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Managing supplier selection problem with integrated fuzzy AHP and fuzzy VIKOR: A manufacturing company case

Cansel ÇEKİÇ, Nezihe Nazlı GÜL*, Ali Fuat GÜNERİ

Department of Industrial Engineering, Yıldız Technical University, İstanbul, Türkiye

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ABSTRACT

The ability of businesses to gain a strong place in the sector in which they operate is directly related to the effective management of each member of the supply chain. In the globalizing world with increasing competitive conditions, businesses have to manage their supply chains efficiently to be successful in the market. Companies should improve their strategies by rapidly adapting to the new circumstances formed by various crises such as wars, climate change, or pandemics. The high performance of a business is greatly correlated with the performance of its suppliers. Therefore, supplier selection by evaluating supplier performance is a Multi-Criteria Decision-Making (MCDM) problem that simultaneously includes many qualitative and quantitative factors. In this article, the performances of the suppliers of a Turkish small-medium enterprise (SME) operating in the manufacturing sector during COVID-19 are evaluated using an integrated fuzzy MCDM technique. Despite its importance, supplier selection is less considered for SMEs. The purpose of including fuzzy logic in the study is to ensure that linguistic expressions are converted into fuzzy numbers to overcome uncertainty and subjectivity. Four supplier alternatives are evaluated by four main criteria, and in total by eleven sub-criteria determined by expert opinions. The weights of the performance criteria are obtained by the Fuzzy Analytic Hierarchy Process (FAHP), and the performance ranking of the suppliers is determined by the fuzzy VIKOR. The absence of a manufacturing sector-based study on SMEs operating in Turkey during the COVID-19 period constitutes the main motivation of this article.

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INTRODUCTION

The supply chain is a complex network of components that perform many functions such as distribution, finance, marketing, and customer service, with a continuous flow of information, funds, and materials in both directions of the chain. A manufacturer can buy from multiple suppliers and supply to multiple distributors [1]. Supplier management is one of the main concerns that businesses have to highlight to have a powerful place in the market in today's competitive environment. Selecting and evaluating the suppliers in line with the strategies of the enterprises is one of the most substantial supplier management activities. Investigating the objectives of the business and determining the criteria

***Corresponding author.**
*E-mail address: gul.n.nazli@gmail.com

related to these objectives is at the beginning of the supplier selection process. The selection and evaluation of suppliers in the most appropriate manner are called the Supplier Selection Problem (SSP) in the literature and have become one of the most imperative management matters today.

A decision-making process consists of some decision alternatives, objectives, and criteria for comparison. Numerous approaches have been established and developed over time in decision-making problems. Multi-Criteria Decision-Making (MCDM) methodologies aim to reach solutions to problems involving a large quantity of qualitative and quantitative factors. The existence of many conflicting conditions and alternative firms obscures the decision-making process. In such cases, it is more suitable to make inferences by using decision support systems. In this paper, a fuzzy MCDM process is applied for the SSP of an SME specialized in the manufacture of machine parts. The case study is conducted during the pandemic period to picture the current situation. In the first part, the criteria weights are calculated by fuzzy AHP, and in the second part, the alternatives are ranked by applying fuzzy VIKOR.

The negative conditions created by the COVID-19 pandemic have been effective in many sectors as well as in our daily lives. Turkey, which hosts many SMEs, owes a significant part of its economy to the manufacturing sector. This study aims to examine whether there are criteria that increase or decrease importance in the supplier selection behavior of SMEs during the pandemic. Also, with this work, contribution to the application of MCDM methods in supplier management, one of the most significant management issues, will be presented. It is not possible to evaluate multiple and conflicting criteria together intuitively. For this reason, at the end of the study, a more flexible decision-making opportunity is offered to the companies for the evaluation of supplier alternatives. In addition, it is quite easy to make updates in the decision-making process according to changing alternatives and conditions. Regular performance measurements and considerations of new criteria are essential in the developing world for the company's success in the market. Adding an integrated fuzzy MCDM method case study to the literature on an SME operating in the manufacturing sector, which is one of the sectors where supplier selection is critical, will emphasize the use of hybrid models in different areas.

Although MCDM is a widely performed topic in literature, there are not any integrated fuzzy MCDM approaches applied to SSP for a manufacturing-based SME operating in Turkey within the scope of the COVID-19 period. Authors believe that the crisis environment can sharply affect the behaviors and strategies of the companies, therefore they assume that a new study is necessary to interpret the current mindset of the businesses. This establishes the main motivation behind this work. Besides, to present a wider perspective to the reader, sensitivity analysis is given at the end of the application section to improve the potential of the study.

The contributions of the paper can be summarized as follows. First, a hybrid MCDM model by combining AHP and VIKOR in the fuzzy logic perspective is proposed for the evaluation and selection of the suppliers of an SME in Turkey based on many factors. More accurate ranking results are offered by the combination of FAHP and FVIKOR methods. Second, the obtained outputs of the case study of four alternative suppliers provide managerial insights into the manufacturing industry in Turkey. Third, the current picture of manufacturing-based SMEs during the pandemic is revealed for further studies.

LITERATURE

The attention of Supply Chain Management (SCM) has moved from production efficiency to customer-driven approaches. Therefore, implementing strategies requires a high level of cooperation between each element in the supply chain [2]. Most theories in the field of SCM provide a static view of its components and process, however recent crises show that supply chains are not static, but rather fluid. A new theory, panarchy theory, proposes that supply chains are a social-ecological system of cycles linked at different levels on scales of time and space [3]. Also, SCM must be rethought and reinterpreted to cope with extreme conditions such as pandemics, wars, climate change, or biodiversity collapse [4].

Supplier selection is an important process for companies and is critical to their success [5]. The right supplier selection for different products imposes suitable problem framing and a proper approach [6]. Effective supplier selection is of great importance in financial, operational, strategic, and managerial issues. One of the most important processes in supplier selection is determining the selection criteria appropriate for the objectives of the business. Although there are some common criteria valid in many businesses, the selection criteria are shaped according to the company's strategy. Some difficulties encountered in solving supplier selection problems, which play an important role in the success of businesses, can be grouped into three main groups as follows: (1) many qualitative or quantitative main and sub-criteria, (2) many supplier alternatives, and (3) conflicting and complementing criteria presence [7].

The first study in determining the supplier selection criteria was carried out by Dickson in 1966 with a survey. In this survey, 273 managers selected from the members of the National Association of Purchasing Managers answered 170 questions [8]. After this research based on 23 criteria, Weber supported Dickson's paper by accepting the price, quality, and distribution performance as the main criteria in supplier selection. In addition to these three main criteria, Weber also determined geographical location, capacity and possibilities, and technical skills as significant criteria in supplier selection. Contrary to expectations, in this study, it has been stated that price is not the most important criterion in SSP, whereas the most important criterion, quality, is followed by price and distribution performance, respectively [9]. According to Winston and Goldberg, the geographical locations and capacities of the suppliers, the preferences of the decision-makers, the product structure, and the supply policies of the enterprise, are among the criteria to be used for the measurement of supplier performance, making the supplier selection problem a multi-criteria problem [10]. In addition to the main criteria such as cost, quality, and service, Haq and Kannan stated around 15 sub-criteria in supplier selection [11]. The key approaches regarding supplier-related issues such as supplier-buyer relationships and supplier-buyer flexibility were reviewed [2]. Moreover, new criteria such as flexibility, innovation, and customer service have been added as a result of developing technology and increasing competition [12]. For the selection of suppliers, both qualitative and quantitative factors should be considered [13]. In this field, the green and agile parameters have been ignored by many researchers [14].

MCDM is an operational research area performed in a wide variety of academic fields and deals with decision problems under many conflicting criteria to discover the best alternative [15, 16]. MCDM methods are analytical tools and they enable the simultaneous assessment of many qualitative and quantitative factors [17]. MCDM techniques are used to resolve many real-life problems that comprise several criteria and alternatives [18–22]. These methods can be implemented in a variety of sectors and domains. In literature, the electrical-electronics, automotive, and manufacturing sectors have widely benefited from MCDM methods. 13% of the multi-criteria supplier selection studies carried out between 2000 and 2008 belong to the manufacturing sector, which is also the field of this paper [23]. The complex nature of SSP tends to create hybrid approaches with the integration of multiple MCDM techniques in practice [24–31]. SSP is generally recognized as MCDM, consequently, there are comprehensive reviews devoted to SSP including MCDM methodologies [32–36]. These MCDM methods can be grouped into four: (1) multi-featured utility methods (AHP, ANP), (2) outranking methods (ELECTRE, PROMETHEE), (3) compromise methods (TOPSIS, VIKOR), and (4) other MCDM techniques [34]. Authors must be careful while choosing normalization methods and parameters, as each MCDM method yields different results [37].

Utility value for each alternative is obtained in utility methods. Developed by Professor Thomas L. Saaty in the 1970s, Analytic Hierarchy Process (AHP) is a decision-making method used in complex problems involving multiple criteria [38]. In this method, the weight values of the criteria and the alternatives according to each criterion are determined by pairwise comparisons. With these values, the weight scores of each criterion and alternatives are calculated. Total scores are calculated for each decision alternative, and the options are ranked starting with the highest score. This method is used extensively in a wide range of areas, from decisions in simple personal problem areas to decisions in complex and capital-intensive problem areas [39]. Analytic Network Process (ANP) method is an extension of AHP in problems with feedback and dependencies. The priorities in the ANP are determined indirectly from pairwise comparison, similar to AHP [40].

Outranking methods consist of ELECTRE and PROMETHEE. The ELECTRE method and its derivatives have an important place in the outranking MCDM methods. The proper utilization is of the relations is the main objective of ELECTRE [41]. The preference functions are determined by a pair-wise comparison of alternatives in the PROMETHEE method developed by Brans [42].

Compromise methods are based on aggregating functions that denote the closeness to the ideal. Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) is an MCDM technique first developed by Ching-Lai Hwang and Yoon in 1981. This method is based on selecting the alternative with the shortest distance from the positive ideal solution and the farthest distance from the negative ideal solution [43]. Having conflicting criteria cases, the VIKOR method allows to choose the best of the set of alternatives or to rank the alternatives. A consensus ranking is obtained by comparing the closeness values of each alternative to the ideal alternative [44]. TOPSIS employs linear normalization to eliminate the units of criteria, while VIKOR uses vector normalization [45].

There are other MCDM methods applied in other studies. The utility functions which can be implemented to transform the raw performance values of the alternatives against criteria to a dimensionless scale, form the basis of the Multi-Attribute Utility Theory (MAUT) method in MCDM. Simple Multi-attribute Rating Technique (SMART) is the easier version of the MAUT methods [46]. Introduced in 2006, Multi-objective Optimization by Ratio Analysis (MOORA) is mainly proposed to overcome the weighting problem. The advantages of the method are its simplicity of mathematical computation and high stability [47]. Unlike the approaches that consider the relative distances from the ideal positive and negative solution, the Additive Ratio Assessment (ARAS) method is based on the comparison of the utility function values of the alternatives with the optimal utility function value determined by the decision-maker [48].

METHODOLOGY

Fuzzy sets and fuzzy logic concepts are employed in SSP since they are powerful methods for understanding human thoughts and using thoughts as mathematical tools by pouring them into models. In fuzzy logic, each element is associated with the degree of membership in a set expressed by numbers [49]. Evaluations with linguistic expressions are used by converting them into numerical values with fuzzy set theory. Apart from the triangular fuzzy functions used in this study, there are various types of fuzzy functions. Many methods combining fuzzy logic and MCDM techniques have been practiced in the field of SSP.

By integrating fuzzy set theory and hierarchical structure, various methods have been developed to determine the most suitable alternative in a multi-criteria environment or to rank the alternatives. Due to the fuzzy nature of the comparison process, rather than setting their pairwise comparisons as a fixed value, decision-makers prefer to express or verbalize them on a range. For this purpose, fuzzy AHP (FAHP) inserts the fuzzy theory into classical AHP which was developed by Saaty [50]. In the FAHP method, fuzzy numbers characterize the degree of relative importance in pairwise comparisons to manage the uncertainty [51]. Ho et al. [52] introduced a FAHP approach for the selection of wastewater technologies based on the objectives such as cost, carbon footprint, and are footprint. Tavana et al. [53] proposed an integrated MCDM model including fuzzy AHP which measures the importance of criteria for supply chain risk-benefit assessment. In a bearing manufacturing company, suppliers are compared and ranked according to criteria of quality and service [54]. The steps followed in FAHP are as follows [55]:

1. Decision-maker compares the criteria or alternatives with linguistic expressions, and these expressions are converted to equivalent fuzzy numbers.
2. The pairwise comparison matrice is shown below. $\tilde{d}_{ij}$ indicates the decision-maker's preference for i[th] criterion over the j[th] criterion, via fuzzy triangular numbers.

$$\tilde{A} = \begin{matrix} A_1 \\ A_2 \\ \vdots \\ A_m \end{matrix} \begin{bmatrix} \tilde{d}_{11} & \tilde{d}_{12} & \dots & \tilde{d}_{1n} \\ \tilde{d}_{21} & \tilde{x}_{22} & \cdots & \tilde{d}_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ \tilde{d}_{n1} & \tilde{d}_{n2} & \cdots & \tilde{d}_{nn} \end{bmatrix} \tag{1}$$

3. If there is more than one decision-maker, the preference of each decision-maker is averaged.
4. According to averaged preferences, pairwise comparison matrice is updated.
5. According to Buckley, the geometric mean of fuzzy comparison values of each criterion is calculated.

$$\tilde{r}_i = \prod_{j=1}^{n} \tilde{d}_{ij} \quad , i = 1, 2, \dots, n \tag{2}$$

6. Each vector summation of $\tilde{r}_i$ is calculated. (-1) power of summation vector is found, and the fuzzy triangular numbers are replaced to create increasing order. To find the fuzzy weight of criterion i, $\tilde{w}_i$, each $\tilde{r}_i$ is multiplied with a reverse vector.

$$\tilde{w}_i = \tilde{r}_i \otimes (\tilde{r}_1 \oplus \tilde{r}_2 \oplus .. \oplus \tilde{r}_n)^{-1} = (\mathrm{l}w_i + \mathrm{m}w_i + \mathrm{u}w_i) \tag{3}$$

7. Defuzzification is fulfilled.

$$M_i = \frac{\mathrm{l}w_i + \mathrm{m}w_i + \mathrm{u}w_i}{3} \tag{4}$$

8. M_i is a nonfuzzy number, but it has to be normalized.

$$N_i = \frac{M_i}{\sum_{i=1}^{n}(M_i)} \tag{5}$$

Sorting alternatives with conflicting criteria enables decision-makers to obtain the most suitable decision in the VIKOR method. In reality, it is not easy to have accurate criteria weights, therefore uncertain information with linguistic expressions have to be transformed into fuzzy numbers by applying fuzzy logic to the VIKOR method. The most effective cold chain supplier in Pakistan according to key factors responsible for a sustainable supplier is studied by the fuzzy VIKOR approach [56]. Another study in selecting green suppliers for sponge iron and steel manufacturing company is conducted by employing fuzzy VIKOR to generate an overall score for each supplier [57]. An integrated model for evaluating and selecting the third-party logistics provider is employed by integrated fuzzy AHP and fuzzy VIKOR methods [58]. The steps followed in the fuzzy VIKOR method are as follows:

1. Decision-makers(n), alternatives(m) and criteria(k) are determined.
2. Fuzzy numbers corresponding to linguistic expressions are determined.
3. The integrated fuzzy weight for each criterion is calculated from the combined evaluation of decision-makers.

$$\tilde{w}_j = \frac{1}{n}\left[\sum_{e=1}^{n} \tilde{w}_j^e\right] \; j = 1,2,\dots,k \tag{6}$$

$$\tilde{x}_{ij} = \frac{1}{n}\left[\sum_{e=1}^{n} \tilde{x}_{ij}^e\right] \quad i = 1,2,\dots,m \tag{7}$$

4. The degrees of alternatives are calculated according to each criterion. $\tilde{x}_{ij}$ is the degree of alternative, $\tilde{w}_j$ is the weight of j[th] criterion.

$$\tilde{D} = \begin{matrix} \\ A_1 \\ A_2 \\ \vdots \\ A_m \end{matrix} \begin{matrix} C_1 & C_2 & \dots & C_k \\ \tilde{x}_{11} & \tilde{x}_{12} & \dots & \tilde{x}_{1n} \\ \tilde{x}_{21} & \tilde{x}_{22} & \cdots & \tilde{x}_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ \tilde{x}_{m1} & \tilde{x}_{m2} & \cdots & \tilde{x}_{mk} \end{matrix} \tag{8}$$

$$i = 1,2,\dots,m\,; \; j = 1,2,\dots,k$$

$$\tilde{W} = [\tilde{w}_1, \quad \tilde{w}_2, \quad \dots \quad \tilde{w}_k], \; j = 1,2,\dots,k \tag{9}$$

5. The fuzzy best and worst values are evaluated. $\tilde{f}_j^*$ is the fuzzy best, and $\tilde{f}_j^-$ is the fuzzy worst value.

$$\tilde{f}_j^* = \max_i \tilde{x}_{ij}, \quad \tilde{f}_j^- = \min_i \tilde{x}_{ij} \tag{10}$$

6. $\tilde{S}_i$ is the sum of the distances of criteria values of alternative A_i from the fuzzy best value. $\tilde{R}_i$ is the maximum distance from the fuzzy worst value of the alternative A_i according to criterion j.

$$\tilde{S}_i = \sum_{j=1}^{k} \tilde{w}_j(\tilde{f}_j^* - \tilde{x}_{ij}) / (\tilde{f}_j^* - \tilde{f}_j^-) \quad (11)$$

$$\tilde{R}_i = \max_j [\tilde{w}_j(\tilde{f}_j^* - \tilde{x}_{ij}) / (\tilde{f}_j^* - \tilde{f}_j^-)] \quad (12)$$

7. $\tilde{S}^*$ is the maximum group utility, and $\tilde{R}^*$ is the minimum regret of the opposing viewers. According to these values, $\tilde{Q}_i$ index is calculated with the following equation. The v value below represents the weight of the strategy at maximum group utility. Compromise (v>0.5), consensus (v=0.5), or veto (v<0.5) can be achieved.

$$\tilde{S}^* = \min_i \tilde{S}_i, \quad \tilde{S}^- = \max_i \tilde{S}_i \quad (13)$$

$$\tilde{R}^* = \min_i \tilde{R}_i, \quad \tilde{R}^- = \max_i \tilde{R}_i \quad (14)$$

$$\tilde{Q}_i = (v)(\tilde{S}_i - \tilde{S}^*)/(\tilde{S}^- - \tilde{S}^*) + (1-v)(\tilde{R}_i - \tilde{R}^*)/(\tilde{R}^- - \tilde{R}^*) \quad (15)$$

8. The triangular fuzzy number $\tilde{Q}_i$, is converted into the Q_i index with the BNP (Best Nonfuzzy Performance Value) method and the smallest value of this index represents the best alternative. u_i represents the upper value of the triangular fuzzy number, m_i the middle value, and l_i the lower value.

$$BNP_i = \frac{[(u_i - l_i) + (m_i - l_i)]}{3} + l_i \quad \forall i \quad (16)$$

9. If the following two conditions are met, a compromise solution is found with the index Q_i (a').

Condition 1: According to the value of Q, the value a'' becomes the alternative that takes second in the ranking.

$$Q(a'') - Q(a') \geq DQ \quad (17)$$

$$DQ = \frac{1}{m-1} \quad (if\ m \leq 4\ and\ DQ = 0.25) \quad (18)$$

Condition 2: The best alternative is a' in the order made according to the S and/or R values. Unlike condition 1, if $Q(a^{(m)})-Q(a')<DQ$ and condition 1 is not satisfied, $a^{(m)}$ and a' are similar conciliatory solutions therefore a' does not have a comparative advantage. If Condition 2 is not satisfied, a' will have a comparative advantage but there appears to be no stability for decision-making, so the conciliatory solution of a' and a'' will be the same [59].

APPLICATION

In the application part, a Turkish SME that carries out the manufacturing and sales activities of machine parts is investigated during the COVID-19 pandemic conditions. There is a research gap on how the pandemic has affected the supplier selection criteria and become an important moderator in Turkey. For this company, which has a growth-oriented strategy of improving its position in the sector, the analysis of supplier performances and the selection of the most beneficial supplier are vital issues. Since there are many supplier alternatives, it is necessary to decide on the appropriate criteria in the selection process. For this reason, the factors that are thought to have the most critical effects on SSP are determined by 3 experts working in the enterprise. 4 supplier alternatives are evaluated according to 11 sub-criteria formed from the 4 main criteria. The main and sub-criteria are given in the Table 1.

Table 1. Criteria in the model

Main criteria	Sub-criteria
Quality	Technical capability (Q1)
	Defect rate (Q2)
	Shelf life (Q3)
Time	Delivery time (T1)
	Latency rate (T2)
	Distance (T3)
Service	Suitability (S1)
	Continuity (S2)
	Response time (S3)
Cost	Price (C1)
	Deferred payment (C2)

As the fuzzy logic purposes to reach the closest results corresponding to the linguistic expressions with fuzzy numbers, this approach is applied in the study to overcome uncertainty. Thus, it is aimed to reach the best option by analyzing the alternatives of supplier companies with different geographical regions, costs, quality, and time during COVID-19. The obtained linguistic variables from the questionnaires are transformed into fuzzy numbers by equivalent triangular values. The hierarchical structure of the problem is as Figure 1.

The proposed model can be divided into two sections. In the first part of the study, fuzzy pairwise comparison matrices are formed with the values obtained from the questionnaires by using FAHP to determine the fuzzy criterion weights. In the second part, the rankings of different suppliers are determined to obtain a compromise solution by using the Fuzzy VIKOR methodology. Criteria are assessed with the linguistic variables by the decision-makers. The fuzzy significance levels used in the pairwise comparisons are shown in Table 2.

The geometric mean of pairwise comparison matrices obtained from decision-makers are constructed and the weights calculated (Table 3–6).

Normalized weight vector for sub-criteria of quality is calculated as $W=(0.55, 0.34, 0.11)^T$. The main criterion, *quality*, consists of the sub-criteria as technical capability, defect rate, and shelf life. Technical capability has been observed as the most significant sub-criterion.

Normalized weight vector for sub-criteria of *time* is calculated as $W=(0.74, 0.26, 0.00)^T$. The main criterion, time, consists of the sub-criteria as delivery time, latency rate, and dis-

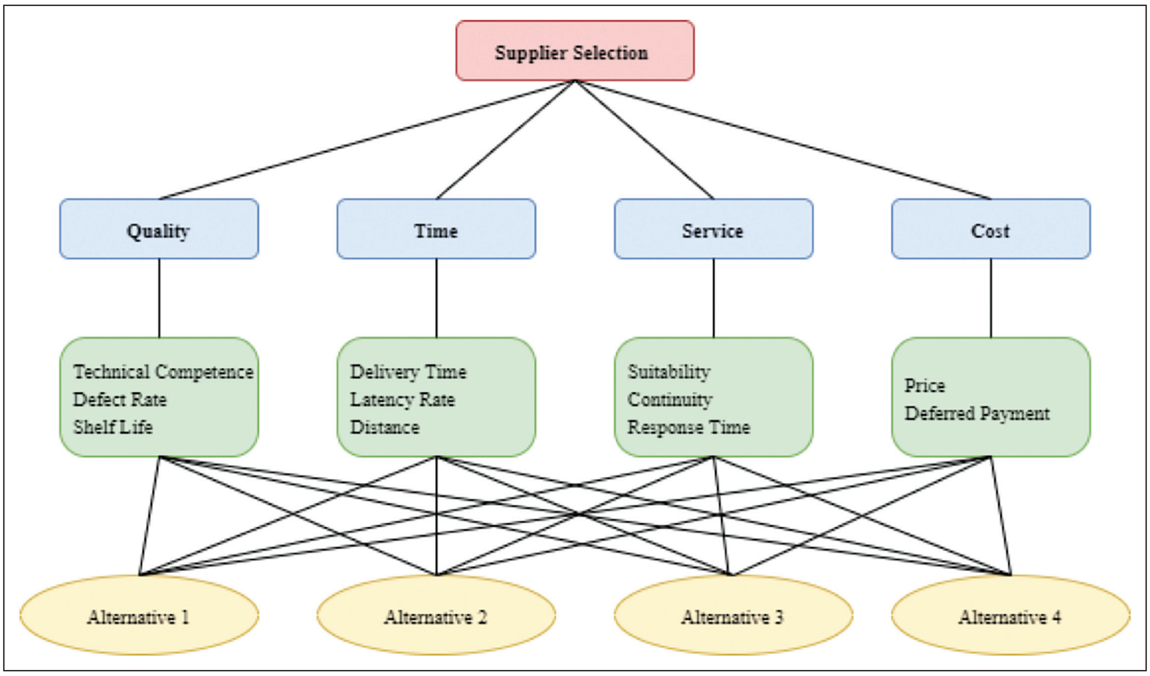

Figure 1. Hierarchical structure.

Table 2. Triangular fuzzy numbers for linguistic expressions for the criteria [60]

Linguistic variables	Fuzzy Scale
Q Equally preferred (EP)	(1, 1, 1)
	(1, 2, 3)
Weakly preferred (WP)	(2, 3, 4)
	(3, 4, 5)
Fairly strongly preferred (FSP)	(4, 5, 6)
	(5, 6, 7)
Very strongly preferred (VSP)	(6, 7, 8)
	(7, 8, 9)
Absolutely preferred (AP)	(8, 9, 9)

tance. Delivery time has been observed as the most significant sub-criterion, however, distance is an ineffective sub-criterion.

Normalized weight vector for sub-criteria of *service* is calculated as $W=(0.50, 0.26, 0.24)^T$. The main criterion, service, consists of the sub-criteria as suitability, continuity, and response time. Suitability has been observed as the most significant sub-criterion. However, continuity and response time have similar effects on the decision-making process.

The normalized weight vector for sub-criteria of *cost* is calculated as $W=(0.89, 0.11)^T$. The main criterion, cost, consists of sub-criteria as price, and deferred payment. Price has been observed as the most significant sub-criterion of cost.

The most effective criterion in the supplier selection is price, and it is followed by delivery time, and technical capability whereas distance is ineffective, according to the decision-makers (Fig. 2). Depending on the criterion weight values obtained at the end of the first stage, fuzzy VIKOR is implemented in the second stage for the preference rankings of the alternatives. The triangular fuzzy numbers corresponding to the linguistic expressions for alternatives are as Table 7.

The fuzzy weights and integrated fuzzy decision matrices are determined (Table 8, 9). The fuzzy best(f_j^*) and worst (f_j^-) values are calculated for each criterion (Table 10).

The distance values of the alternative to the best value are exposed as $\tilde{S}_i$ and the values of the distance to the worst value are shown as $\tilde{R}_i$ (Table 11).

The maximum group utility denoted by $\tilde{S}^*$and the minimum regret value denoted by $\tilde{R}^*$ is calculated (Table 12). Based on $\tilde{S}_i$ and $\tilde{R}_i$ values, $\tilde{Q}_i$ values are calculated using each v value as 0.5. and alternatives are listed according to index values (Table 13).

The orders of the alternatives are illustrated in Table 14 for Q, S, and R indexes. In all 3 cases, it is seen that Alternative 2 is in the first place. However, to obtain a compromise solution, conditions must be checked. In the application, since there are 4 alternatives, the DQ value is determined as 0.33 and the Qi index difference between A1 and A2 is 0.476, which is greater than the DQ value. Also, the Si index difference between A1 and A2 is 0.416, which is again greater than DQ value. Thus, both conditions are met and the compromise solution is acquired, and the second alternative should be preferred for the SSP.

The projected model can provide supplementary information. If the v value is 0, according to equation 15, $\tilde{Q}_i$ value is only impacted by the $\tilde{R}_i$ value. This fact points out which factor should be considered the most essential to SSP. Thus,

Table 3. The geometric mean of fuzzy pairwise comparison matrices for quality

	Technical capability (Q1)	Defect rate (Q2)	Shelf life (Q3)
Technical capability (Q1)	(1.00, 1.00, 1.00)	(1.26, 2.29, 3.30)	(1.59, 2.62, 3.63)
Defect rate (Q2)	(0.30, 0.44, 0.79)	(1.00, 1.00, 1.00)	(1.00, 2.00, 3.00)
Shelf life (Q3)	(0.28, 0.38, 0.63)	(0.33, 0.50, 1.00)	(1.00, 1.00, 1.00)

Table 4. The geometric mean of fuzzy pairwise comparison matrices for time

	Delivery time (T1)	Latency rate (T2)	Distance (T3)
Delivery time (T1)	(1.00, 1.00, 1.00)	(1.59, 2.62, 3.63)	(2.62, 3.63, 4.64)
Latency rate (T2)	(0.28, 0.38, 0.63)	(1.00, 1.00, 1.00)	(1.00, 2.00, 3.00)
Distance (T3)	(0.22, 0.28, 0.38)	(0.33, 0.50, 1.00)	(1.00, 1.00, 1.00)

Table 5. The geometric mean of fuzzy pairwise comparison matrices for service

	Suitability (S1)	Continuity (S2)	Response time (S3)
Suitability (S1)	(1.00, 1.00, 1.00)	(1.00, 1.59, 2.08)	(0.69, 1.00, 1.44)
Continuity (S2)	(0.48, 0.63, 1.00)	(1.00, 1.00, 1.00)	(1.00, 1.26, 1.44)
Response time (S3)	(0.69, 1.00, 1.44)	(0.69, 0.79, 1.00)	(1.00, 1.00, 1.00)

Table 6. The geometric mean of fuzzy pairwise comparison matrices for cost

	Price (C1)	Deferred payment (C2)
Price (C1)	(1.00, 1.00, 1.00)	(1.26, 1.82, 2.29)
Deferred payment (C2)	(0.44, 0.55, 0.79)	(1.00, 1.00, 1.00)

Table 7. Triangular fuzzy numbers for linguistic expressions for the alternatives [60]

Alternative evaluation	
Linguistic variables	**Fuzzy numbers**
Very bad (VB)	(0, 0, 1)
Bad (B)	(0, 1, 3)
Moderate bad (MB)	(1, 3, 5)
Medium (M)	(3, 5, 7)
Moderate good (MG)	(5, 7, 9)
Good (G)	(7, 9, 10)
Very good (VG)	(9, 10, 10)

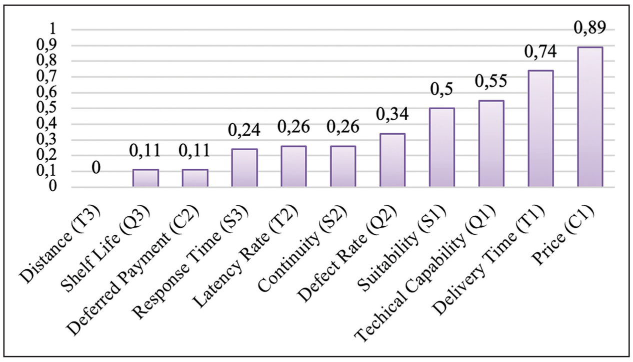

Figure 2. Weights of criteria.

improvement areas can be identified. For instance, concerning $\tilde{R}_i$ values in Table 15, suppliers should focus on improving Deferred Payment (C2), Continuity (Q2), and Delivery Time (T1). Although A2 presented a high performance for all the sub-criteria, still Continuity (Q2) could be enhanced.

In this business, the first supplier alternative was preferred due to subjective choices considering only cost and quality factors. After this study, it is encouraged by the authorities to identify and consider other impactful criteria in the supplier selection process. From a broader perspective with many factors included in the decision-making process, it is specified that Alternative 2, not Alternative 1, provides more advantages for the company's strategic goals.

To maximize the potential of the proposed model, one more issue should be explored. The sensitivity analysis for influence levels of v value in VIKOR can be advanced to identify which supplier alternatives are affected considerably by *maximum group utility* and *minimum individual regret*. The parameter v represents the weight of the maximum group utility strategy, while (1-v) presents the weight of individual regret. It is common in the literature to take the v value as 0.5 [61]. It is aimed to determine the ranking order of supplier alternatives according to the influence level of the v value. According to Figure 3, the v value does not

Table 8. Integrated fuzzy decision matrix

Main criteria	Sub-criteria	Alternatives	(l, m, u)
Quality (Q)	Technical capability (Q1)	A1	(4.33, 6.33, 8.33)
		A2	(7.67, 9.33, 10.00)
		A3	(6.33, 8.33, 9.67)
		A4	(8.33, 9.67, 10.00)
	Defect rate (Q2)	A1	(4.33, 6.33, 8.33)
		A2	(4.33, 6.33, 8.33)
		A3	(5.67, 7.67, 9.00)
		A4	(6.33, 8.33, 9.67)
	Shelf life (Q3)	A1	(4.33, 6.33, 8.00)
		A2	(7.00, 8.67, 9.67)
		A3	(6.33, 8.33, 9.67)
		A4	(0.67, 2.33, 4.33)
Time (T)	Delivery time (T1)	A1	(8.33, 9.67, 10.00)
		A2	(7.00, 9.00, 10.00)
		A3	(6.33, 8.00, 9.33)
		A4	(3.67, 5.67, 7.67)
	Latency rate (T2)	A1	(5.67, 7.67, 9.33)
		A2	(3.00, 5.00, 7.00)
		A3	(4.33, 6.33, 8.33)
		A4	(1.33, 3.00, 5.00)
	Distance (T3)	A1	(3.67, 5.67, 7.67)
		A2	(4.33, 6.33, 8.33)
		A3	(3.00, 5.00, 7.00)
		A4	(0.67, 2.33, 4.33)
Service (S)	Suitability (S1)	A1	(7.67, 9.33, 10.00)
		A2	(6.33, 8.00, 9.00)
		A3	(6.33, 8.33, 9.67)
		A4	(4.33, 6.33, 8.33)
	Continuity (S2)	A1	(5.00, 7.00, 8.67)
		A2	(7.00, 8.67, 9.67)
		A3	(5.67, 7.67, 9.33)
		A4	(2.33, 4.33, 6.33)
	Response time (S3)	A1	(5.00, 7.00, 8.67)
		A2	(6.33, 8.33, 9.67)
		A3	(6.33, 8.33, 9.67)
		A4	(5.00, 7.00, 8.67)
Cost(C)	Price (C1)	A1	(8.33, 9.67, 10.00)
		A2	(8.33, 9.67, 10.00)
		A3	(7.00, 8.67, 9.67)
		A4	(8.33, 9.67, 10.00)
	Deferred payment (C2)	A1	(8.33, 9.67, 10.00)
		A2	(5.00, 7.00, 8.67)
		A3	(3.00, 5.00, 7.00)
		A4	(2.33, 4.33, 6.33)

Table 9. Sub-criteria and fuzzy weights

Main criteria	Sub-criteria	Sub-criteria fuzzy weights
Quality	Techical capability (Q1)	(0.25, 0.52, 1.00)
	Defect rate (Q2)	(0.15, 0.30, 0.61)
	Shelf life (Q3)	(0.10, 0.17, 0.33)
Time	Delivery time (T1)	(0.31, 0.55, 0.95)
	Latency rate (T2)	(0.14, 0.26, 0.47)
	Distance (T3)	(0.09, 0.14, 0.24)
Service	Suitability (S1)	(0.30, 0.40, 0.50)
	Continuity (S2)	(0.28, 0.32, 0.38)
	Response time (S3)	(0.27, 0.31, 0.38)
Cost	Price (C1)	(0.44, 0.65, 0.89)
	Deferred payment (C2)	(0.28, 0.35, 0.49)

Table 10. The fuzzy best and worst values

Main criteria	Sub-criteria	Fuzzy best	Fuzzy worst
Quality	Technical capability (Q1)	(8.33, 9.67, 10.00)	(4.33, 6.33, 8,33)
	Defect rate (Q2)	(6.33, 8.33, 9.67)	(4.33, 6.33, 8.33)
	Shelf life (Q3)	(7.00, 8.67, 9.67)	(0.67, 2.33, 4.33)
Time	Delivery time (T1)	(8.33, 9.67, 10.00)	(3.67, 5.67, 7.67)
	Latency rate (T2)	(5.67, 7.67, 9.33)	(1.33, 3.00, 5.00)
	Distance (T3)	(4.33, 6.33, 8.33)	(0.67, 2.33, 4.33)
Service	Suitability (S1)	(7.67, 9.33, 10.00)	(4.33, 6.33, 8.33)
	Continuity (S2)	(7.00, 8.67, 9.67)	(2.33, 4.33, 6.33)
	Response time (S3)	(6.33, 8.33, 9.67)	(5.00, 7.00, 8.67)
Cost	Price (C1)	(8.33, 9.67, 1.00)	(7.00, 8.67, 9.67)
	Deferred payment (C2)	(8.33, 9.67, 10.00)	(2.33, 4.33, 6.33)

Table 11. $\tilde{S}_i$ and $\tilde{R}_i$ values

Alternatives	$\tilde{S}_i$	$\tilde{R}_i$
A1	(0.85, 1.03, 2.25)	(0.27, 0.52, 1.00)
A2	(0.61, 0.92, 1.34)	(0.15, 0.30, 0.61)
A3	(1.28, 2.14, 2.39)	(0.44, 0.65, 0.89)
A4	(1.77, 1.88, 3.74)	(0.31, 0.55, 0.95)

affect the ranking order of A2. In other words, A2 has the highest performance among the alternatives given the maximum group utility and minimum individual regret. Likewise, A1 is not impacted by the influence level. This alternative provides the second-best option from the perspective of maximum group utility and minimum individual regret. Conversely, there is an improvement in the ranking of A3 after the influence level of v exceeds 0.4, while A4 ranking is enhanced at v values less than 0.5. These changes reveal that the performance of A3 has been enriched when concentrating on minimum individual regret, whereas A4 has enhanced when focusing on maximum group utility.

Table 12. Maximum group values and minimum regret values

$\tilde{S}^*$	(0.61, 0.92, 1.34)
$\tilde{S}^-$	(1.77, 2.14, 3.74)
$\tilde{R}^*$	(0.15, 0.30, 0.61)
$\tilde{R}^-$	(0.44, 0.65, 0.95)

MANAGERIAL IMPLICATIONS

By utilizing the proposed methodology, an effective computation of the relative importance of the SSP criteria is achieved. As a result of the empirical research, the authors found that the proposed approach is a practical tool for evaluating supplier alternatives in terms of their overall performance. The proposed method also guides identifying improvement areas. Technical capability has been observed as the most significant sub-criterion of *quality*. Delivery time has been observed as the most significant sub-criterion, however, distance is an ineffective sub-criterion of *time*. Suitability has been observed as the most significant

Table 13. Index values and ranking of alternatives

Alternatives	Q_i index	Ranking	S_i index	Ranking	R_i index	Ranking
A1	0.476	2	1.375	2	0.597	2
A2	**0.000**	**1**	**0.958**	**1**	**0.353**	**1**
A3	0.807	3	1.939	3	0.660	4
A4	0.842	4	2.463	4	0.603	3

Table 14. Order of alternatives

Q_i	A2>	A1>	A3>	A4>
S_i	A2>	A1>	A3>	A4>
R_i	A2>	A1>	A4>	A3>

Table 15. $\tilde{R}_i$ values of alternatives

Alternatives	Q1	Q2	Q3	T1	T2	T3	S1	S2	S3	C1	C2
A1	0.59	0.35	0.07	0.00	0.00	0.03	0.00	0.12	0.22	0.00	0.00
A2	0.04	**0.35**	0.00	0.06	0.16	0.00	0.20	0.00	0.00	0.00	0.15
A3	0.18	0.15	0.01	0.21	0.08	0.05	0.12	0.12	0.10	0.66	0.32
A4	0.00	0.00	0.20	0.60	0.29	0.16	0.40	0.40	0.11	0.00	0.37

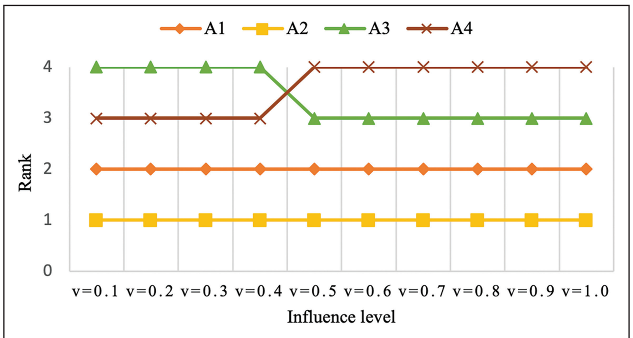

Figure 3. Sensitivity analysis for influence levels of the v value in VIKOR.

sub-criterion of *service*. However, continuity and response time have similar effects on the decision-making process. Price has been observed as the most significant sub-criterion of *cost*. The most effective criterion in the supplier selection is price, and it is followed by delivery time, and technical capability whereas distance is ineffective, according to the decision-makers. According to the compromise solution, A2 should be preferred for the SSP.

The projected model can provide supplementary information. Although A2 presented a high performance for all the sub-criteria, still Continuity (Q2) could be enhanced. A2 has the highest performance among the alternatives given the maximum group utility and minimum individual regret. Likewise, A1 is not impacted by the influence level of v value. This alternative provides the second-best option from the viewpoint of maximum group utility and minimım individual regret. Conversely, there is an improvement in the ranking of A3 after the influence level of v exceeds 0.4, while A4 ranking is enhanced at v values less than 0.5. These changes reveal that the performance of A3 has been enriched when focusing on minimum individual regret, whereas A4 has enhanced when focusing on maximum group utility. Since a decision support system is not used in the supplier selection process in the company, it is anticipated that the decision-making procedure obtained with this application will be effective in the company's effort to preserve its success sustainability. In addition, it is planned to make performance measurements periodically.

CONCLUSION

Supplier selection is a strategic issue that is highly influential on long-term business performance. In the supplier selection process of the SME examined during the COVID-19 conditions in this study, the selection criteria are determined according to the enterprise objectives. Delivery time, latency rate, and distance of the supplier are important indicators for the time criteria. A decrease in quality offered to customers can risk the reliability of the business. Therefore, a great focus should be put on quality criteria, technical capability, defect rate, and shelf life to retain the customer. The suitability, continuity, and response time directly impact customer experience. In addition to the role in the success of the company, suppliers may also become solution partners and establish strategic relationships. The supplier selection decision is of great importance for manufacturing companies.

The performances of four different alternative suppliers are examined using a hybrid MCDM method in the scope of the pandemic. The criteria weights are determined by fuzzy AHP, and the ranking of alternatives is organized by fuzzy VIKOR. The conversion of linguistic expressions into mathematical values while resorting to expert opinions is made possible by the inclusion of fuzzy logic philosophy. As a result of the evaluations, a compromise solution is obtained and Alternative 2 is recommended to be chosen. It is predicted that working with Alternative 2, instead of Alternative 1 that the company actively supplies, will be more profitable in a strategic sense. In today's changing conditions and competitive environment, it is suggested that the company should regularly measure the performance of its suppliers and update these criteria at certain intervals to offer its customers ever-increasing quality with minimum cost.

There are some areas for further studies. First, more evaluation criteria including sustainability, social, and extreme conditions criteria can be included in the SSP and different hybrid models can be compared. Second, objective weighting methods, for example, entropy and multiple objective programming can be added to the model to compare the efficiency between these methods and subjective weighting methods. Third, a computer-aided decision support system may be developed for the automated evaluation of suppliers. Forth, other advanced fuzzy logics such as the Pythagorean fuzzy set can be used to overcome uncertainty, and different fuzzy logics can be compared in terms of their effectiveness.

Data Availability Statement

The authors confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

Author's Contributions

Cansel Çekiç: Conceptualization, methodology, original draft preparation, investigation, computation.

Nezihe Nazlı Gül: Conceptualization, methodology, investigation, writing, computation.

Ali Fuat Güneri: Conceptualization, methodology, investigation.

Conflict of Interest

The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Ethics

There are no ethical issues with the publication of this manuscript.

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