A Fuzzy Multicriteria Decision Making Approach for Lean Supplier Selection

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Abstract

Supplier selection is a problem that is tried to be solved using many different methods and approaches. However, it is known that it is mainly handled with Multicriteria Decision Making Methods (MCDM) since it is affected by many conflicting criteria. This study discusses the supplier selection problem of a company working under a lean management approach. A detailed literature review was conducted to reveal the lean criteria taken into account in the literature of supplier selection. In the first phase of this study, the criteria obtained from the literature review were examined and weighted with the Fuzzy DEMATEL (Decision-Making Trial and Evaluation Laboratory) Method, widely used in the research fields and provides successful solutions. As a result of the application of the method, the weight of each evaluation criterion was determined and used as an input in the selection of the suppliers. In the second phase of the study, the fuzzy EDAS was employed to obtain the final ranking and select the most effective supplier for the company's success. Then obtained result is presented to the managers for better decisions.

Keywords
Supplier Selection, Lean Supply, Fuzzy MCDM, Fuzzy DEMATEL, Fuzzy EDAS

1. Introduction
Lean philosophy aims to minimize costs and increase customer satisfaction by eliminating waste (Birgün and Kulakli, 2022). With the lean approach, processes are improved by using lean techniques to produce customer-defined value (Birgün and Kulakli, 2020; Birgün and Gülen, 2020; Birgün and Kulakli, 2021). Lean requires integration and cooperation with the supplier in line with the company's goals. It advocates working with a single supplier and long-term relationships (Durmuşoğlu and Durmuşoğlu, 1997). Although ensuring the desired quality and quantity during production and timely production and delivery can be achieved with adequate planning and management, none of these can be achieved if the supply is faulty. Therefore, the supply function is one of the most critical factors for the firm's success.

Supplier selection is critical for realizing a collaborative approach for the time, cost, and quality. It is a fundamental problem from which suppliers the related goods will be purchased. Contrary to the strategy of working with many suppliers in traditional procurement, lean recommends working with a small number of suppliers - if possible, with a single supplier. There are supplier selection criteria in the literature with the lean perspective. However, new criteria can be set according to the targets of the companies.

This study discusses the supplier selection problem for a company operating in the metal industry. The study consisted of a brief literature review, research methodology, case study, and conclusions. The criteria determined as a result of the literature review were grouped, and their weights were determined with Fuzzy DEMATEL, and the selection was made with Fuzzy EDAS.

2. Literature review

There are many studies in the literature on lean supplier selection. While some create new models, some survey the literature on selection criteria and/or solution methods. Birgün Barla (2003) conducted a supplier selection case study for a metal cutting process in a glass mold manufacturer by using a multiattribute selection model (MSM). As a result of developing the MSM criteria under lean principles, the author identified the quality organization of the supplier and serves as the most critical evaluation factor. Utilizing the QFD, Gözlü and Birgün Barla (2003) evaluated the suppliers for a company in the glass sector. They stated that QFD is also useful for examining suppliers' weaknesses and strengths. Cagliano et al. (2004) investigated the lean, agile and traditional supply strategies and their impact on operational performance. They carried out an empirical study for four clusters of 284 manufacturing companies in Europe. The survey results indicated that the lean and agile supply strategies give more performance than the traditional strategies; however, no significant difference emerges between agile and lean.

Birgün and Cihan (2010) considered supplier selection problems in a computer hardware manufacturer using the ELECTRE method. They used 13 lean criteria for selection. Calvi et al. (2010) developed and implemented an AHP-based decision model to select the supplier to be developed from among 15 suppliers in a German industrial company that implements lean management. Yuluğkural et al. (2013) discussed the supplier selection problem in their studies in which the modeling ability of the ANP method was statistically evaluated using the structural equation model. Four main criteria, namely delivery, quality, flexibility, and price, and nine sub-criteria were used in the study. Gokturk et al. (2011) proposed a two-step solution using the AAS and VİKOR methods to determine the most suitable supplier for a company that manufactures machinery. In the study, which was conducted using 11 sub-criteria belonging to the primary delivery criteria, quality, service, and price, the weights were calculated using the AAS method. 14 alternative suppliers were evaluated using the VIKOR method in the second stage. Galankashi (2013) provided a flexible supplier selection approach according to the manufacturer's supply chain strategy. The author analyzed three electrical suppliers based on balanced scorecard performance measurement and compared suppliers for manufacturer's lean and agile supply chain strategies by AHP. Abdollahi et al. (2015) proposed a supplier evaluation and selection framework on lean and agile criteria using DEMATEL–ANP–DEA approaches.

El Mokadem (2017) classified supplier selection criteria into three groups: lean capability criteria (delivery, safety, and risk), agile capability criteria (technology, services, research development, manufacturing capability, and flexibility), and standard capability criteria (quality, cost, management capabilities, financial position, reputation, and relationship). The results of this empirical study indicated that lean capability criteria are a factor that increases the company's leanness. Considering non-developed supplier markets, Aamer (2018) proposed a lean supplier selection framework in addressing supplier operational-level capability and capacity. In an empirical study, utilizing 29 critical factors, the author identified the operation level in seven Value Stream elements: Customer Service/Sales, Purchasing, Production Planning and Control, Manufacturing Engineering, Shop Floor and Quality Control, Receiving and Shipping. Torgul and Paksoy (2019) presented a fuzzy multi-objective linear programming model by integrating FAHP-FTOPSIS for lean and green supplier selection. Under the integrated, lean and green concept, Çalık et al. (2019) divided the drivers of supplier selection into three categories as *Economic Drivers* (Cost, Price, Quality, On-Time (JIT) Delivery, Reduction of Materials and Packages Used in Supplied Parts, Flexibility), *Environmental Drivers* (Carbon dioxide (CO2) Emission, Energy Efficiency, Environmental Standards and Certificates, Waste Reduction, Avoidance and Treatment of Hazardous Materials) and *Social Drivers* (Employee Involvement and Suggestion/incentive Systems, Occupational Health and Safety, Corporate Social Responsibility Projects and Campaigns). The authors developed a new Fuzzy Weighted Additive Max-Min approach with the Group Decision-Making model using these drivers. They also conducted a case study to test the model validity in Turkey's electrical and electronics companies. Li et al. (2020) collected 15 standard leagile criteria from the literature survey for supplier selection and determined that quality was the most influential leagile criteria by using the DEMATEL method. They conducted the supplier selection in a Chinese textile company.

Rezai et al. (2020) investigated the factors influencing supplier selection and order allocation under the lean concept. The authors determined the 17 criteria from the related literature, developed lean supplier selection criteria using AHP, selected the supplier with FAHP, and developed a bi-objective model for optimal order allocation. They conducted a case study for a car manufacturer in Iran. Tay and Aw (2021) conducted an action research case study using Six Sigma techniques such as DMAIC, 5S, stakeholder analysis, and standard operating procedure to logistics services in a multinational healthcare company.

3. Research Methodology

In this study, the supplier selection problem of a manufacturer, which is in transition to lean production, according to lean criteria, is discussed. The manufacturer operates in the metal industry and produces various products. Due to the high costs and inefficiencies, a lean transformation project was initiated in the company. With the lean transformation project, the company aims to reduce its costs, increase its production and quality performance, and increase customer satisfaction. In addition to improving manufacturing processes in lean transformation, improving the procurement process is vital to reaching the goal.

As a result of the analysis of the procurement process in the company, it was determined that short-term relations with different suppliers adversely affected the supply control, and it was decided to work long-term with few suppliers according to lean principles. For this reason, it was deemed appropriate to evaluate existing suppliers and search for new suppliers. In the company, it was decided to choose a supplier for the steel pipes of different sizes, which were purchased from outside and constitute the raw material of the production. The study was carried out in two stages. Fırst, the criteria taken into consideration for lean supplier selection in the literature, have been researched, and according to the opinions of company managers and experts, it was decided to consider the criteria divided into categories in the table to be used in supplier selection. The determining criteria were weighted with Fuzzy DEMATEL. DEMATEL is a successful method in determining the weight of the criteria, but it should be used in conjunction with other multicriteria decision-making methods in order to grade the alternatives (Birgün and Ulu, 2021). Second, Fuzzy EDAS was applied to select the most efficient supplier, and the result was presented to the managers. The framework of the study is shown in Figure 1 below;

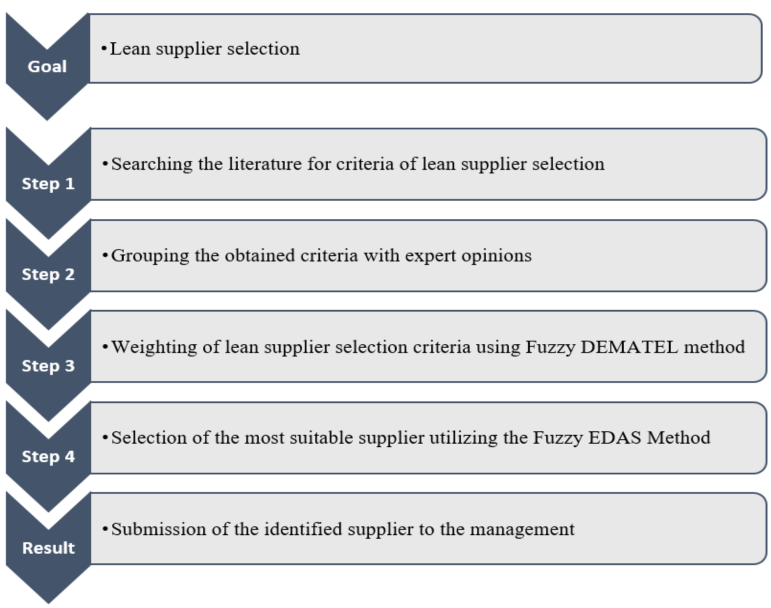

Figure 1. The research framework for a supplier selection

3.1. Fuzzy DEMATEL

The DEMATEL method has been developed as a method that enables to obtain meaningful results by visualizing the complex cause-effect relationships between the criteria (Gabus and Fontela, 1972). DEMATEL enables the conversion of qualitative expressions to quantitative values (Lee et al., 2011; Dalalah et al., 2011). This method can be applied in many areas, from marketing to human resources, where more than one criterion affects the preference between alternatives (Birgün and Ulu, 2021). Although the DEMATEL method visualizes the causal relationships between the criteria, it may be insufficient in explaining these relationships numerically (Şahin et al., 2020). Therefore, Lin and Wu (2004) extended the DEMATEL method to the fuzzy environment. The application steps of the fuzzy DEMATEL method can be summarized as follows:

1. Determination of evaluation criteria and conversion of expert opinions consisting of linguistic expressions into fuzzy numbers

Table 1. Linguistic variables and related fuzzy numbers (Li, 1999)

Linguistic Terms	Corresponding Triangular Fuzzy Numbers
Very high influence (VH)	(0.75, 1.0, 1.0)
High influence (H)	(0.5, 0.75, 1.0)
Moderate influence (M)	(0.25, 0.5, 0.75)
Low influence (L)	(0.0, 0.25, 0.5)
Very low influence (VL)	(0.0, 0.0, 0.25)

2. Evaluation of the interactions between the factors by the decision-makers: In order to measure the level of the relationship between the criteria, a direct relationship matrix based on pairwise comparison is created. Linguistic expressions were transformed into fuzzy triangular numbers in the scale with equation 1.

$$\tilde{Z}^{(k)} = \begin{bmatrix} 0 & \cdots & \tilde{Z}_{1n}^{(k)} \\ \vdots & \ddots & \vdots \\ \tilde{Z}_{n1}^{(k)} & \cdots & 0 \end{bmatrix} \quad k = 1,2, \ldots p \tag{1}$$

$\tilde{Z}_{ij} = \left(l_{ij}, m_{ij}, u_{ij}\right)$ criteria i refers to the degree to which it affects the criteria j.

3. Generating a normalized direct relationship matrix: The matrices obtained in line with the expert opinions are converted into a single value with the arithmetic mean. This obtained direct relationship matrix is normalized using equations (2) and (3). The normalized direct relationship matrix obtained is as in equation (4).

$$\tilde{x}_{ij}^{(k)} = \frac{\tilde{z}_{ij}^{(k)}}{r^k} = \left(\frac{l_{ij}^k}{r^k}, \frac{m_{ij}^k}{r^k}, \frac{u_{ij}^k}{r^k}\right) \tag{2}$$

$$r^{(k)} = max_{1 \le i \le n}\left(\sum_{j=1}^{n} u_{ij}^k\right) \tag{3}$$

$$\tilde{X} = \begin{bmatrix} \tilde{X}_{11} & \cdots & \tilde{X}_{1n} \\ \vdots & \ddots & \vdots \\ \tilde{X}_{n1} & \cdots & \tilde{X}_{nn} \end{bmatrix} \tag{4}$$

4. Creating the total relationship matrix: In this step, the operation is performed using equation (5). By processing separately for l, m, and u, they are finally combined, and equality (6) is obtained.

$$\tilde{T} = \tilde{X} + \tilde{X}^2 + \tilde{X}^3 + \cdots = \sum_{i=1}^{\infty} \tilde{X}^i = \tilde{X}(1 - \tilde{X})^{-1} \tag{5}$$

$$\tilde{T} = \begin{bmatrix} \tilde{T}_{11} & \cdots & \tilde{T}_{1n} \\ \vdots & \ddots & \vdots \\ \tilde{T}_{n1} & \cdots & \tilde{T}_{nn} \end{bmatrix} \tag{6}$$

5. Formation of cause-effect factor groups: In order to evaluate whether the criteria are affecting or being affected, first of all, given in equation (7) $\widetilde{D}_i$ and $\widetilde{R}_i$ is calculated. Then, using these obtained row and column totals,$\widetilde{D}_i + \widetilde{R}_i$ and $\widetilde{D}_i - \widetilde{R}_i$ values are calculated.

$$\widetilde{D}_i = \sum_{i=1}^{n} \widetilde{T}_{ij} \quad (i = 1,2, \dots, n)$$
$$\widetilde{R}_i = \sum_{j=1}^{n} \widetilde{T}_{ij} \quad (j = 1,2, \dots, n) \tag{7}$$

6. Defuzzification process: Obtained $\widetilde{D}_i + \widetilde{R}_i$ and $\widetilde{D}_i - \widetilde{R}_i$ In order to make the values into a single value, the defuzzification process is applied using equality (8).

$$D_i^{def} + R_i^{def} = {}^1\!/_4\,(l + 2m + u)$$
$$D_i^{def} - R_i^{def} = {}^1\!/_4\,(l + 2m + u) \tag{8}$$

7. Obtaining weights: Equations (9) and (10) are used to determine the weight of each criterion.

$$W_i = \left(\left(D_i^{def} + R_i^{def}\right)^2 + \left(D_i^{def} - R_i^{def}\right)^2\right)^{1/2} \tag{9}$$

$$W_i = \frac{W_i}{\sum_{i=1}^{n} W_i} \tag{10}$$

3.2. Fuzzy EDAS

The EDAS method was developed by Keshavarz Ghorabaee et al. (2015) for the multicriteria inventory classification problem. Fuzzy EDAS (Evaluation based on Distance from Average Solution) is one of the methods used to evaluate alternatives with the help of fuzzy decision matrices.). In the EDAS method, the best alternative is a function of the distance from the mean solution (Keshavarz Ghorabaee et al., 2017; Şahin et al., 2020). In this method, the first two indicators are given as positive distance from the mean (PDA) and negative distance from the mean (NDA). Higher PDA values and lower NDA values indicate the optimal solution (Keshavarz Ghorabaee et al., 2015).

A scale consisting of fuzzy triangular numbers is used to determine the degree of importance of the criteria that affect the problem's solution. The steps of the fuzzy EDAS method for *m* alternatives and *n* criteria can be summarized as follows (Keshavarz Ghorabaee et al., 2016):

1. Constructing the fuzzy decision matrix ($\tilde{X}$): A fuzzy decision matrix with alternatives in rows and criteria in columns is created by decision-makers. In the integrated fuzzy decision matrix, where k decision-makers evaluate, x shows the value of alternative i by criterion j.

$$\tilde{X} = \left[\tilde{x}_{ij}\right]_{m\times n} \tag{11}$$

$$\tilde{x}_{ij} = \left(\prod_{p=1}^{k} \tilde{x}_{ij}^{p}\right)^{\frac{1}{k}} \tag{12}$$

2. Calculation of the mean solution matrix (AV): At this stage, the process is performed using equation (13). Equation (14) expresses the mean solutions of the alternatives for each criterion.

$$AV = \left[\widetilde{av}_j\right]_{1\times n} \tag{13}$$

$$\widetilde{av}_j = \frac{1}{m}\sum_{i=1}^{m} \tilde{x}_{ij} \tag{14}$$

3. Positive fuzzy distance matrix from the mean for each criterion ($\widetilde{PDA}$) and negative fuzzy distance matrix from the mean ($\widetilde{NDA}$ values are calculated by taking into account the criterion being a benefit and a cost criterion.

$$PDA = \left[\widetilde{pda}_{ij}\right]_{m\times n} \tag{15}$$

$$NDA = \left[\widetilde{nda}_{ij}\right]_{m\times n} \tag{16}$$

Here, as explained, equality (17) and equality (18) $\widetilde{pda}_{ij}$ with $\widetilde{nda}_{ij}$ i alternative shows the positive and negative distances from the mean solution in terms of criteria j.

$$\widetilde{pda}_{ij} = \begin{cases} \frac{\psi(\tilde{x}_{ij} - \widetilde{av}_j)}{k(\widetilde{av}_j)}, & eğer\ j \epsilon\ D \\ \frac{\psi(\widetilde{av}_j - \tilde{x}_{ij})}{k(\widetilde{av}_j)}, & eğer\ j\ \epsilon\ N \end{cases} \tag{17}$$

$$\widetilde{nda}_{ij} = \begin{cases} \frac{\psi(\widetilde{av}_j - \tilde{x}_{ij})}{k(\widetilde{av}_j)}, & eğer\ j \epsilon\ D \\ \frac{\psi(\tilde{x}_{ij} - \widetilde{av}_j)}{k(\widetilde{av}_j)}, & eğer\ j\ \epsilon\ N \end{cases} \tag{18}$$

4. For all alternatives, the weighted positive ($\tilde{sp}$) and negative ($\tilde{sn}_i$) distances are found using equation (12) and equation (13).

$$\widetilde{sp}_i = \sum_{j=1}^{n} \left(\widetilde{W}_j \times \widetilde{pda}_{ij} \right) \tag{19}$$

$$\widetilde{sn}_i = \sum_{j=1}^{n} \left(\widetilde{W}_j \times \widetilde{nda}_{ij} \right) \tag{20}$$

5. For each alternative $\widetilde{sp}_i$ ve $\widetilde{sn}_i$ equation (21) and equality (22) are used to normalize the values.

$$\widetilde{nsp}_i = \frac{\widetilde{sp}_i}{max_i(\widetilde{sp}_i)} \tag{21}$$

$$\widetilde{nsn}_i = 1 - \frac{\widetilde{sn}_i}{max_i(\widetilde{sn}_i)} \tag{22}$$

6. Equation (23) is used to calculate fuzzy evaluation scores for alternatives.

$$\widetilde{as}_i = \frac{1}{2} (\widetilde{nsp}_i + \widetilde{nsn}_i) \tag{23}$$

7. Equation (24) is used when converting fuzzy evaluation scores of alternatives to non-fuzzy scores.

$$as_i = \frac{as_i^l + as_i^m + as_i^u}{3} \tag{24}$$

The values considered for the alternatives are ordered from largest to smallest, and the alternative with the highest score is selected as the best candidate.

4. Case Study

The manufacturing company operating in the metal industry has been the subject of the case study. Company managers have realized a lean transition due to the manufacturing problems they have experienced and aimed to manage all the company's functions in line with lean principles. The supply function is one of them. Lean recommends working with a single supplier and advocates long-term cooperation with this supplier. Thus, it will be possible for both vendor-buyers to achieve the desired quality level and work with lower costs. In addition, the transfer of lean principles to the supplier and a mutually balanced production will be realized. In order to achieve these advantages, company managers foresee the need to reduce the number of suppliers and work with one or at most two suppliers per product or process. The company purchases copper and steel pipes as raw materials and uses them in its production. As a result of the meetings held with the senior executives, priority was given to the supplier selection for the steel pipe, as it is the raw material used in the highest amount and there were delays in the lead times. Steel pipes are currently supplied from 6 domestic or foreign sources. Since problems were experienced with some of these suppliers, the managers suggested that new suppliers be searched. The recommendation of the top management was to evaluate two existing suppliers, and three new suppliers found suitable in the market. As a result of the meeting with the managers for the selection and evaluation of suppliers, it was decided to classify the lean criteria obtained through literature research under 15 groups by taking expert opinions. This classification is shown in Table 2.

Table 2. Classification of lean supplier selection criteria

Quality	Management commitment quality * Quality agreement * Quality control applications * Quality improvement * Quality performance * Rejection rate * TQM *Product performance* Certification * Product durability
Cost	Logistics cost * Total cost* Buyer internal cost reduction
Price	Products prices *Sales price * Pricing * Payment method * Payment terms * Price reduction
Delivery	Transportation * Reduction of materials and packages used in parts supplied * Supply lots
Location	Distance * Facility layout and location * Geographic proximity * Geographical location
Flexibility	Flexibility in demand change * Batch flexible
Reliability	Years in business * Earlier business relationship * Experience in the sector * Years of work together with the company * Vulnerability * Uncertainty minimization * Amount of past business * Supplier commitment * Reputation * Reputation and position in the industry
Capability	Supply capacity * Technical capacity and facility * Technology capability * Technology level * Total monthly capacity * Automation and virtual enterprise * Project capability * Supply variety * Production capacity * Production facility and capacity * Production technology * Responsiveness
Finance	Financial capability * Financial position * Financial stability
Time	Processing time * Lead time
Collaboration	Years in work together with * Willingness to share information * Long term relationship * Training aids * Trust * Supply base redesign * Business improvement * Procedural compliance * Process integration * Information * Internal and external integration of supplier * Relationship quality * Relationship
Design	Innovation and development capacity * Product design * Research and development * Design capabilities * Innovativeness
Sustainability	Supply chain continuity management
Lean Culture	Cultural aspects * Culture * Eliminate muda * Employee leanness * Continuous improvement * Kanban systems * JIT purchasing * Production management leanness * Employee involvement and suggestion/incentive systems
Service	After-sales technical support * Accessibility and availability * Customer service * Service level and customer satisfaction

4.1. Weighting of Evaluation Criteria with Fuzzy DEMATEL Method

When the evaluation criteria in Table 2, which were considered within the scope of the study, were examined, it was seen that it would be more appropriate to make verbal evaluations and to include fuzzy logic in the solution process due to some criteria such as "Flexibility", "Reliability", and "Lean Culture".

The first step in applying the Fuzzy DEMATEL method is the creation of the Fuzzy Direct Relationship Matrix. For this purpose, the necessary evaluations were conducted with a group of four decision-makers consisting of a purchasing specialist, a purchasing department manager, and two senior company managers. By combining the verbal evaluations of the four decision-makers, the direct relationship matrix was created based on the verbal expressions listed in Table 3.

The verbal evaluations carried out were converted into fuzzy triangular numbers given in Table 1 and digitized. Calculations were made by considering the equations given in the Fuzzy DEMATEL application steps detailed in the previous section, and the Fuzzy total relation matrix (T) given in Table 4 was obtained. Then, the defuzzification process was performed, and the defuzzified threshold values of the T-matrix in Table 5 were calculated. The DEMATEL method has been used to weigh these supplier evaluation criteria, and the relevant calculations are shown in Tables 3-6.

Table 3. Direct relation matrix with verbal terms

CRITERIA	Q	C	P	D	L	F	R	Ca	Fi	T	Co	D	S	LC	Se
Quality (Q)	0	VH	H	L	L	M	H	H	H	M	M	VH	M	VH	VH
Cost (C)	H	0	H	M	H	M	L	M	VH	L	L	H	H	H	H
Price (P)	VH	M	0	L	H	H	M	M	VH	L	M	VH	H	M	M
Delivery (D)	M	H	L	0	VH	H	H	H	M	VH	H	VL	M	VH	VH
Location (L)	H	VH	L	VH	0	VH	M	H	M	H	H	L	M	H	H
Flexibility (F)	VH	M	L	M	M	0	M	VH	H	H	M	M	L	VH	VH
Reliability ®	H	L	M	H	VH	M	0	H	H	M	VH	L	H	VH	M
Capability (Ca)	M	M	L	M	M	M	H	0	H	M	H	H	M	H	H
Finance (Fi)	H	VH	H	L	M	H	M	VH	0	M	L	H	VH	L	L
Time (T)	H	VH	M	VH	H	VH	M	M	M	0	VL	L	L	VH	H
Collaboration (Co)	M	L	L	L	VH	H	H	H	L	L	0	M	M	H	M
Design (D)	VH	VH	VH	H	L	M	L	M	VL	VL	M	0	VL	L	M
Service (S)	M	L	L	H	M	M	VH	H	VH	M	M	L	0	M	L
Lean Culture (LC)	H	H	M	H	VH	VH	M	H	M	VH	VH	H	H	0	M
Service (Se)	VH	H	H	VH	H	H	H	M	M	H	M	L	L	H	0

Table 4. Fuzzy total relation matrix (T)

	Quality			Cost			Price			…….	Sustainability			Lean Culture			Service		
	l	m	u	l	m	u	l	m	u	…….	l	m	u	l	m	u	l	m	u
Q	0.000	0.000	0.000	0.005	0.014	0.043	0.004	0.012	0.039	…….	0.001	0.005	0.029	0.005	0.015	0.045	0.004	0.014	0.043
C	0.002	0.010	0.047	0.000	0.000	0.000	0.002	0.008	0.039	…….	0.002	0.008	0.039	0.002	0.009	0.045	0.002	0.009	0.043
P	0.005	0.014	0.046	0.001	0.005	0.031	0.000	0.000	0.000	…….	0.002	0.008	0.038	0.001	0.006	0.032	0.001	0.005	0.031
D	0.001	0.006	0.035	0.002	0.010	0.044	0.000	0.002	0.018	…….	0.001	0.005	0.029	0.005	0.015	0.047	0.005	0.014	0.044
L	0.003	0.010	0.049	0.005	0.014	0.045	0.000	0.002	0.019	…….	0.001	0.005	0.030	0.003	0.010	0.047	0.002	0.010	0.045
F	0.005	0.015	0.046	0.001	0.006	0.031	0.000	0.002	0.018	…….	0.000	0.002	0.018	0.005	0.015	0.045	0.005	0.014	0.043
R	0.002	0.010	0.048	0.000	0.002	0.021	0.001	0.005	0.028	…….	0.002	0.008	0.040	0.005	0.015	0.046	0.001	0.005	0.032
Ca	0.001	0.006	0.034	0.001	0.005	0.031	0.000	0.002	0.018	…….	0.001	0.004	0.028	0.002	0.009	0.045	0.002	0.008	0.043
Fi	0.002	0.009	0.045	0.004	0.013	0.041	0.002	0.008	0.037	…….	0.004	0.011	0.038	0.000	0.002	0.020	0.000	0.002	0.019
T	0.003	0.010	0.046	0.005	0.014	0.042	0.001	0.005	0.027	…….	0.000	0.002	0.018	0.005	0.015	0.044	0.002	0.009	0.042
Co	0.001	0.005	0.031	0.000	0.002	0.018	0.000	0.002	0.016	…….	0.001	0.004	0.026	0.002	0.009	0.042	0.001	0.005	0.029
De	0.004	0.012	0.038	0.004	0.012	0.036	0.004	0.010	0.032	…….	0.000	0.000	0.007	0.000	0.002	0.017	0.001	0.004	0.026
S	0.001	0.005	0.031	0.000	0.002	0.018	0.000	0.002	0.016	…….	0.000	0.000	0.000	0.001	0.005	0.030	0.000	0.002	0.018
LC	0.003	0.011	0.051	0.003	0.010	0.047	0.001	0.005	0.030	…….	0.002	0.008	0.043	0.000	0.000	0.000	0.001	0.006	0.034
Se	0.005	0.015	0.049	0.002	0.010	0.045	0.002	0.008	0.040	…….	0.000	0.002	0.019	0.003	0.010	0.047	0.000	0.000	0.000

Table 5. Defuzzified threshold values of T-matrix

	Q	C	P	D	L	F	R	Ca	Fi	T	Co	De	S	LC	Se
Q	0.000	0.019	0.017	0.006	0.006	0.011	0.015	0.017	0.016	0.010	0.006	0.017	0.010	0.020	0.019
C	0.017	0.000	0.014	0.010	0.016	0.011	0.006	0.011	0.018	0.006	0.006	0.014	0.014	0.016	0.016
P	0.020	0.011	0.000	0.006	0.016	0.016	0.010	0.011	0.018	0.005	0.009	0.016	0.014	0.011	0.010
D	0.012	0.017	0.006	0.000	0.020	0.017	0.016	0.017	0.011	0.018	0.015	0.002	0.010	0.021	0.019
L	0.018	0.020	0.006	0.019	0.000	0.020	0.011	0.018	0.011	0.015	0.015	0.006	0.010	0.018	0.017
F	0.020	0.011	0.005	0.010	0.011	0.000	0.010	0.019	0.015	0.014	0.010	0.009	0.005	0.020	0.019
R	0.017	0.006	0.010	0.015	0.019	0.012	0.000	0.017	0.016	0.010	0.017	0.006	0.015	0.020	0.011
Ca	0.011	0.011	0.005	0.010	0.011	0.011	0.015	0.000	0.015	0.010	0.014	0.014	0.009	0.016	0.016
Fi	0.016	0.018	0.014	0.006	0.010	0.016	0.010	0.019	0.000	0.009	0.005	0.014	0.016	0.006	0.006
T	0.017	0.019	0.009	0.018	0.016	0.019	0.010	0.011	0.010	0.000	0.002	0.005	0.005	0.020	0.016
Co	0.010	0.006	0.005	0.005	0.017	0.015	0.014	0.015	0.005	0.005	0.000	0.009	0.009	0.015	0.010
De	0.017	0.016	0.014	0.012	0.005	0.009	0.005	0.009	0.002	0.002	0.008	0.000	0.002	0.005	0.009
S	0.010	0.006	0.005	0.014	0.010	0.010	0.017	0.015	0.017	0.009	0.009	0.005	0.000	0.010	0.006
LC	0.019	0.017	0.010	0.017	0.020	0.021	0.011	0.018	0.011	0.018	0.018	0.015	0.015	0.000	0.012
Se	0.021	0.017	0.015	0.018	0.017	0.017	0.016	0.012	0.011	0.015	0.010	0.006	0.006	0.018	0.000

The threshold value was determined by averaging the defuzzified threshold values of T-matrix values given in Table 5. This value was calculated as 0.012. All the values in Table 5 were reviewed, and the values below the threshold value were colored lightly. The resulting table reveals the interactions with other criteria for each criterion. When the table is examined, it was seen that the "Design" and "Sustainability" criteria had relatively less interaction and were excluded from the supplier evaluation process. The fuzzy and clarified criteria weights obtained after the calculations for the remaining 13 criteria are as in Table 6.

Table 6. Determination of the impact levels and weights of the criteria

Criteria	Fuzzy final weighting values			D+R	D-R	$(D+R)^2$	$(D-R)^2$	$((D+R)^2+(D-R)^2)^{1/2}$	Defuzzified weight values_wi
	l	m	u						
Q	0.0979	0.0923	0.0849	0.4145	-0.0380	0.1718	0.0014	0.4162	0.0875
C	0.0789	0.0776	0.0769	0.3660	-0.0164	0.1339	0.0003	0.3663	0.0770
P	0.0588	0.0626	0.0667	0.3075	0.0394	0.0946	0.0016	0.3101	0.0652
D	0.0832	0.0793	0.0761	0.3660	0.0338	0.1340	0.0011	0.3676	0.0773
L	0.0873	0.0850	0.0818	0.3945	0.0078	0.1556	0.0001	0.3945	0.0830
F	0.0832	0.0831	0.0802	0.3851	-0.0263	0.1483	0.0007	0.3860	0.0812
R	0.0688	0.0726	0.0770	0.3574	0.0256	0.1277	0.0007	0.3583	0.0754
Ca	0.0697	0.0755	0.0830	0.3795	-0.0426	0.1440	0.0018	0.3819	0.0803
Fi	0.0702	0.0709	0.0724	0.3418	-0.0123	0.1168	0.0002	0.3420	0.0719
T	0.0701	0.0688	0.0683	0.3239	0.0315	0.1049	0.0010	0.3254	0.0684
Co	0.0477	0.0542	0.0628	0.2839	-0.0036	0.0806	0.0000	0.2840	0.0597
De				0.2531	-0.0231	0.0640	0.0005	0.2541	
S				0.2823	0.0014	0.0797	0.0000	0.2823	
LC	0.1061	0.0987	0.0894	0.4410	0.0084	0.1944	0.0001	0.4410	0.0928
Se	0.0781	0.0794	0.0806	0.3810	0.0144	0.1451	0.0002	0.3812	0.0802

When the Table 6 is examined, it is seen that the most influential criterion in the solution process is "Lean Culture", followed by the "Quality" and "Location" criteria, respectively.

4.2. Selection of the Most Suitable Supplier with the Fuzzy EDAS Method

The first step in the implementation of the fuzzy EDAS method is the verbal evaluation of all alternative suppliers in terms of each evaluation criteria. For this purpose, four decision-makers who have detailed information about the suppliers were asked to provide the corresponding evaluations. The ratings obtained based on the verbal expressions by averaging the ratings given by the four decision-makers are as in Table 7.

Table 7. Evaluation of alternatives by means of verbal variables

	Q	C	P	D	L	F	R	Ca	Fi	T	Co	LC	S
A1	VL	L	VH	N	L	H	H	VL	VH	VL	H	VL	L
A2	VH	VL	N	VL	VL	VH	N	VL	N	VL	L	N	H
A3	VH	VL	VH	N	VL	VH	N	VL	VL	VL	N	VH	VH
A4	N	VL	L	VL	VL	VH	N	VL	L	VL	L	L	L
A5	L	VH	VL	VH	VH	VL	VH	VH	VH	VH	VH	VL	H

Verbal evaluations of all decision-makers were carried out using the fuzzy triangular numbers in Table 1 and were combined into a single value. Thus, the Average Fuzzy Decision Matrix seen in Table 8 was obtained.

Table 8. The average fuzzy decision matrix

Weight	0.098	0.092	0.085	0.079	0.078	0.077	0.059	0.063	0.067	…….	0.048	0.054	0.063	0.106	0.099	0.089	0.078	0.079	0.081
	QUALITY			COST			PRICE			…….	COLLABORATION			LEAN CULTURE			SERVICE		
1	0	0	0.25	0	0.25	0.5	0.75	1	1	…….	0.5	0.75	1	0	0	0.25	0	0.25	0.5
2	0.75	1	1	0	0	0.25	0.25	0.5	0.75	…….	0	0.25	0.5	0.25	0.5	0.75	0.5	0.75	1
3	0.75	1	1	0	0	0.25	0.75	1	1	…….	0.25	0.5	0.75	0.75	1	1	0.75	1	1
4	0.25	0.5	0.75	0	0	0.25	0	0.25	0.5	…….	0	0.25	0.5	0	0.25	0.5	0	0.25	0.5
5	0	0.25	0.5	0.75	1	1	0	0	0.25	…….	0.75	1	1	0	0	0.25	0.5	0.75	1
avi	0.35	0.55	0.7	0.15	0.25	0.45	0.35	0.55	0.7	…….	0.3	0.55	0.75	0.2	0.35	0.55	0.35	0.6	0.8

The positive distance matrix from the mean (PDA) and the negative distance matrix from the mean (NDA) was calculated using the mean solution values in the last row of the table. The application steps of the method were considered, and finally, the defuzzified evaluation points (Kasj) were calculated for each alternative in the last column of Table 9. When these values are examined, it is seen that the alternatives are listed as A3>A2>A4>A1>A5.

Table 9. Weighted total distances, normalized values, and evaluation scores

spi			sni			nspi			nsni			asj			Kasj	Alternatives
0.313	0.109	0.691	0.483	0.364	0.678	0.385	0.134	0.849	0.637	0.726	0.490	0.511	0.430	0.670	0.537	A1
0.403	0.402	0.779	0.391	0.208	0.227	0.495	0.494	0.956	0.706	0.844	0.829	0.600	0.669	0.893	0.721	A2
0.496	0.591	0.782	0.288	0.219	0.296	0.610	0.726	0.961	0.784	0.835	0.778	0.697	0.780	0.869	0.782	A3*
0.246	0.293	0.814	0.576	0.323	0.180	0.302	0.360	1.000	0.567	0.757	0.865	0.434	0.559	0.932	0.642	A4
0.513	0.645	0.383	0.482	0.926	1.330	0.630	0.792	0.471	0.637	0.303	0.000	0.634	0.548	0.235	0.472	A5

5. Result and Discussion

This study focused and analyzed the case study for lean supplier selection by applying Fuzzy DEMATEL and Fuzzy EDAS methods. The aim of the research also provides a general overview of the supplier selection for a company in the metal industry to highlight important factors to be determined as the selection process. Although the various criteria could be found in the literature, we have focused on the most important and common criteria to finalize them. Therefore, 15 main categories were found with the opinions of experts and the suggestions of the managers in the field. These criteria were weighted with Fuzzy DEMATEL in line with the expert opinions of company officials. The results show that "Lean Culture" is the most prominent factor followed by "Quality", "Location", "Flexibility", and "Service" (see Table 6). On the other hand, the analysis also showed that the least impactful criteria were found as "Collaboration", "Price", "Time", and "Finance". Overall, these findings indicate that the "Design" and "Sustainability" criteria were determined as the least influencing and affected criteria in the evaluation process, so those criteria were excluded. The weights of the remaining 13 criteria were used as input to the Fuzzy EDAS method to be applied in the supplier selection process. By analyzing the results of the selection of five suppliers, two from the old supplier pool and three newly determined, were evaluated. The results reveal and support that the supplier "A3" (as the most suitable supplier for the lean) had the highest scores according to Tables 9 and 10.

Table 10. Ranking and selection of suppliers

Alternatives	A3	A2	A4	A1	A5
Evaluation scores	0.782	0.721	0.642	0.537	0.472

The other alternative suppliers are "A2", "A4", "A1", and "A5", respectively. It is foreseen that fine-tuned work will be possible in collaboration with supplier “A3”, which is from the former supplier group, on cost and transportation issues. The company wishes to continue working with supplier "A3" in line with its business continuity purpose. The result was presented to the senior management's decision, and it was approved. However, in case of any demand growth in the future and the supplier "A3" is insufficient, it may be considered to add the supplier "A2" as a new supplier into the portfolio. The company would use this selection process for similar supplier problems for further collaborations.

6. Conclusion

When determining the lean criteria to be applied in supplier selection, the criteria in the literature were used and these criteria were gathered under 15 top groups. It is possible to say that these groups can change the results of Fuzzy DEMATEL. From the literature survey, it is determined that some authors, for example, combined cost and price under the same criteria, while others considered them separately. Although quality and delivery were the most common criteria, Lean Culture and Sustainability were not considered in most studies. For similar reasons, it can be stated that the description of the criteria is a factor affecting the ranking. Design and sustainability criteria were not taken into account in this study as they were below the threshold values. Accordingly, it can be signified that the company does not need a supplier for design. Although the Lean philosophy foresees integration with the supplier, it is an unexpected result that sustainability and collaboration are in the last place. It can be suggested for future studies to take new criteria for the selection of lean suppliers in more detail by adding them.

On the other hand, if the supplier ranking is evaluated with Fuzzy EDAS based on criteria, it can be seen that supplier A3 has the highest scores in terms of lean culture, quality and location, which are the first three criteria with the highest weight. The same applies to the second supplier (A2), which scores very well in terms of quality and location criteria and moderately in terms of lean culture. Therefore, supplier A3 is in first place, while supplier A2 is its closest follower by a small margin. However, it can be seen that supplier A5 cannot meet these criteria.

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