the selection of suppliers regarding quality. Wang et al. [27] offered fuzzy hierarchical TOPSIS method which is the revised and improved form of fuzzy TOPSIS for supplier selection problem. Wu [28] developed a hybrid model including DEA, NN and decision trees for supplier selection.

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Bhattacharya et al. [2] proposed an integrated approach consisting of AHP, QFD and cost factor measure (CFM) for supplier selection problem. Chamodrakas et al. [29] presented a model consisting of two stages which are satisficing technique and fuzzy preference programming. Kuo et al. [30] developed an integrated methodology including artificial neural network (ANN) and two multi-attribute decision making techniques which are DEA and ANP. The developed methodology was applied in an electronic company. Lam et al. [31] offered a methodology which was based on fuzzy principal component analysis (FPCA) for material supplier selection problem. Sanayei et al. [32] applied fuzzy Vise Kriterijumska Optimizacija I Kompromisno Resenje (VIKOR) method for supplier selection problem. Tsai et al. [33] proposed a dynamic ant colony based approach for supplier selection problem. Aksoy and Öztürk [34] utilized neural network based systems for supplier selection and supplier performance evaluation for just in time manufactures. Bilsel and Ravindran [35] developed a multi-objective stochastic sequential supplier allocation model for supplier selection under uncertainty. Büyüközkan and Çifçi [1] presented an ANP based approach within multi-person decision-making schema under fuzzy environment. A real case including a number of suppliers was conducted to show the applicability of the presented methodology. Dalalah et al. [36] proposed an integrated fuzzy multi-criteria decision making model consisting of modified fuzzy decision making trial and evaluation laboratory (DEMATEL) and fuzzy TOPSIS for the supplier selection problem. An application was conducted in a nutridar factory to validate the proposed model. Feng et al. [37] dealt with a multi-objective model for supplier selection in multi-service outsourcing. Depending on the NP-hard structure of the problem, they developed a tabu search algorithm for solving it. Kilincci and Onal [38] used fuzzy AHP for supplier selection in their study. An application was performed in a washing machine company to find the best supplier of a certain part used. Liao and Kao [39] developed an integrated approach including fuzzy TOPSIS and multiple choice goal programming (MCGP) for supplier selection problem. An application in a watch firm was

1 performed so as to show the validity of the developed approach. Shemshadi et al. [40]
2 presented a methodology based on fuzzy VIKOR. While the subjective weights of the criteria
3 used within VIKOR were obtained from decision makers directly, objective weights were
4 gathered from entropy method. Toloo and Nalchigar [41] offered a new DEA method which
5 takes into account both cardinal and ordinal data. A mixed integer programming model was
6 also developed for prioritization. Vinodh et al. [42] utilized fuzzy ANP for supplier selection
7 problem. For validating the approach, an application in an electronics firm was performed.
8
9 Yücel and Güneri [43] proposed a methodology mainly including two parts. In the first part,
10 the weights of the factors were determined benefiting from the linguistic values expressed by
11 trapezoidal fuzzy numbers. Then, using the obtained weights as input, a fuzzy multi-objective
12 linear model was developed to select the most proper supplier and assign optimum order
13 quantity. Zouggari and Benyoucef [44] offered a combined methodology including fuzzy
14 AHP and simulation based fuzzy TOPSIS. Firstly, fuzzy AHP was used to select the suppliers
15 regarding qualitative criteria, then simulation based fuzzy TOPSIS was used to determine
16 order allocation among the selected suppliers.
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Büyüközkan and Çifçi [45] developed an integrated methodology consisting of DEMATEL, ANP and TOPSIS for green supplier evaluation in fuzzy environment. The developed methodology was applied in a real case study. Chen and Chao [46] firstly used AHP for constructing the structure of criteria and then they used consistent fuzzy preference relations (CFPR) for the decision matrices. An application was performed in an electronic company considering 15 criteria. Golmohammadi and Mellat-Parast [47] proposed an approach based on the grey relational analysis for the supplier selection problem. A case study in the auto industry was conducted to show the validity of the proposed model. Hu et al. [48] presented a hybrid “adaptive target strategy” for maximizing expected profits in an environment of selecting among multiple suppliers. Kilic [49] used fuzzy TOPSIS to select the best supplier. Mendoza and Ventura [50] developed two mixed integer non-linear

1 programming models for supplier selection by considering the inventory management of the
2 items purchased. Shaw et al. [51] used a methodology based on fuzzy AHP and fuzzy multi-
3 objective linear programming model for developing low carbon supply chain. For showing the
4 effectiveness of the model, data from a realistic case was used.
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9 As can be inferred from the analyzed studies, there is not an integrated approach including
10 fuzzy TOPSIS and mixed integer linear programming model for supplier selection in multi-
11 item/multi-supplier environment. With this study, contribution is provided to the literature by
12 presenting an integrated methodology to select the best suppliers and determine the quantities
13 to be provided from the selected suppliers.
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21 **3. Fuzzy TOPSIS method**

22 It is clear that there can be differences in the properties of different product types provided
23 by a supplier. That is, some product types of a supplier can have better quality or some of
24 them can be more expensive when compared to similar products of other suppliers. This case
25 indicates that value of a supplier can change with respect to each product it provides. For this
26 reason, importance values of each supplier with respect to the related product is determined
27 via fuzzy TOPSIS which takes into consideration the distances from positive and negative
28 ideal solutions. Different from the TOPSIS, vagueness of decision making environment is
29 regarded by the fuzzy evaluations included in the fuzzy TOPSIS process.
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43 TOPSIS was firstly proposed by Hwang and Yoon [52] and has been studied a lot since
44 then. The main logic behind the method is to determine the best alternative by considering the
45 closeness to the positive ideal solution and distance from the negative ideal solution.
46 Although there are a lot of applications of TOPSIS in various fields such as facility layout
47 design [53], evaluation of photovoltaic cells [54], plant location selection [55] and so on, there
48 is debate on the inadequacy of it in handling the vagueness about the decision maker's
49 preferences. So as to overcome this drawback, fuzzy TOPSIS and its extensions were
50 developed [56]. The steps of fuzzy TOPSIS were presented with slight differences in the
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literature [57], [58] and [59]. The steps presented by Çevikcan et al. [58] are used in this study.

Step 1: The evaluation of criteria importance and alternative ratings with respect to the criteria are performed. Each criterion is evaluated by the decision makers via linguistic variables as shown in Table 1 and alternatives are rated according to Table 2.

Table 1
Linguistic variables for criteria evaluation

Linguistic variable	Fuzzy number
Very Low (VL)	(0, 0, 0.1)
Low (L)	(0, 0.1, 0.3)
Medium Low (ML)	(0.1, 0.3, 0.5)
Medium (M)	(0.3, 0.5, 0.7)
Medium High (MH)	(0.5, 0.7, 0.9)
High (H)	(0.7, 0.9, 1)
Very High (VH)	(0.9, 1, 1)

Table 2
Linguistic variables for alternative ratings

Linguistic variable	Fuzzy number
Very Poor (VP)	(0, 0, 1)
Poor (P)	(0, 1, 3)
Medium Poor (MP)	(1, 3, 5)
Fair (F)	(3, 5, 7)
Medium Good (MG)	(5, 7, 9)
Good (G)	(7, 9, 10)
Very Good (VG)	(9, 10, 10)

Step 2: By using Table 1 and Table 2, linguistic terms are transformed into triangular fuzzy numbers. Alternative ratings (\tilde{x}_{ij}) and criteria importance (\tilde{w}_j) are computed by performing the equations (1) and (2).

The definitions of the related symbols used in the equations are as follows.

The definitions of the symbols

i: Alternative

j: Criterion

\tilde{x}_{ij} : The rating of alternative “i” with respect to criterion “j”

\tilde{w}_j : The importance of criterion “j”

K: The number of decision makers

(a_{ij}, b_{ij}, c_{ij}): The lower, middle and upper values in the triangular fuzzy numbers indicating the rating of alternative “i” with respect to criterion “j”

(w_{j1}, w_{j2}, w_{j3}): The lower, middle and upper values in the triangular fuzzy numbers indicating the importance of criterion “j”

$$\tilde{x}_{ij} = \frac{1}{K} (\tilde{x}_{ij}^1 + \tilde{x}_{ij}^2 + \dots + \tilde{x}_{ij}^K), \quad \tilde{x}_{ij} = (a_{ij}, b_{ij}, c_{ij}) \quad (1)$$

$$\tilde{w}_j = \frac{1}{K} (\tilde{w}_j^1 + \tilde{w}_j^2 + \dots + \tilde{w}_j^K), \quad \tilde{w}_j = (w_{j1}, w_{j2}, w_{j3}) \quad (2)$$

Step 3: Normalization is performed via linear scale transformation as expressed in the equations (3) and (4).

The definitions of the related symbols used in the equations are as follows.

The definitions of the symbols

\tilde{r}_{ij} : Normalized triangular fuzzy number

\tilde{R} : Matrix consisting of normalized triangular fuzzy numbers

If criterion is benefit then $c_j^* = \max_i c_{ij}$ and equation (3) is used.

$$\tilde{R} = [\tilde{r}_{ij}]_{m \times n} \Rightarrow \tilde{r}_{ij} = \left(\frac{a_{ij}}{c_j^*}, \frac{b_{ij}}{c_j^*}, \frac{c_{ij}}{c_j^*} \right) \quad i = 1, 2, \dots, m \quad j = 1, 2, \dots, n \quad (3)$$

If criterion is cost, $a_j^- = \min_i a_{ij}$ and the following equation (4) is used.

$$\tilde{r}_{ij} = \left(\frac{a_j^-}{c_{ij}}, \frac{a_j^-}{b_{ij}}, \frac{a_j^-}{a_{ij}} \right) \quad (4)$$

Step 4: The weighted normalized fuzzy decision matrix is obtained via the equations (5) and (6).

The definitions of the related symbols used in the equations are as follows.

The definitions of the symbols

\tilde{v}_{ij} : Weighted normalized triangular fuzzy number

\tilde{V} : Matrix consisting of weighted normalized triangular fuzzy numbers

$$\tilde{V} = [\tilde{v}_{ij}]_{m \times n} \quad i = 1, 2, \dots, m \quad j = 1, 2, \dots, n \quad (5)$$

$$\tilde{v}_{ij} = \tilde{r}_{ij} \cdot \tilde{w}_j \quad (6)$$

Step 5: The distances of each alternative from fuzzy positive and negative ideal solutions are computed via the equations (7), (8) and (9).

The definitions of the related symbols used in the equations are as follows.

The definitions of the symbols

A^* : Fuzzy positive ideal solution

A^- : Fuzzy negative ideal solution

v_j^* : Fuzzy positive ideal point for the criterion “j”

v_j^- : Fuzzy negative ideal point for the criterion “j”

d_i^* : The distance of alternative “i” from the fuzzy positive ideal solution

d_i^- : The distance of alternative “i” from the fuzzy negative ideal solution

$$A^* = (v_1^*, v_2^*, \dots, v_n^*) \quad \text{where } v_j^* = (1, 1, 1) \quad (7)$$

$$A^- = (v_1^-, v_2^-, \dots, v_n^-) \quad \text{where } v_j^- = (0, 0, 0) \quad (8)$$

$$d_i^* = \sum_{j=1}^n d(\tilde{v}_{ij}, \tilde{v}_j^*) \quad i = 1, 2, \dots, m \quad d_i^- = \sum_{j=1}^n d(\tilde{v}_{ij}, \tilde{v}_j^-) \quad i = 1, 2, \dots, m \quad (9)$$

Step 6: The fuzzy closeness coefficient CC_i is computed as shown in the equation (10) and the highest of them is selected as the best alternative.

$$CC_i = \frac{d_i^-}{d_i^* + d_i^-} \quad i = 1, 2, \dots, m \quad (10)$$

4. Proposed methodology

The proposed methodology consists of two main steps as shown in Fig. 1. In the first step, importance value of each supplier with respect to each item is obtained via fuzzy TOPSIS.

Then these values are used in the mixed integer linear programming (MILP) model so as to find the best suppliers and the assigned items.

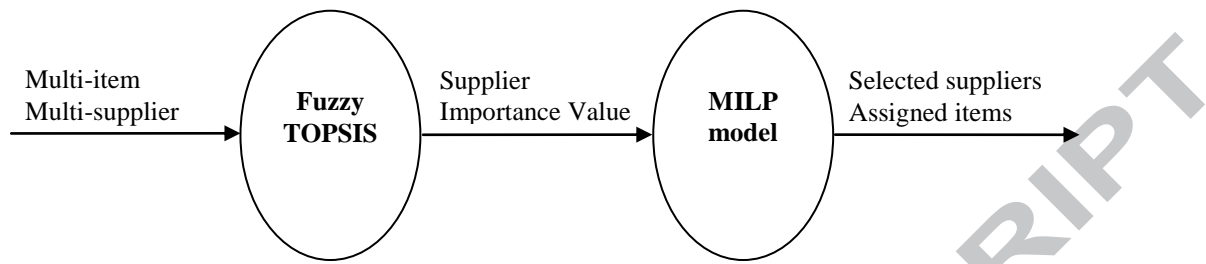


Fig. 1. The main structure of the proposed methodology

Within the first step of the proposed methodology, each supplier's importance value with respect to each item is determined by applying the required steps of fuzzy TOPSIS mentioned in the previous section. Afterwards, these importance values are used in the mathematical model which is explained below.

Assumption

Demand is constant and does not change during the planning period.

Subscripts

i : Item $\{1,2,\dots, I\}$

j : Supplier $\{1,2,\dots,J\}$

Decision variables

A_{ij} : Amount of item "i" provided by supplier "j"

X_{ij} : Any amount of item "i" is provided or not provided by supplier "j" (1 or 0)

Y_j : Supplier "j" is selected or not selected (1 or 0)

Parameters

SIV_{ij} : Importance value of supplier "j" with respect to item "i"

S_{ij} : The amount of item "i" that the supplier "j" can produce

S_j : The set of items that the supplier "j" can produce

D_i : The demand of item "i"

maxNS: Maximum number of suppliers that can be selected

M: A big number

Objective function

$$\text{Min } z = \sum_{i=1}^I \sum_{j=1}^J ((M - SIV_{ij}) * X_{ij}) \quad (11)$$

Constraints

$$\sum_j A_{ij} = D_i \quad \forall_i \quad (12)$$

$$\sum_{i \notin S_j} X_{ij} = 0 \quad \forall_j \quad (13)$$

$$A_{ij} \leq S_{ij} \quad \forall_i, \forall_j \quad (14)$$

$$M * X_{ij} \geq A_{ij} \quad \forall_i, \forall_j \quad (15)$$

$$M * Y_j \geq \sum_i X_{ij} \quad \forall_j \quad (16)$$

$$\sum_j Y_j \leq \max NS \quad (17)$$

$$X_{ij}, Y_j \in \{0,1\}, \quad A_{ij} \in \text{Positive Integers} \quad (18)$$

(11) The objective of the model is to provide the highest importance value of selected suppliers for each item by minimizing the related expression.

(12) Demand of each item “i” is satisfied.

(13) An item which is not produced by the related suppliers cannot be assigned to those suppliers.

(14) The capacity of the supplier “j” with respect to the item “i” cannot be exceeded.

(15) If the item “i” is provided by supplier “j”, X_{ij} becomes 1 otherwise becomes 0.

(16) If any item “i” is provided by supplier “j” then Y_j becomes 1 otherwise becomes 0.

(17) The number of selected suppliers is restricted by a maximum number.

(18) The decision variables are 0-1 integer variables or positive integers.

5. Application in air filter sector

So as to validate the proposed methodology, an application is performed in the air filter sector with the support of an air filter company which is located in Istanbul. The main air filters that are in the sector are bag filters, carbon filters compact filters, hepa filters, panel filters and roll filters as shown in Fig. 2.



Fig. 2. From left to right; bag filter, carbon filter, compact filter, hepa filter, panel filter and roll filter

Due to the variety and technological requirements of the air filters, not all the suppliers can produce them. Moreover, there are differences among the product types of the same producer with respect to quality, delivery time and cost. This situation requires determining different importance values for the same producer regarding each product type. Another limitation is that the producers have limited capacities and cannot completely provide orders for some products. Regarding this case, the integrated approach proposed in this study is applied and solutions are obtained for determining the best suppliers and required quantities. Since the presented practical example is based on real applications in air filter sector, the names of the suppliers have not been provided explicitly. Moreover, parameter values have been determined considering the case in the sector. The steps are as follows:

Step 1: Evaluation of the criteria and alternative ratings with respect to each criterion are performed.

1 Firstly, the criteria are determined by negotiating with the managers of the air filter
 2 company. The related criteria are quality, cost, delivery time, geographical location and
 3 references.
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 7 For applying fuzzy TOPSIS to obtain the importance values of the suppliers, first of
 8 all, the determined criteria are assessed as shown in Table 3. The assessment values are the
 9 compromise decisions of the related decision makers in the air filter company.
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 14 **Table 3**
 15 The evaluation for criterion importance weight

Criterion	Evaluation
Cr1 (Quality)	VH
Cr2 (Cost)	VH
Cr3 (Delivery time)	H
Cr4 (Geographical location)	M
Cr5 (References)	H

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 24 After determining and assessing the criteria, five suppliers represented by A, B, C, D
 25 and E are assessed for each of the six products (from pr1 to pr6) with respect to each criterion.
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 27 The evaluations for bag filters (pr1) are shown in Table 4. Other evaluations are provided in
 28 the appendix Table A1. The required operations will be done only for product 1 (bag filters).
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 34 **Table 4**
 35 The evaluation for product 1

Criterion	Suppliers				
	A	B	C	D	E
Cr1	F	-	G	-	MP
Cr2	MG	-	VG	-	MG
Cr3	MG	-	G	-	F
Cr4	G	-	VG	-	MG
Cr5	F	-	G	-	G

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 45 **Step 2:** Linguistic terms of criteria evaluation and alternative ratings are transformed
 46 into triangular fuzzy numbers. The results for product 1 are shown in Table 5. The results for
 47 other products are provided in the appendix Table A2.
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53 **Table 5**
 54 Fuzzy decision matrix for product 1 and the weights of criteria

Supplier	Criteria				
	Cr1	Cr2	Cr3	Cr4	Cr5
A	(3, 5, 7)	(5, 7, 9)	(5, 7, 9)	(7, 9, 10)	(3, 5, 7)
C	(7, 9, 10)	(9, 10, 10)	(7, 9, 10)	(9, 10, 10)	(7, 9, 10)
E	(1, 3, 5)	(5, 7, 9)	(3, 5, 7)	(5, 7, 9)	(7, 9, 10)
Weight	(0.9, 1, 1)	(0.9, 1, 1)	(0.7, 0.9, 1)	(0.3, 0.5, 0.7)	(0.7, 0.9, 1)

Step 3: Normalization is performed as shown in Table 6 for product 1. The results for other products are provided in the appendix Table A3.

Table 6
Fuzzy normalized decision matrix for product 1

Supplier	Criteria				
	Cr1	Cr2	Cr3	Cr4	Cr5
A	(0.3, 0.5, 0.7)	(0.5, 0.7, 0.9)	(0.5, 0.7, 0.9)	(0.7, 0.9, 1)	(0.3, 0.5, 0.7)
C	(0.7, 0.9, 1)	(0.9, 1, 1)	(0.7, 0.9, 1)	(0.9, 1, 1)	(0.7, 0.9, 1)
E	(0.1, 0.3, 0.5)	(0.5, 0.7, 0.9)	(0.3, 0.5, 0.7)	(0.5, 0.7, 0.9)	(0.7, 0.9, 1)

Step 4: The weighted normalized fuzzy decision matrix for product 1 is obtained by incorporating the weights of the criteria as shown in Table 7. The results for other products are provided in the appendix Table A4.

Table 7
Fuzzy weighted normalized decision matrix for product 1

Supplier	Criteria				
	Cr1	Cr2	Cr3	Cr4	Cr5
A	(0.27, 0.5, 0.7)	(0.45, 0.7, 0.9)	(0.35, 0.63, 0.9)	(0.21, 0.45, 0.7)	(0.21, 0.45, 0.7)
C	(0.63, 0.9, 1)	(0.81, 1, 1)	(0.49, 0.81, 1)	(0.27, 0.5, 0.7)	(0.49, 0.81, 1)
E	(0.09, 0.3, 0.5)	(0.45, 0.7, 0.9)	(0.21, 0.45, 0.7)	(0.15, 0.35, 0.63)	(0.49, 0.81, 1)

Step 5: The distance of each supplier from fuzzy positive and negative ideal solutions are computed for product 1 and shown in Table 8. The distance values for other products are provided in the appendix Table A5.

Table 8
The distances of suppliers from fuzzy positive and negative ideal solutions for product 1

Supplier	d^*	d^-
A	4.340	4.997
C	2.596	6.771
E	4.571	4.787

Step 6: The fuzzy closeness coefficients CC_i which are also regarded as supplier importance values (SIV) for all the suppliers with respect to each related product are computed and provided in Table 9.

Table 9The fuzzy closeness coefficient CC_i for all suppliers with respect to each related product

Supplier	Products					
	pr1	pr2	pr3	pr4	pr5	pr6
A	0.535	-	0.408	-	0.582	-
B	-	0.629	0.496	-	0.657	-
C	0.723	0.494	0.707	0.723	-	-
D	-	0.527	-	0.614	-	0.643
E	0.512	-	-	0.539	0.626	0.614

After performing the last step of fuzzy TOPSIS, the importance value of each supplier with respect to the related products is obtained as shown in Table 9. Afterwards, the mathematical model is applied by using these obtained importance values. The mathematical model is coded in GAMS optimization program and optimum solution is found. The required parameter values are given below.

The amount of products that suppliers can provide within the related planning period is given in Table 10.

Table 10

The amount of products that can be provided by the suppliers

Supplier	Products					
	pr1	pr2	pr3	pr4	pr5	pr6
A	200	-	1000	-	750	-
B	-	600	1000	-	800	-
C	1000	800	1250	1750	-	-
D	-	500	-	750	-	600
E	400	-	-	1000	750	800

The demand for each product is given in Table 11 and maximum number of suppliers is determined as 3.

Table 11

The demand of products

Demand	Products					
	pr1	pr2	pr3	pr4	pr5	pr6
	1250	1000	1600	750	1200	800

After running the mathematical model, optimum solution is obtained in a very short time. The selected suppliers are B, C and E. The quantities to be ordered from each supplier are shown in Table 12.

Table 12

Selected suppliers and quantities to be ordered from each supplier

Supplier	Products					
	pr1	pr2	pr3	pr4	pr5	pr6
B	-	600	1000	-	800	-
C	1000	400	600	750	-	-
E	250	-	-	-	400	800

6. Conclusion

One of the important competitive factors in the success of organizations is the supply chain management including different activities. Within the initial activities, supplier selection process which aims to determine the best suppliers is very important. Due to the importance of the subject, many studies have been conducted to provide a solution methodology to this problem.

With this study, a special case of supplier selection problem in multi item/multi supplier environment is considered. In the investigated problem type, there is more than one product type and the suppliers can provide some of the products with limited capacities. Different from the existing solution methodologies in the literature, a novel integrated approach including fuzzy TOPSIS and mixed integer linear programming model is developed in this study. Within the first stage of the methodology, the importance value of each supplier with respect to each product is obtained via fuzzy TOPSIS. Afterwards, these importance values are used in the mathematical model to determine the best suppliers and the quantities to be provided by each supplier. So as to validate the proposed methodology, an application is performed in air filter sector. Five criteria; quality, cost, delivery time, geographical location and references are taken into account. The best suppliers and the required quantities are obtained via the proposed methodology. The proposed methodology can be applied in different sectors in the further studies. Moreover, different combined methodologies including the strong sides of various decision making techniques can be developed for the related type of problem.

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Appendixes

Appendix A. The operations of fuzzy TOPSIS steps for product 2 to product 6

Table A1

The evaluation matrix for product 2 to product 6

Product	Criterion	Suppliers				
		A	B	C	D	E
pr2	Cr1	-	G	P	F	-
	Cr2	-	MG	MP	MP	-
	Cr3	-	MG	G	MG	-
	Cr4	-	F	VG	G	-
	Cr5	-	G	G	G	-
pr3	Cr1	MP	F	VG	-	-
	Cr2	P	MP	MG	-	-
	Cr3	MG	MG	G	-	-
	Cr4	G	F	VG	-	-
	Cr5	F	G	G	-	-
pr4	Cr1	-	-	VG	F	G
	Cr2	-	-	G	G	MP
	Cr3	-	-	G	MG	F
	Cr4	-	-	VG	G	MG
	Cr5	-	-	G	G	G
pr5	Cr1	G	VG	-	-	G
	Cr2	F	MG	-	-	MG
	Cr3	MG	MG	-	-	F
	Cr4	G	F	-	-	MG
	Cr5	F	G	-	-	G
pr6	Cr1	-	-	-	VG	MG
	Cr2	-	-	-	F	G
	Cr3	-	-	-	MG	F
	Cr4	-	-	-	G	MG
	Cr5	-	-	-	G	G

Table A2

Fuzzy decision matrix for product 2 to product 6

Product	Supplier	Criteria				
		Cr1	Cr2	Cr3	Cr4	Cr5
pr2	B	(7, 9, 10)	(5, 7, 9)	(5, 7, 9)	(3, 5, 7)	(7, 9, 10)
	C	(0, 1, 3)	(1, 3, 5)	(7, 9, 10)	(9, 10, 10)	(7, 9, 10)
	D	(3, 5, 7)	(1, 3, 5)	(5, 7, 9)	(7, 9, 10)	(7, 9, 10)
pr3	A	(1, 3, 5)	(0, 1, 3)	(5, 7, 9)	(7, 9, 10)	(3, 5, 7)
	B	(3, 5, 7)	(1, 3, 5)	(5, 7, 9)	(3, 5, 7)	(7, 9, 10)
	C	(9, 10, 10)	(5, 7, 9)	(7, 9, 10)	(9, 10, 10)	(7, 9, 10)
pr4	C	(9, 10, 10)	(7, 9, 10)	(7, 9, 10)	(9, 10, 10)	(7, 9, 10)
	D	(3, 5, 7)	(7, 9, 10)	(5, 7, 9)	(7, 9, 10)	(7, 9, 10)
	E	(7, 9, 10)	(1, 3, 5)	(3, 5, 7)	(5, 7, 9)	(7, 9, 10)
pr5	A	(7, 9, 10)	(3, 5, 7)	(5, 7, 9)	(7, 9, 10)	(3, 5, 7)
	B	(9, 10, 10)	(5, 7, 9)	(5, 7, 9)	(3, 5, 7)	(7, 9, 10)
	E	(7, 9, 10)	(5, 7, 9)	(3, 5, 7)	(5, 7, 9)	(7, 9, 10)
pr6	D	(9, 10, 10)	(3, 5, 7)	(5, 7, 9)	(7, 9, 10)	(7, 9, 10)
	E	(5, 7, 9)	(7, 9, 10)	(3, 5, 7)	(5, 7, 9)	(7, 9, 10)

Table A3

Fuzzy normalized decision matrix for product 2 to product 6

Pr.	Sup.	Criteria				
		Cr1	Cr2	Cr3	Cr4	Cr5
pr2	B	(0.7, 0.9, 1)	(0.56, 0.78, 1)	(0.5, 0.7, 0.9)	(0.3, 0.5, 0.7)	(0.7, 0.9, 1)
	C	(0, 0.1, 0.3)	(0.11, 0.33, 0.56)	(0.7, 0.9, 1)	(0.9, 1, 1)	(0.7, 0.9, 1)
	D	(0.3, 0.5, 0.7)	(0.11, 0.33, 0.56)	(0.5, 0.7, 0.9)	(0.7, 0.9, 1)	(0.7, 0.9, 1)
pr3	A	(0.1, 0.3, 0.5)	(0, 0.11, 0.33)	(0.5, 0.7, 0.9)	(0.7, 0.9, 1)	(0.3, 0.5, 0.7)
	B	(0.3, 0.5, 0.7)	(0.11, 0.33, 0.56)	(0.5, 0.7, 0.9)	(0.3, 0.5, 0.7)	(0.7, 0.9, 1)
	C	(0.9, 1, 1)	(0.56, 0.78, 1)	(0.7, 0.9, 1)	(0.9, 1, 1)	(0.7, 0.9, 1)
pr4	C	(0.9, 1, 1)	(0.7, 0.9, 1)	(0.7, 0.9, 1)	(0.9, 1, 1)	(0.7, 0.9, 1)
	D	(0.3, 0.5, 0.7)	(0.7, 0.9, 1)	(0.5, 0.7, 0.9)	(0.7, 0.9, 1)	(0.7, 0.9, 1)
	E	(0.7, 0.9, 1)	(0.1, 0.3, 0.5)	(0.3, 0.5, 0.7)	(0.5, 0.7, 0.9)	(0.7, 0.9, 1)
pr5	A	(0.7, 0.9, 1)	(0.33, 0.56, 0.78)	(0.56, 0.78, 1)	(0.7, 0.9, 1)	(0.3, 0.5, 0.7)
	B	(0.9, 1, 1)	(0.56, 0.78, 1)	(0.56, 0.78, 1)	(0.3, 0.5, 0.7)	(0.7, 0.9, 1)
	E	(0.7, 0.9, 1)	(0.56, 0.78, 1)	(0.33, 0.56, 0.78)	(0.5, 0.7, 0.9)	(0.7, 0.9, 1)
pr6	D	(0.9, 1, 1)	(0.3, 0.5, 0.7)	(0.56, 0.78, 1)	(0.7, 0.9, 1)	(0.7, 0.9, 1)
	E	(0.5, 0.7, 0.9)	(0.7, 0.9, 1)	(0.33, 0.56, 0.78)	(0.5, 0.7, 0.9)	(0.7, 0.9, 1)

Table A4

Fuzzy weighted normalized decision matrix for product 2 to product 6

Pr.	Sup.	Criteria				
		Cr1	Cr2	Cr3	Cr4	Cr5
pr2	B	(0.63, 0.9, 1)	(0.50, 0.78, 1)	(0.35, 0.63, 0.9)	(0.09, 0.25, 0.49)	(0.49, 0.81, 1)
	C	(0, 0.1, 0.3)	(0.10, 0.33, 0.56)	(0.49, 0.81, 1)	(0.27, 0.5, 0.7)	(0.49, 0.81, 1)
	D	(0.27, 0.5, 0.7)	(0.10, 0.33, 0.56)	(0.35, 0.63, 0.9)	(0.21, 0.45, 0.7)	(0.49, 0.81, 1)
pr3	A	(0.09, 0.3, 0.5)	(0, 0.11, 0.33)	(0.35, 0.63, 0.9)	(0.21, 0.45, 0.7)	(0.21, 0.45, 0.7)
	B	(0.27, 0.5, 0.7)	(0.10, 0.33, 0.56)	(0.35, 0.63, 0.9)	(0.09, 0.25, 0.49)	(0.49, 0.81, 1)
	C	(0.81, 1, 1)	(0.50, 0.78, 1)	(0.49, 0.81, 1)	(0.27, 0.5, 0.7)	(0.49, 0.81, 1)
pr4	C	(0.81, 1, 1)	(0.63, 0.9, 1)	(0.49, 0.81, 1)	(0.27, 0.5, 0.7)	(0.49, 0.81, 1)
	D	(0.27, 0.5, 0.7)	(0.63, 0.9, 1)	(0.35, 0.63, 0.9)	(0.21, 0.45, 0.7)	(0.49, 0.81, 1)
	E	(0.63, 0.9, 1)	(0.09, 0.3, 0.5)	(0.21, 0.45, 0.7)	(0.15, 0.35, 0.63)	(0.49, 0.81, 1)
pr5	A	(0.63, 0.9, 1)	(0.30, 0.56, 0.78)	(0.39, 0.70, 1)	(0.21, 0.45, 0.7)	(0.21, 0.45, 0.7)
	B	(0.81, 1, 1)	(0.50, 0.78, 1)	(0.39, 0.70, 1)	(0.09, 0.25, 0.49)	(0.49, 0.81, 1)
	E	(0.63, 0.9, 1)	(0.50, 0.78, 1)	(0.23, 0.50, 0.78)	(0.15, 0.35, 0.63)	(0.49, 0.81, 1)
pr6	D	(0.81, 1, 1)	(0.27, 0.5, 0.7)	(0.39, 0.70, 1)	(0.21, 0.45, 0.7)	(0.49, 0.81, 1)
	E	(0.45, 0.7, 0.9)	(0.63, 0.9, 1)	(0.23, 0.50, 0.78)	(0.15, 0.35, 0.63)	(0.49, 0.81, 1)

Table A5

The distances of suppliers from fuzzy positive and negative ideal solutions for product 2 to product 6

Product	Supplier	d*	d ⁻
pr2	B	3.510	5.938
	C	4.745	4.630
	D	4.447	4.947
pr3	A	5.520	3.807
	B	4.724	4.647
	C	2.755	6.650
pr4	C	2.596	6.771
	D	3.625	5.775
	E	4.320	5.047
pr5	A	3.935	5.490
	B	3.239	6.212
	E	3.543	5.920
pr6	D	3.354	6.050
	E	3.635	5.781