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Research Article

A COMPARATIVE PERSPECTIVE IN SUSTAINABLE SUPPLIER SELECTION BY INTEGRATED MCDM TECHNIQUES

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ABSTRACT

In recent years, concept of sustainability has emerged with increasing awareness of environment-friendly practices and social issues of organizations, researchers, and the business community. For this reason, enterprises have integrated this concept into supply chain management (SCM) by revising on supply chains. In this study, the sustainability concept is combined with the supplier selection process and an integrated approach is proposed to identify best sustainable suppliers. Because of the uncertainties present in individual judgments in sustainable supplier selection (SSS), fuzzy integrated multi-criteria decision making (MCDM) methods are applied in this study. Sustainability criteria are identified from the existing literature and narrowed by NGT (Nominal Group Technique) to build a consensus in group decision-making. A two-stage approach is reported after the identification of criteria and suppliers. In the first stage, the fuzzy Analytic Hierarchy Process (AHP) approach is used to obtain the weights of the SSS criteria and the fuzzy TOPSIS, fuzzy VIKOR and fuzzy MULTIMOORA methods are used to generate the ranking of sustainable suppliers in the second stage. The validity and effectiveness of the proposed approach is illustrated in a foundry manufacturer through a case study. Results show that the three applied fuzzy integrated methods reach similar supplier rankings and the economic perspective between the three dimensions of sustainability is held the first rank.
Keywords: Foundry sector, fuzzy AHP, fuzzy TOPSIS, fuzzy VIKOR, fuzzy MULTIMOORA, sustainable supplier selection.

1. INTRODUCTION

Companies have investigated new ways to respond customer requests in a timely, accurate and fast as a result of changing competitive environment. Supply chain management (SCM) is a network between a company and its corporates who are interlinked by each other even they require a lot of skill and expertise. Purchasing and sourcing in a company is crucial, and successful SCM operations are based on strategic alliances with the right suppliers. The purchasing cost of parts for a business involves a large part of the total cost of a product. A large part of the total production cost (about 70%) of companies is composed of parts costs and the selection of suitable suppliers leads to a considerable decrease in the purchasing costs of the

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companies. Therefore, supplier selection is considered the key for achieving intended objectives in the SCM [1, 2].

Instead of fo cusing only on economic performance, businesses have begun to address social, environmental and economic dimensions together in SCM. The need to change in increasing market demand and consumption models has led to the emergence of the concept of sustainability beginning in the 1990s [3]. Leading international companies such as Shell, Bristol-Myers Squibb and Unilever who recognize the importance of sustainability have included three dimensions of sustainability for sustainable development into the overall strategies of their companies [4].

As well as all over the world, some of the leading companies in Turkey have begun to implement sustainability practices to survive in the global market. The Turkish foundry sector is one of the keystones of the Turkish manufacturing industry. Foundry products are used as inputs in almost all industrial branches, thus foundry sector has an essential significance in the manufacturing industry. In fact, there is at least one foundry product in 90% of the produced industrial products [5]. In order to keep the size of the Turkish foundry industry reached in recent years, foundry manufacturers have begun to focus on selecting and evaluating suppliers.

The supplier selection is a Multi-Criteria Decision Making (MCDM) problem that allow the evaluation of many strategic and operational factors at the same time. Usage of these methods guide to the managers and allows them to make the right decisions [6]. Over the years, changing consumer requirements, strict legislation and legal regulations have led to changes in priorities of criteria that enterprises use in supplier evaluation and reveals the concept of sustainable suppliers [7, 8].

Sustainable supplier selection (SSS) requires operational considerations to take into account certain qualifications beyond conventional supplier selection criteria [9, 10]. Even though companies evaluate suppliers' performance considering conventional criteria such as cost, quality, and on time delivery however dimensions of sustainability should be taken into consideration in the selection of suppliers [11]. The economic dimension [7, 10], environmental dimension[12] and social dimension [10] has been investigated from many researchers. In the light of these discussed issues, companies must address not only on the traditional criteria for supplier selection but also dimensions of sustainability. Therefore, in this study, the three dimensions of sustainability are investigated in the Turkish foundry industry for SSS. In this sense, the following research questions will be answered:

- To identify the criteria for SSS in the foundry industry
- To determine which sustainability dimension is important for the assessment of sustainable suppliers in the foundry industry
- To obtain the level of importance of main criteria and sub-criteria for SSS in the foundry industry
- Identifying and ranking the appropriate suppliers with different MCDM methods for SSS in the foundry industry
- To determine which method is the most suitable for the SSS in the foundry industry
- To determine whether there is a relationship between supplier rankings obtained for the SSS in the foundry industry
- To demonstrate the managerial and practical results of working in the foundry industry

Based on the above questions the main purpose of this work is to present a framework for SSS in a foundry company which is the main supplier of production plants in Turkey. For this purpose, an integrated approach has been proposed to find answers and identify appropriate sustainable suppliers. A nominal group technique is used at a meeting with government officials, business managers and academics to define the criteria to be used in selecting and evaluating sustainable suppliers in the foundry sector. Later the level of importance of the criteria are obtained by industry managers and experts responsible for field experts based on a questionnaire. The fuzzy AHP method is utilized to address uncertainty of experts' views and to determine the level of importance of main criteria and sub-criteria by of paired comparisons. Later on, Techniques for Order Preference by Similarity to Ideal Solution (TOPSIS), Vlsekriterijumska Optimizacija I Kompromisno Resenje (VIKOR) and MULTIMOORA methods are used in a fuzzy environment to select sustainable suppliers and compare the performance of these three popular MCDM methods.

The rest of paper is structured as follows. Section 2 provides an overview of supplier selection and SSS. Section 3 introduces Fuzzy AHP, fuzzy TOPSIS, fuzzy VIKOR and fuzzy MULTIMOORA methods. Section 4 contains the case study application and discussion of results. Section 5 clarifies conclusion and outlook for future studies.

2. LITERATURE REVIEW

For first time, Dickson [13] raised considerable ideas about supplier selection and prepared a list for supplier selection and shed light on the next researcher who will work on this area. This work was later extended by Weber et al. [14] for supplier selection. In the past five decades, various studies have been performed to evaluate suppliers. However, most of the studies in supplier selection utilities economic criteria, including cost, quality, delivery time and service level. In terms of environmental criteria, many authors have completed a series of literature reviews with supplier selection. Igarashi et al. [15] reviewed articles in the field of green supplier selection. Saputro et al. [16] presented a literature survey for material handling equipment selection problem.

Since suppliers can be assessed from different perspectives, various models of MCDM are proposed for supplier selection. [17–21]. According to Zimmer et al. [22] the electronics and automotive industry is the most preferred research area in sustainable supplier management. Textile, chemicals and pharmaceuticals and mining and quarrying industries are coming after the electronics and automotive industry. Although, the number of studies has increased rapidly in last decades, it has not been found any study on supplier selection in foundry sector.

By controlling the sustainability factors, companies take a more economically proper position, and for this reason many researchers have researched the sustainable SCM in different areas [17]. Rajeev et al. [3] performed a literature review over the period 2000-2015 (July) by studying 1068 articles. They showed that studies in developed economies have led than from developing economies and general sustainable development studies have potential for future researches especially for developing economies. Since there are more than 2500 articles between 2000 and 2015, only SSS has been considered in this section.

SSS has a number of advantages while the above studies deal with supplier selection in crisp and fuzzy environments. Some of the recent researches on SSS are described as follows: Kahraman et al. [23] used fuzzy AHP to select best supplier for a white good manufacturer in Turkey. Rouyendegh and Saputro [24] combined fuzzy TOPSIS with Multi Choice Goal Programming to specify the appropriate supplier and determine order allocation of each appropriate supplier. Rouyendegh [25] presented a hybrid model using both the ANP and Intuitionistic Fuzzy TOPSIS models for supplier selection. Dai and Blackhurst [26] developed an integrated approach using AHP with quality function deployment to express the sustainability requirements of the stakeholders. Azadi et al. [11] proposed a Data Envelopment Analysis (DEA) model to evaluate suppliers for an Iranian company. Zimmer et al. [22] analyzed the publications between 1997 and 2014 to address on sustainable supplier management. Fallahpour et al. [17] determined the importance of sustainable criteria in the evaluation of suppliers' sustainability and developed an integrated MCDM model using fuzzy preference programming and fuzzy TOPSIS methods. Luthra et al. [8] used AHP-VIKOR based approach to prioritize SSS criteria on an automotive company in India. Song et al. [27] proposed an integrated approach considering pairwise comparison method, DEMATEL, and rough set theory that is validated in a case study of solar air-conditioner manufacturer. Awasthi et al. [28] presented a fuzzy AHP-VIKOR approach for SSS dealing with risk concerns. Kannan [29] implemented a real-world case study designing a decision support system based on the triple bottom line approach. Vahidi et al. [30] proposed a hybrid framework with SWOT and quality function deployment for choosing the most relevant sustainability criteria. Rouyendegh et al. [31] applied Intuitionistic Fuzzy TOPSIS method to determine the most appropriate green supplier according to 10 criteria. Rouyendegh et al. [32] determined the best suitable site for wind power plant in Turkey by Intuitionistic Fuzzy TOPSIS method.

Table 1 contains a summary and comparison of studies on SSS. Integrated MCDM methods are generally used for SSS, as seen in the literature review. AHP or fuzzy AHP methods have been used in different areas for companies in their strategic decisions to calculate criteria weights and achieve better results [7]. Although there are many techniques for identifying suitable suppliers, Fuzzy TOPSIS, VIKOR and MULTIMOORA methods that ease of calculation, representing human preferences and generating an alternative order based on the ideal solution approximation are preferred in this study [2, 28]. Additionally, different criteria weights are used in the solution phase in the Fuzzy TOPSIS and VIKOR methods however the criteria weights are not used in the MULTIMOORA method. Therefore, MULTIMOORA method also is applied in this study in order to investigate influence of weights in solution.

Table 1. Summary of literature on SSS

			Dimension		
Authors / year	**Supplier selection method**	**Economic**	**Environmental**	**Social**	**Application**
Fallahpour et al. [17]	Fuzzy preference programming - Fuzzy TOPSIS	*	*	*	Iranian textile manufacturing company
Shaw et al. [18]	Fuzzy AHP - Fuzzy multi-objective linear programming	*	*		Garment manufacturing company
Azadi et al. [11]	Non-radial DEA model	*	*	*	Resin production company
Luthra et al. [8]	AHP - VIKOR	*	*	*	Automotive company
Song et al. [27]	DEMATEL	*	*	*	Solar air-conditioner manufacturing company
Awasthi et al. [28]	Fuzzy AHP - VIKOR	*	*	*	Electronic goods manufacturing company
Bai and Sarkis [10]	Rough set theory	*	*		Hypothetical data
Kannan [29]	Fuzzy DELPHI, ISM, ANP and COPRAS-G	*	*	*	Textile company
Kannan et al. [33]	Fuzzy AHP, fuzzy TOPSIS and multi objective programming	*	*		Automobile manufacturing company
Govindan et al. [7]	Fuzzy TOPSIS	*	*	*	Hypothetical data
Azadnia et al. [9]	Fuzzy AHP and weighted fuzzy method	*	*	*	Packaging films in a food industry
Govindan and Sivakumar [2]	Fuzzy TOPSIS and multi objective programming	*	*		A paper manufacturing company
Gören [34]	Fuzzy DEMATEL, Taguchi Loss Functions and bi-objective model	*	*	*	Online retailer company
Lo et al. [35]	Best–worst method, TOPSIS and fuzzy multi-objective linear programming	*	*		Computer purchasing company
Proposed Model	Fuzzay AHP - Fuzzy TOPSIS - Fuzzy VIKOR - Fuzzy MULTIMOORA	*	*	*	A foundry manufacturing company

3. THE PROPOSED INTEGRATED METHODOLOGY

In this section, the integrated methodology is introduced and the steps of the methodology are explained. The methodology starts with using the fuzzy AHP method to reach criteria weights and the methodology is terminated by the ordering of alternatives with TOPSIS, VIKOR, and

MULTIMOORA methods under fuzzy environment. Flowchart of the proposed methodology is given in Fig. 1. In construction stage of the problem, the hierarchical structure of the problem is designed by defining the purpose and scope of the problem, main criteria, sub-criteria and alternatives, decision makers (DMs) and linguistic variables. Then weights of the main criteria and sub-criteria are determined through the pairwise of the DMs by using fuzzy AHP method. Then, fuzzy TOPSIS, fuzzy VIKOR and fuzzy MULTIMOORA methods are applied to evaluate sustainable suppliers considering relevant criteria.

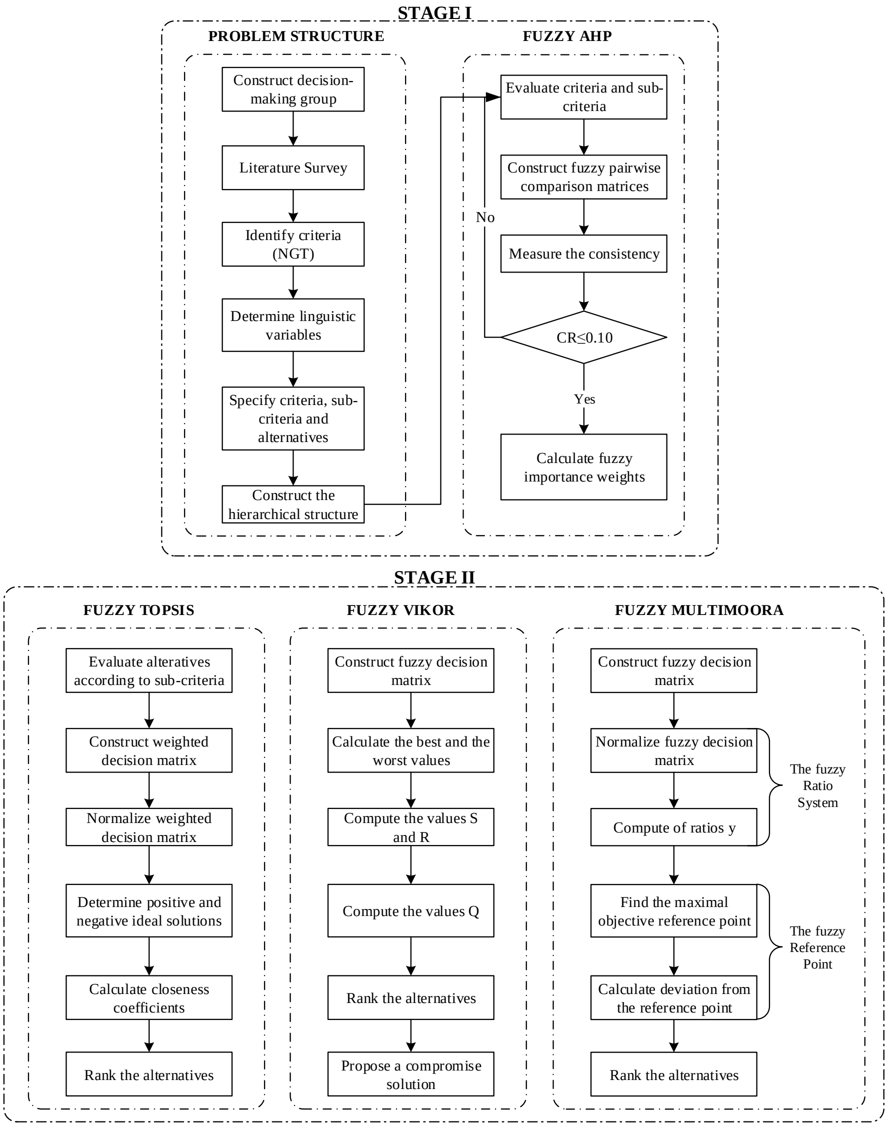

Figure 1. The steps of the proposed methodology

4. THE NUMERICAL APPLICATION

SSS problem in foundry which producing bearing house, V-belt pulley, and coupling for many firms in Turkey is sought by using the integrated methodology stated in Section 3. The company began to operate in foundry sector in 1973 (abbreviated as MP), and have been manufacturing bearing house, V-belt pulley, and Coupling since 1980. MP is one of the leading foundry company in Konya. MP is installed in a total area of 5500m² with 3000m² closed area, has a foundry capacity of 20 tons per day. It also has ISO 9001:2008 OHSAS18001 and TSE certified. It produces the highest quality foundry products used in different industries such as engineering, automotive and durable consumer sectors. The commitment of the company in improving environmental or sustainability performance is a significant advantage for the prospect of this work.

Company managers need to maximize their performance for sustainable development and capture continuous improvement in production activities. Additionally, the company produce innovative products due to increasing competition conditions and varying customer needs. Recently, problems arising in orders have forced the company to reassess its relationships with its suppliers and to identify suppliers that can work for long periods of time in accordance with company requests. Although the company has undertaken various activities in the SCM (procurement, transportation, packaging, recycling, etc.), there is still shortage of SSS criteria and evaluation of existing suppliers among the managers. Therefore, the company seeks to select the best sustainable supplier, taking into account the sustainability dimensions. Another important point is that the company wants to achieve the priority of sustainability dimensions for further development in long-term operations. In this context, we help with the managers to determine the SSS criteria and alternative suppliers with the proposed methodology.

4.1. Obtaining Criteria Weights

The first step of the application section is to determine the criteria to be used in evaluation of suppliers. A list of the criteria set by the literature survey on SSS is prepared and discussed with the managers. Subsequently, an interview is conducted with the managers and NGT is used to determine appropriate criteria for the company. The proposed hierarchical structure of the research problem is constructed after the interview and is given in Fig. 2. The aim of the study is to determine which suppliers are suitable for the SSS (Level 1). Under the overall objective, the second level, there are three basic dimensions of sustainability, namely economic, environmental, and social (Level 2). The sub-criteria are tied to the third level in relation to each criterion in the second level. Candidate suppliers are placed in the fourth level. In addition, a committee (D1, D2, and D3) consisting of CEO, production and procurement manager and logistics manager is formed to evaluate the suppliers in order to carry out the proposed approach.

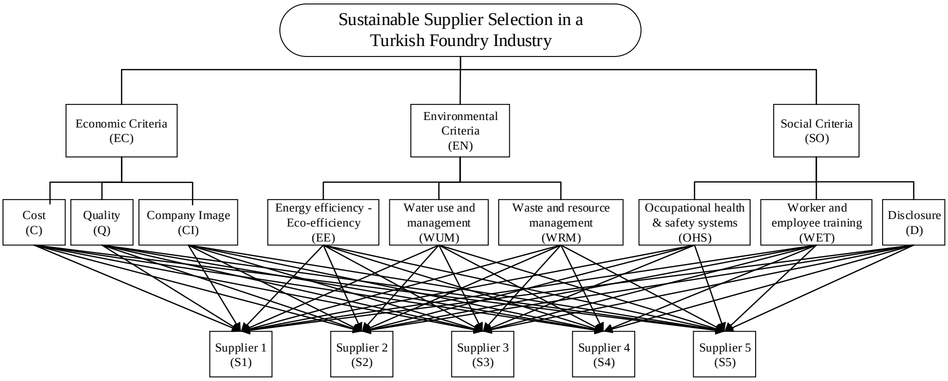

Figure 2. The hierarchical structure for SSS

The fuzzy AHP method is used because of the nature of the DMs and the inherent ambiguities of the problem in the analysis process to determine the level of importance of the main criteria and sub-criteria. A survey based on the hierarchical structure described above is designed for pairwise comparisons. The three DMs use the linguistic variables shown in Table 2 to assess the level of importance of the criteria.

Table 2. Linguistic variables for the importance level of criteria

Linguistic variables	**Intensity of importance**	**Triangular fuzzy scale**
Equally important	1	(1, 1, 1)
Intermediate	2	(1, 2, 3)
Weakly more important	3	(2, 3, 4)
Intermediate	4	(3, 4, 5)
Strongly more important	5	(4, 5, 6)
Intermediate	6	(5, 6, 7)
Very strongly more important	7	(6, 7, 8)
Intermediate	8	(7, 8, 9)
Absolutely more important	9	(9, 9, 9)

The fuzzy pairwise comparison matrix of the main criteria and the calculated weights are presented in Table 3-5. Using Buckley [36]'s geometric mean method, level of importance of criteria are calculated.

Table 3. The judgments of decision makers for the criteria

	D1			D2			D3		
	EC	EN	SO	EC	EN	SO	EC	EN	SO
EC	(1,1,1)	(5,6,7)	(3,4,5)	(1,1,1)	(6,7,8)	(2,3,4)	(1,1,1)	(5,6,7)	(2,3,4)
EN		(1,1,1)	(1/4,1/3,1/2)		(1,1,1)	(1/4,1/3,1/2)		(1,1,1)	(1/6,1/5,1/4)
SO			(1,1,1)			(1,1,1)			(1,1,1)

Table 4. The aggregate judgments for the criteria

	EC	EN	SO
EC	(1,1,1)	(5.313,6.316,7.319)	(2.289,3.302,4.309)
EN		(1,1,1)	(0.218,0.281,0.397)
SO			(1,1,1)

The consistency of the matrix is found to be 0.01, by calculating the consistency rate. Since the calculated value is smaller than 0.1, we can say that the pairwise comparison matrix is consistent. For more information on AHP consistency calculation examples, please see. [37, 38].

Table 5. The weights for main criteria

	Fuzzy Weights	Crisp Weights	Normalized Weights
EC	(0.475,0.666,0.917)	0.686	0.660
EN	(0.064,0.086,0.122)	0.091	0.087
SO	(0.173,0.248,0.366)	0.262	0.252

According to Table 5, the economic dimension of sustainability (EC) is the top priority. The last priority dimension is obtained as the environmental dimension. For the managers in the company, which are treated as if they are in many types of research, the economic dimension stands out as the criterion with the highest priority [17, 28]. In the Turkish business world, it seems that there is a lack of sustainability in meaning and practice. In the survey conducted by İstanbul Menkul Kıymetler Borsası (İMKB) [39] although 95% of the respondents indicated that sustainability is related to the way they do business, environmental issues are only able to find themselves in the last place in sustainable issues. In response to this point, it seems that economic and social aspects of sustainability are more preferential for companies. Similar calculations are performed within the sub-criteria to obtain the following local weights. Table 6 shows the local fuzzy weights and global fuzzy weights of the sub-criteria.

Table 6. The weights for sub-criteria

Criteria	Sub-criteria	Local Fuzzy Weights	Global Fuzzy Weights
EC	C	(0.334,0.532,0.806)	(0.159,0.355,0.739)
(0.475,0.666,0.917)	Q	(0.141,0.225,0.376)	(0.009,0.019,0.046)
	CI	(0.165,0.243,0.380)	(0.028,0.060,0.139)
EN	EE	(0.146,0.221,0.334)	(0.069,0.148,0.306)
(0.064,0.086,0.122)	WUM	(0.077,0.109,0.172)	(0.005,0.009,0.021)
	WRM	(0.467,0.669,0.943)	(0.081,0.166,0.345)
SO	OHS	(0.17,0.24,0.37)	(0.08,0.16,0.34)
(0.173,0.248,0.366)	WET	(0.07,0.09,0.13)	(0.00,0.01,0.02)
	D	(0.46,0.67,0.94)	(0.08,0.16,0.34)

4.2. Ranking of Suppliers

The ranking of suppliers is evaluated by fuzzy TOPSIS, fuzzy VIKOR and fuzzy MULTIMOORA methods.

4.2.1. Fuzzy TOPSIS analysis

Fuzzy TOPSIS method starts with an evaluation of suppliers by DMs. The constituted committee is constructed fuzzy evaluation matrix using the linguistic variables given in Table 7.

Table 7. Linguistic variables for supplier ratings [28]

Linguistic variable	Corresponding triangular fuzzy number
Very Poor (VP)	(1, 1, 3)
Poor (P)	(1, 3, 5)
Fair (F)	(3, 5, 7)
Good (G)	(5, 7, 9)
Very good (VG)	(7, 9, 9)

Table 8 shows the DMs' linguistic evaluation results. It can be converted to triangular fuzzy numbers using linguistic variables given in Table 7. Aggregated fuzzy decision matrix of suppliers each criterion is generated and is shown in Table 9. The normalized fuzzy decision matrix is determined and is presented in Table 10.

Table 8. Rating of suppliers by DMs based on economic criteria

	Suppliers	Decision makers				Suppliers	Decision makers				Suppliers	Decision makers		
		DM1	DM2	DM3			DM1	DM2	DM3			DM1	DM2	DM3
	S1	VG	G	G		S1	F	F	G		S1	P	F	P
	S2	F	G	G		S2	G	G	G		S2	F	F	F
C	S3	VG	VG	VG	**EE**	S3	P	P	P	**OHS**	S3	G	G	VG
	S4	F	G	F		S4	VP	P	VP		S4	G	G	F
	S5	VG	G	F		S5	G	F	F		S5	F	G	F
	S1	G	VG	VG		S1	F	F	F		S1	G	G	VG
	S2	G	G	G		S2	F	F	P		S2	G	F	G
Q	S3	G	F	F	**WUM**	S3	G	G	F	**WET**	S3	G	G	VG
	S4	P	VP	VP		S4	P	VP	P		S4	G	VG	G
	S5	VG	G	G		S5	F	G	F		S5	F	F	G
	S1	G	G	G		S1	P	P	VP		S1	G	F	G
	S2	F	G	P		S2	P	P	P		S2	P	P	P
CI	S3	VG	G	G	**WRM**	S3	G	G	F	**D**	S3	F	G	G
	S4	F	P	F		S4	F	P	P		S4	F	F	P
	S5	F	VG	G		S5	G	G	G		S5	G	G	G

Table 9. Fuzzy aggregated decision evaluation matrix

	C	Q	CI	EE	WUM	WRM	OHS	WET	D
S1	(5.66,7.66,9)	(6.33,8.33,9)	(5,7,9)	(3.66,5.66,7.66)	(3,5,7)	(1,2.33,4.33)	(1.66,3.66,5.66)	(5.66,7.66,9)	(4.33,6.33,8.33)
S2	(4.33,6.33,8.33)	(5,7,9)	(3,5,7)	(3.66,7,9)	(2.33,4.33,6.33)	(1,3,5)	(3,5,7)	(4.33,6.33,8.33)	(1,3,5)
S3	(7,9,9)	(3.66,5.66,7.66)	(5.66,7.66,9)	(1,3,5)	(4.33,6.33,8.33)	(4.33,6.33,8.33)	(5.66,7.66,9)	(5.66,7.66,9)	(4.33,6.33,8.33)
S4	(3.66,5.66,7.66)	(1,1.66,3.66)	(2.33,4.33,6.33)	(1,1.66,3.66)	(1,2.33,4.33)	(1.66,3.66,5.66)	(4.33,6.33,8.33)	(5.66,7.66,9)	(2.33,4.33,6.33)
S5	(5,7,8.33)	(5.66,7.66,9)	(5,7,8.33)	(3.66,5.66,7.66)	(3.66,5.66,7.66)	(5,7,9)	(3.66,5.66,7.66)	(3.66,5.66,7.66)	(5,7,9)

Table 10. Normalized fuzzy decision matrix

	C	Q	CI	EE	WUM	WRM	OHS	WET	D
S1	(0.629,0.851,1.000)	(0.703,0.926,1.000)	(0.556,0.778,1.000)	(0.407,0.629,0.851)	(0.360,0.600,0.840)	(0.111,0.259,0.481)	(0.184,0.407,0.629)	(0.629,0.851,1.000)	(0.481,0.703,0.926)
S2	(0.481,0.703,0.926)	(0.556,0.778,1.000)	(0.333,0.556,0.778)	(0.407,0.778,1.000)	(0.280,0.520,0.760)	(0.111,0.333,0.556)	(0.333,0.556,0.778)	(0.481,0.703,0.926)	(0.111,0.333,0.556)
S3	(0.778,1.000,1.000)	(0.407,0.629,0.851)	(0.629,0.851,1.000)	(0.111,0.333,0.556)	(0.520,0.760,1.000)	(0.481,0.703,0.926)	(0.629,0.851,1.000)	(0.629,0.851,1.000)	(0.481,0.703,0.926)
S4	(0.407,0.629,0.851)	(0.111,0.184,0.407)	(0.259,0.481,0.703)	(0.111,0.184,0.407)	(0.120,0.280,0.520)	(0.184,0.407,0.629)	(0.481,0.703,0.926)	(0.629,0.851,1.000)	(0.259,0.481,0.703)
S5	(0.556,0.778,0.926)	(0.629,0.851,1.000)	(0.556,0.778,0.926)	(0.407,0.629,0.851)	(0.439,0.679,0.920)	(0.556,0.778,1.000)	(0.407,0.629,0.851)	(0.407,0.629,0.851)	(0.556,0.778,1.000)

The closeness coefficient of alternatives is computed and is shown in table 11.

Table 11. The results of fuzzy TOPSIS method

Suppliers	d_i^+	d_i^-	CC_i	Ranking
S1	8.084	1.239	0.133	3
S2	8.225	1.079	0.116	4
S3	8.032	1.279	0.137	1
S4	8.330	0.933	0.101	5
S5	8.059	1.257	0.135	2

Finally, the ranking of each alternative is shown by the decreasing order of the closeness coefficient, as $S3 > S5 > S1 > S2 > S4$.

4.2.2. Fuzzy VIKOR analysis

The steps of the fuzzy VIKOR method are applied using the fuzzy decision matrix obtained in the TOPSIS method. First, the fuzzy best (f_j^*) and the fuzzy worst (f_j^-) values are computed, then the values of fuzzy $\tilde{S}_i, \tilde{R}_i$ and $\tilde{Q}_i$ are calculated by taking $\nu = 0.5$ for each alternative. In the last stage, the fuzzy numbers are defuzzified and S, R and Q values are found. The obtained results are shown in Table 12. According to the index values, alternatives are sorted by in ascending order.

Table 12. The results of fuzzy VIKOR method

	Q		S		R	
Suppliers	Value	Ranking	Value	Ranking	Value	Ranking
S1	0.459409	3	0.806399	2	0.142285	2
S2	0.817618	5	2.24993	4	0.369493	3
S3	0.095118	1	0.362324	1	0.086464	1
S4	0.810269	4	3.104481	5	0.738986	5
S5	0.160997	2	1.037793	3	0.369493	3

It can be reached from the results of Table 12 the ranking of suppliers are $S3 > S5 > S1 > S2 > S4$.

4.2.3. Fuzzy MULTIMOORA analysis

The fuzzy decision matrix is normalized. Then, suppliers are ranked by fuzzy ratio system, and the results are given in Table 13. Also, suppliers are ranked by fuzzy reference point (see Table 14).

Table 13. The results of fuzzy ratio system

Suppliers	$\tilde{y}_i^*$	y_i^*	Rank
S1	(3.881,5.315,6.560)	2,376	3
S2	(2.967,5.093,6.608)	2,244	4
S3	(4.478,5.836,6.949)	2,582	1
S4	(2.437,4.108,5.558)	1,907	5
S5	(4.406,5.768,7.078)	2,592	2

Table 14. The results of reference point approach

Suppliers	C	Q	CI	EE	WUM	WRM	OHS	WET	D	$max\ d$	Ranking
S1	0.040	0.000	0.022	0.054	0.038	0.225	0.164	0.000	0.017	0.225	4
S2	0.080	0.043	0.099	0.000	0.057	0.202	0.106	0.042	0.102	0.202	3
S3	0.000	0.092	0.000	0.180	0.000	0.034	0.000	0.000	0.017	0.180	2
S4	0.103	0.230	0.126	0.230	0.096	0.169	0.050	0.000	0.068	0.230	5
S5	0.061	0.022	0.027	0.054	0.019	0.000	0.078	0.066	0.000	0.078	1

The third supplier (S3) is considered the best one, whereas the fourth supplier the worst one (S4) for the fuzzy Ratio System.

Table 15. Ranking of suppliers by integrated MCDM techniques

Suppliers	Fuzzy TOPSIS	Fuzzy VIKOR	Fuzzy MULTIMOORA (Fuzzy Ratio)	Fuzzy MULTIMOORA (Reference Point Approach)
S1	3	3	3	4
S2	4	5	4	3
S3	1	1	1	2
S4	5	4	5	5
S5	2	2	2	1

Similar ranking results are achieved by using different methods in the evaluation of SSS. While S3 has highest second rank only according to the fuzzy reference point approach, it has the first rank in all other methods (see Table 15). These results show that S3 supplier is the best sustainable supplier in the case study. Although the criteria weights obtained in the first stage are used in distance calculation in the fuzzy TOPSIS method, the weights used in the last S and R calculation in the fuzzy VIKOR method. Additionally, fuzzy MULTIMOORA method does not take into account the weights for calculations. Different ranks can be obtained with the fuzzy MULTIMOORA method that it uses only the assessments of suppliers, not the criteria weights. Three different methods use different normalization techniques. While the fuzzy TOPSIS method uses vector normalization, the linear normalization function in the fuzzy VIKOR method and the internal normalization in the fuzzy MULTIMOORA method.

Table 16. Spearman's rank correlation coefficients for integrated MCDM techniques

	Fuzzy TOPSIS	Fuzzy VIKOR	Fuzzy MULTIMOORA (Fuzzy Ratio)	Fuzzy MULTIMOORA (Reference Point Approach)
Fuzzy TOPSIS	1	-	-	-
Fuzzy VIKOR	.900*	1	-	-
Fuzzy MULTIMOORA (Fuzzy Ratio)	1.000**	,900*	1	-
Fuzzy MULTIMOORA (Reference Point Approach)	0.8	0.6	0.8	1

*. Correlation is significant at the 0.05 level (2-tailed).

**. Correlation is significant at the 0.01 level (2-tailed).

Spearman rank-order correlations are conducted in order to determine if there are any relationships between the rankings of MCDM techniques. A two-tailed test of significance indicated the there is a significant positive relationship between the rankings. Except for the Fuzzy MULTIMOORA (Reference Point Approach) technique, all correlation coefficients are statistically significant since threshold value is 0.05 (see Table 16).

4.3. Sensitivity Analysis

In this section, sensitivity analysis is performed to observe the effects of possible changes in the weight of criteria in the selection of sustainable suppliers. The following experiments are applied to evaluate the effect of criteria weights on supplier ranks for fuzzy TOPSIS and fuzzy VIKOR. In general, a total of 17 experiments are performed.

- In the first set of experiments, the weight of the main criteria is fixed to 1, one by one, and others are equal to 0. Likewise, the sub-criteria are set to receive the highest weight, in order, and a total of nine experiments are obtained.
- In the second set of experiments, the equal weight is assigned to all main criteria while the highest weight is assigned to the lower criterion weights (A total of seven experiments)
- In the third set of experiment, all main criteria and sub-criteria are obtained as equal.

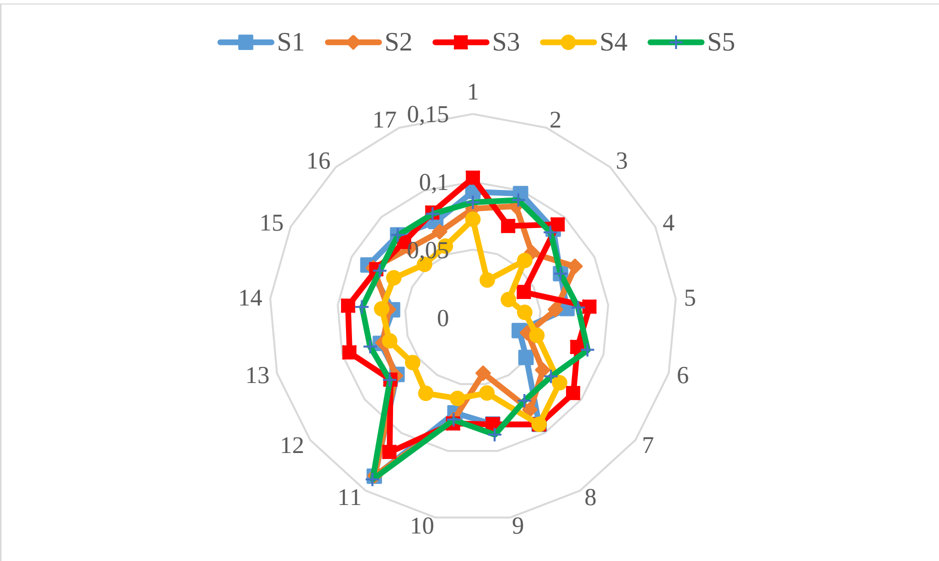

Figure 3. Results of sensitivity analysis for fuzzy TOPSIS

Fig. 3 shows that S3 has the first rank in eight experiments at 17 experiments (1, 3, 5, 7, 10, 13-14, 17), S5 has the first rank in four experiments (6, 9, 11-12), S1 has the first rank in three experiments (2, 15, 16) and finally S2 (2) and S4 (8) has the first rank in one experiment. Herewith, sensitivity analysis has been found to be meaningful in terms of evaluating alternatives for SSS.

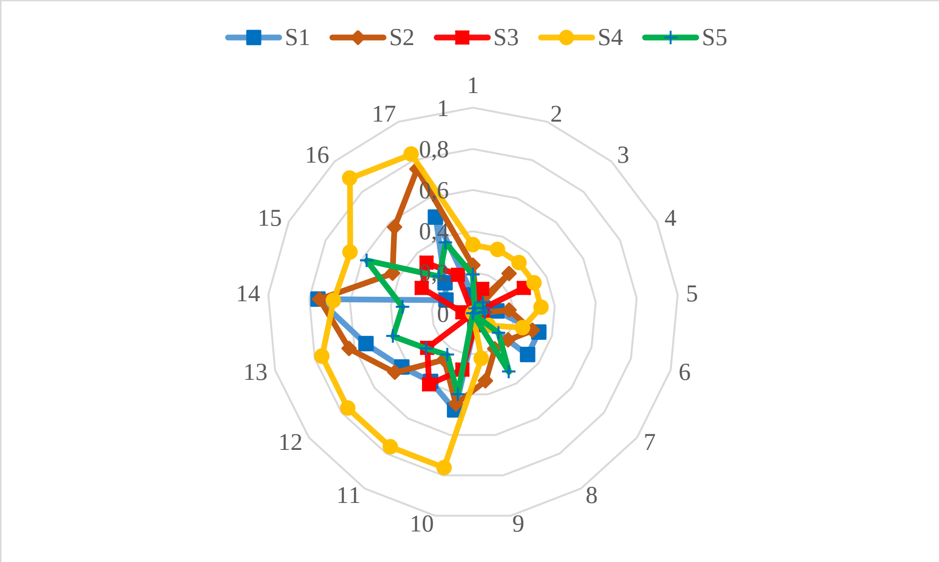

Figure 4. Results of sensitivity analysis for fuzzy VIKOR

From Fig. 4, it can be concluded that S3 has the first rank among all alternatives when weights are changed; the ranking of the sustainable supplier in descending order is $S3 > S5 > S1 > S2 > S4$.

4.4. Research Implications

This case study provides additional information on theoretical and practical applications for researchers. The results of this work are helping companies to develop a systematic approach to addressing the problem of selection and assessment in SSS. Increased emphasis on sustainability provides for greater adoption by businesses of strategies in which savings are front-line and where natural resources are used less and waste materials are economically recovered.

The foundry sector, which is one of the indispensable producers of the manufacturing industry, continues its production structure and strengthening its competitive advantage, is of great importance for the future of the country's industry. For this reason, this work has attempted to provide a framework for facilitating sustainable development. Some of the important implications of this study are summarized here:

- Allows practitioners to better understand the importance and applicability of sustainability criteria.
- Develops evaluation criteria for SSS by literature review and NGT.
- Helps to find compromise solutions between DMs, by considering views of the company on decision-making processes by NGT.
- Presents a hierarchical model as shown in Fig. 2 for the SSS.
- Define the most effective and important SSS dimensions. The results show that economic dimension is still the most important dimension, and then the social dimension has arrived.
- Divides suppliers into risk groups to achieve sustainability standards. Choosing the right suppliers can reduce the risk in supply chain network.

- Summarizes the evaluation results of the upstream suppliers for the rest. Thus, suppliers can be aware of their weaknesses and pay attention to what conditions they need to fulfill for their future strategies.
- Composes managers' decisions more effectively and identify the level of importance of supplier characteristics.

5. CONCLUSION AND OUTLOOK

With the increasing influence of environmental awareness and globalization, companies have begun to develop new business strategies to preserve their competitive position. In addition, technological developments have changed consumer behaviour to a large extent and have begun to exert high pressure on companies. These pressures have led businesses to invest in environmental and social issues as well as economic investments. Sustainable supply chain dimensions, such as economic, social and environmental co-operation, play an important role in achieving triple bottom-line benefits and contributing to the sustainable development of the community. For this reason, it is very important for businesses to tackle all dimensions of sustainability together and establish a balance between them so that they can continue their existence in the future. The SSS process is seminal to achieving a successful SCM in business. In this context, when choosing suppliers, it is appropriate not only to focus on cost but to evaluate on different dimensions. In this paper, an integrated approach that companies achieve high benefits usage of sustainability is proposed in supplier selection.

The aim of this study is to propose a decision-making framework that takes into account sustainability dimensions and uncertainties in the DMs' assessments. The sustainable supplier problem is a MCDM problem which qualitative and quantitative factors influence this decision-making process. For MCDM problems, it is the most important stage is to specify main criteria and sub-criteria clusters. For this reason, in this study, firstly a comprehensive literature search is carried out to determine the main criteria and sub-criteria clusters, and then the sub-criteria to be used in the research are listed with the NGT. As a result, three main criteria and three sub-criteria to be grouped under each criterion are determined.

Decision-makers who evaluate the specified criteria often make linguistic assessments that are not fully expressed by crisp numbers. For this reason, in many studies to deal with uncertainty in evaluations, the fuzzy set theory is preferred by combining MCDM methods. From this viewpoint, SSS problem is presented combining with fuzzy MCDM approaches and sustainability criteria. During the weighting and evaluation process, the opinions of the experienced experts from two to twelve years working in the business are converted into a single group decision. The proposed approach is carried out in two stages. First, the fuzzy AHP method is applied to obtain the weights of the criteria. Second, fuzzy TOPSIS, VIKOR and MULTIMOORA methods are used to measure the sustainable performance of suppliers and to generate a general performance score for each supplier. Finally, a sensitivity analysis is conducted to determine the effect of criteria weights in the decision-making process.

During the implementation phase, a case study is presented to a better understanding of the proposed approach. The fuzzy AHP method is performed for the main criteria and sub- criteria weights. When the results are examined, the most important criterion is determined as economic criteria with the rate of 66% for fuzzy AHP. The other criteria are social criteria with the rate of 25% in the second place. After determining the weights, first of all, the application is carried out by the fuzzy TOPSIS method, and the TOPSIS method results showed that supplier 3 (S3) as the most preferred supplier. According to this result, if the main manufacturer expands the current business volume with the S3 supplier, it will gain a more efficient supply chain network. After the S3 supplier, the most preferred supplier would be the supplier 2. The fact that the main producer works with multiple suppliers at every turn is particularly important in terms of having a competitive edge in the price criteria. Later, the fuzzy VIKOR and MULTIMOORA methods are used to rank suppliers and found that the S3 ranks first.

There are many limitations in this work. First of all, it is difficult to establish SSS criteria in the foundry sector. In addition, the criteria specified are applied only to small and medium-sized enterprises operating in the foundry industry. Another limitation of our work is the lack of quantitative data and the presence of a limited number of participants in the study.

For a possible future study, sustainability criteria such as carbon footprint, resource consumption, reliability and employees' interests and rights can be added as new criteria by looking at supplier selection criteria. Companies can create a supplier selection model not only for supplier selection but also for order allocation. In addition, supplier selection problem can be solved in addition to these solution techniques, such as ELECTRE, PROMETHEE, DEA and so on. The proposed methodology may be extended considering different objectives such as digitalization, blockchain smart technologies smart supply chain management, and other emerging areas of operations research and economics. Furthermore, the obtained results for the problem can be addressed to different sectors or may be considered or evaluated as a large-scale enterprise in different regions of Turkey.

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