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SUPPLIER SELECTION CONSIDERING SUSTAINABILITY MEASURES: AN APPLICATION OF WEIGHT RESTRICTION FUZZY-DEA APPROACH

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Abstract. With the growing of consumer awareness in environmental and social issues sustainable development has become an essential element in supply chain management. Supplier evaluation and selection is one of the main strategic decisions for purchasing management in supply chain. This paper use Data Envelopment Analysis (DEA) to propose a new model for evaluation and ranking of a given set of suppliers from sustainable point of view. The proposed model integrates the fuzzy set theory and DEA to consider the decision makers' preferences and handle the ambiguity and uncertainty in supplier selection process. For this purpose, linguistic values in the form of triangular fuzzy numbers are used to assess the weights of criteria, sub-criteria, and the ratings of suppliers' performance with respect to sub-criteria. Then, a fuzzy-DEA model, using α-cut approach, is developed considering weight constraints. An application from Supplying Automotive Parts Company (SAPCO) Company, which is one of the largest suppliers of automotive parts in the Middle-East, is presented to show the applicability of the proposed model. Finally, the proposed weight restriction fuzzy-DEA model is validated through comparing with one of the recent supplier selection methods.

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1. Introduction

Recent years firms in supply chain witnessed a lot of pressure to consider environmental and social sustainability for keeping competitive position around the world. Sustainability has acquired a dominant place in many subjects and now is being discussed seriously in supply chain management [6, 14, 32]. Supplier evaluation and selection is a vital decision in supply chain management and to progress the sustainability, all of the components of the chain must have affinity with this issue. Therefore, supplier selection considering sustainability measures is a decision process, which must be consider the economic, environmental, and social aspects for choosing the appropriate supplier. However, a lot of research have been reported on supplier selection issues (readers are referred to [12, 15, 37] but not many on sustainable supplier selection. Therefore, supplier selection indicators (criteria and sub-criteria) have been focused from a sustainable point of view in this paper to improve supplier selection process and make it compatible to the present-day requirements.

Data Envelopment Analysis (DEA) is one of the appropriate tools for supplier selection since DEA can consider several criteria to be optimized simultaneously [3, 8, 16]. However, authors in the related papers in

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literature, do not consider some points. First, they do not take into account the relative importance of input and output criteria. In fact, the weights to be allocated to the inputs and outputs can be selected so that DEA maximizes the efficiency of decision-making unit (DMU) and may allocate a zero weight to the inputs and/or outputs on which its performance is worst. However, decision makers could not justify neglecting of some of inputs and/or outputs. The most widespread method to overcome this drawback in DEA models is, perhaps, the weight restrictions inclusion. Weight restrictions are allowed to integrate the managerial preferences in terms of relative importance levels of various inputs and outputs. The idea of conditioning the DEA calculations to consider the presence of additional information arose first in the context of bounds on factor weights in DEA's multiplier side problem [36]. This led to the development of assurance region models by Thompson *et al.* (1990) [38]. Second, the supplier selection decision is involved a high degree of vagueness and ambiguity in practice and DEA cannot handle with imprecise and fuzzy data. The related data, which divided into inputs and outputs in the conventional DEA models must be numeric and precise. To deal with this impreciseness and ambiguity, various fuzzy-DEA models have been proposed (readers are referred to [29]for more details). From literature, it may be pointed that incorporation of weight restrictions was not yet considered in fuzzy-DEA models for supplier selection in earlier works. Third, there is a limitation on the number of inputs and outputs (criteria) in accordance with the number of DMUs (suppliers) in DEA technique. If number of DMUs is not large enough, then the likelihood of most or all DMUs receiving efficiency scores at or near 1.0 is great and this limits the discrimination power of the DEA [21,23]. Therefore, improvement of DEA applications for decision-making would be a fertile area.

In this paper, one of the most popular fuzzy-DEA models, namely, α-cut approach [20] is developed for supplier selection problem. The proposed model integrates the fuzzy set theory and α-cut approach while imposing some weight restrictions to consider the decision makers' preferences and handle the ambiguity and uncertainty in supplier selection process. For this purpose, linguistic terms in the form of fuzzy numbers are used to assess the relative importance of criteria, sub-criteria, and the ratings of suppliers' performance with respect to sub-criteria.

The rest of this paper is organized as follows. The following section discusses the issue of supplier selection considering sustainability measures. This is followed by some preliminaries on fuzzy theory and fuzzy-DEA in Section 3. Section 4 proposes a model for supplier selection in several steps. Managerial implications, validation procedure, and an application with real data from Supplying Automotive Parts Company (SAPCO) Company, which is the leading motivator to supply localized auto parts for producing various automobiles, is given in section 5 for ranking suppliers. Finally, conclusions and recommendations for future research are given in Section 6.

2. Supplier selection from sustainable point of view

Sustainability has multi-dimensional facets that includes topics related to the "triple-bottom-line" of balancing corporate social responsibility including balancing economic, environmental and social dimensions [32]. Since, supplier selection is a key decision in supply chain management; to have a *sustainable supply chain* the supplier selection should be considered with *sustainability measures*. Sustainability has been just received attentions in supplier selection problem recently [1,2,25,28,33,35]. Choosing the appropriate criteria is a challengeable subject in supplier evaluation. According to the aforementioned references, the most widely adopted economic criteria for supplier selection were quality, price, service, delivery, flexibility, and reputation. In terms of environmental aspect, the most widely used criteria are including "environmental management system", "green image", "green competencies", and "design for environment". In terms of social aspects, "human rights", "health and safety", information disclosure", and "right of stakeholders". Readers are referred for more information about sustainable aspects in supplier selections to [12,22,41,45].

Since, the existing framework in literature [9] has covered the most common criteria in supplier selection. Therefore, the framework can be lent to this work as shown in Table 1. Considering some experts' view, a questionnaire has been designed in this paper on the basis of the mentioned framework to derive the relative importance of criteria and sub-criteria in the related company. Further, the second questionnaire is designed to

Table 1. The literature of selection indicators in supplier selection [25].

		References Criteria												
	Criteria and sub-criteria	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10	P11	P12	P13
Economic	Cost/price					√			√	√		√	√	√
	Quality			√				√	√	√	√	√	√	√
	Technology capability					√		√		√			√	
	Production facilities and capacity					√				√				
	Financial capability					√		√		√				
	Organization & management							√		√	√		√	
	Delivery								√		√	√	√	√
	Service								√	√	√			
	Relationship									√	√		√	
	Flexibility										√		√	
Environmental	Environmental costs	√										√		√
	Green design	√			√						√	√		√
	Environmental management system	√	√	√	√		√		√		√	√	√	√
	Environmental competencies	√	√	√				√		√				√
	Green R &D				√						√			
	Pollution control			√	√	√	√						√	
	Green product			√							√		√	
	Resource consumption						√						√	
	ECO-design requirements for energy using product								√					
	Ozone depleting chemicals								√					
	Waste electrical and electronic equipment								√					
	Recycling											√		
	Green supply chain management										√	√		
	Innovation										√			
Social	The interests and rights of employee								√					
	The rights of stakeholders								√					
	Work safety & labor health					√								
	Information disclosure								√					
	Respect for the policy								√					

get information on the sub-criteria for the suppliers' performance. It is worthy to note that, there is no limitation on the number of sub-criteria and any new sub-criteria can be added for each economic, environmental, and social groups in the designed questionnaires (See Appendix A).

3. Preliminaries on fuzzy set theory and fuzzy-DEA

We applied fuzzy set theory to present the decision makers' preferences on criteria and sub-criteria weights and also to show the suppliers' performance with respect to each sub-criterion. Some related descriptions of fuzzy theory are used that include membership functions, linguistic variables, fuzzy numbers, fuzzy operators, and defuzzification as follows. In addition, the fuzzy-DEA model, which utilized in this paper is explained in this section.

3.1. Fuzzy membership function

In the fuzzy set theory, as the degree to which an element belongs to a certain set increases its membership function grade approaches 1, otherwise it approaches 0. Therefore, the concept of characteristic function from general set can be extended in to the concept of membership function for the fuzzy set [27]. Several functional forms of the membership function are available to represent different situations of fuzziness; for example, linear

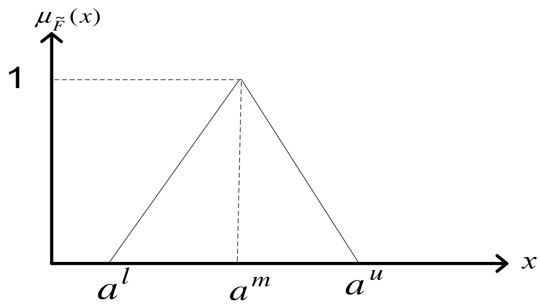

FIGURE 1. Triangular membership function.

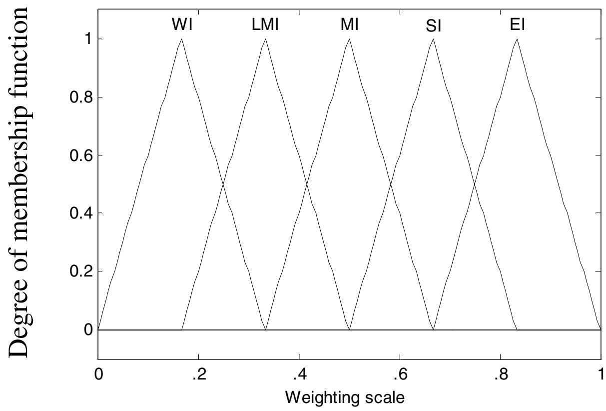

FIGURE 2. Membership functions for the weights of criteria and sub-criteria.

shape, concave shape, and exponential shape. Triangular membership function gives reasonably good performance in terms of theoretical calculations as compared to other shapes. The triangular membership function is applied in this paper because of linear interpolation between fuzzy set elements [42]. A triangular fuzzy number can be shown as $\tilde{w} = (a^l, a^m, a^u,)$ where,a^l, a^m, and a^u are the lower, medium,and upper amount of fuzzy number, respectively in Figure 1. The triangular membership function is also defined as below.

$$\mu_{\tilde{F}}(x) = \begin{cases} 0 & \text{if} \quad x < a^l \\ \dfrac{1}{a^m - a^l}(x - a^l) & \text{if} \quad a^l \leqslant x \leqslant a^m \\ \dfrac{1}{a^m - a^u}(x - a^u) & \text{if} \quad a^m \leqslant x \leqslant a^u \\ 0 & \text{if} \quad x > a^u \end{cases} \tag{3.1}$$

To show the decisions makers' preferences, two membership functions have been set out in this paper, one for estimation of the criteria and sub-criteria weights as shown in Figure 2 and the other for the supplier's performance with respect to sub-criteria as shown in Figure 3.

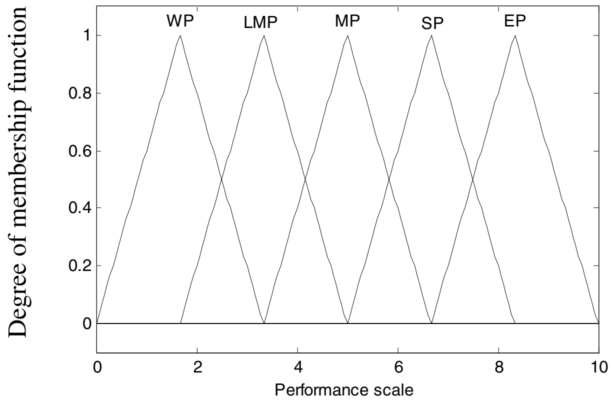

FIGURE 3. Membership functions for the supplier's performance.

3.2. Fuzzy linguistic variable

The linguistic variable is used mainly to express the size of the data. In this paper, two groups of linguistic variables are utilized, one group for the importance of criteria and sub-criteria weights including: WI, LMI, MI, SI and EI, respectively for weak, low moderate, moderate, strong, and extreme important. The other group for the supplier's performance with respect to sub-criteria including WP, LMP, MP, SP and EP, respectively, for weakly, low moderately, moderately, strongly, and extremely preferred. In respect to Figures 2 and 3, for example, "weak important" can be represented as (0, 0.1667, 0.334) and "strongly preferred" can be represented as (5.0, 6.67, 8.34).

3.3. Fuzzy operator

Among all fuzzy operators, multiplication is utilized in the proposed model. Suppose equation (3.2) and (3.3) be two triangular fuzzy numbers as,

$$\tilde{X} = (x^l, x^m, x^u) \tag{3.2}$$

$$\tilde{Y} = (y^l, y^m, y^u) \tag{3.3}$$

So, multiplication of them is as follows respectively.

$$\tilde{X} * \tilde{Y} = (x^l * y^l, x^m * y^m, x^u * y^u) \tag{3.4}$$

3.4. Defuzzification

Fuzzy number is converted to crisp number through the defuzzification action. Popular defuzzication approaches are included the center of area method (COA), bisector of area method (BOA), mean of maximum method (MOM), smallest of maximum method (SOM), and the largest of maximum method (LOM). Among deffuzzification methods, the COA method which is the most popular method is applied in the proposed fuzzy-DEA model (the readers are referred to [17] for more information).

3.5. Fuzzy-DEA model

DEA is a nonparametric programming method, which was proposed by Charnes *et al.* (1978). Their model was named CCR, which is the abbreviation of their names (Charnes, Cooper, and Rodhs). It was developed by Banker *et al.* (1984) to evaluate the relative efficiency of decision-making units (DMUs) using crisp inputs and outputs. Strong literatures (Emrouznejad, *et al.*, 2008 and Emrouznejad, De Witte, 2011) identified DEA as one of the main tools for performance management. Today, in many real applications the inputs and outputs are not usually precise and can be represented by fuzzy numbers. Various fuzzy methods for dealing with this impreciseness and ambiguity in DEA have been proposed. Hatami *et al.* (2011) reviewed the fuzzy-DEA methods and presented a taxonomy by classifying the fuzzy-DEA papers published over the past two decades into four primary categories, namely, the tolerance approach, the α-level based approach, the fuzzy ranking approach, and the possibility approach; and a secondary category to group the pioneering papers that did not fall into the four primary classifications [20]. Among these categories, the α-level based approach which is the most common fuzzy-DEA model has been applied in this paper. The CCR model with fuzzy inputs and outputs can be written as shown in (3.5) to measure the efficiency of s^{th} supplier to a set of peer suppliers in the model below:

$$\begin{aligned}
&\text{Max } \sum_{o=1}^{t} w_{os}\tilde{y}_{os}\\
&\text{st :}\\
&\sum_{i=1}^{e} v_{is}\tilde{x}_{is} = 1\\
&\sum_{o=1}^{t} w_{on}\tilde{y}_{on} - \sum_{i=1}^{e} v_{in}\tilde{x}_{in} \leqslant 0 \quad n = 1,2,\ldots,f\\
&w_{on}, v_{in} \geqslant \varepsilon \;\; o = 1,2,\ldots,t\,; \;\; i = 1,2,\ldots,e
\end{aligned} \tag{3.5}$$

Where, "i" represents inputs; subscript "o" represents outputs; subscript $n = 1,2,\ldots,f$ represents the DMUs(suppliers); the variables w_{on} and v_{in} are the weights of inputs and outputs, respectively which are obtained by the model and named multipliers; y_{os} is the amount of output o provided by unit "s"; x_{is} is the amount of input "i" used by unit "s"; the symbol "ε" is non-Archimedean constant; and '$\tilde{}$' shows the fuzziness. For s^{th} supplier if the optimum value of objective function is 1 and all slacks are zero, it is said an efficient supplier; otherwise, it is an inefficient supplier. Fuzzy numbers in this formula are considered as triangular fuzzy numbers. Then, equation (3.5) can be written as follows:

$$\begin{aligned}
&\tilde{x}_{is} = \left(x_{is}^{l}, x_{is}^{m}, x_{is}^{u}\right)\\
&\tilde{y}_{os} = \left(y_{os}^{l}, y_{os}^{m}, y_{os}^{u}\right)\\
&\text{Max } \sum_{o=1}^{t} w_{os}(y_{os}^{l}, y_{os}^{m}, y_{os}^{u})\\
&\text{st :}\\
&\sum_{i=1}^{e} v_{is}(x_{is}^{l}, x_{is}^{m}, x_{is}^{u}) = 1\\
&\sum_{o=1}^{t} w_{on}(y_{on}^{l}, y_{on}^{m}, y_{on}^{u}) - \sum_{i=1}^{e} v_{in}(x_{in}^{l}, x_{in}^{m}, x_{in}^{u}) \leqslant 0 \quad n = 1,2,\ldots,f\\
&w_{on}, v_{in} \geqslant \varepsilon \;\; o = 1,2,\ldots,t\,; \;\; i = 1,2,\ldots,e
\end{aligned} \tag{3.6}$$

This fuzzy CCR model can be transformed into an interval programming by using α-cut method as follows [4]:

$$\begin{aligned}
&\text{Max } \sum_{o=1}^{t} w_{os}((1-\alpha)y_{os}^{l} + \alpha y_{os}^{m}, (1-\alpha)y_{os}^{u} + \alpha y_{os}^{m})\\
&\text{st :}\\
&\sum_{i=1}^{e} v_{is}((1-\alpha)x_{is}^{l} + \alpha x_{is}^{m}, (1-\alpha)x_{is}^{u} + \alpha x_{is}^{m}) = 1\\
&\sum_{o=1}^{t} w_{on}((1-\alpha)y_{on}^{l} + \alpha y_{on}^{m}, (1-\alpha)y_{on}^{u} + \alpha y_{on}^{m}) - \sum_{i=1}^{e} v_{in}((1-\alpha)x_{in}^{l} + \alpha x_{in}^{m}, (1-\alpha)x_{in}^{u} + \alpha x_{in}^{m}) \leqslant 0\\
&n = 1,2,\ldots,f, \quad w_{on}, v_{in} \geqslant \varepsilon, o = 1,2,\ldots,t \;\;, i = 1,2,\ldots,e\,;
\end{aligned} \tag{3.7}$$

The above model can be divided into two models which give upper bound and lower bound of efficiency as, respectively [4].

$$\begin{aligned}
&\text{Max} \quad \sum_{o=1}^{t} w_{os}((1-\alpha)y_{os}^{u} + \alpha y_{os}^{m}) \\
&\text{st}: \\
&\sum_{i=1}^{e} v_{is}((1-\alpha)x_{is}^{u} + \alpha x_{is}^{m}) = 1 \\
&\sum_{o=1}^{t} w_{on}((1-\alpha)y_{on}^{u} + \alpha y_{on}^{m}) - \sum_{i=1}^{e} v_{in}((1-\alpha)x_{in}^{u} + \alpha x_{in}^{m}) \leqslant 0 \\
&n = 1,2,\ldots,f\,,\ w_{on}, v_{in} \geqslant \varepsilon\,,\ o = 1,2,\ldots,t\ ,\ i = 1,2,\ldots,e\,;
\end{aligned} \tag{3.8}$$

$$\begin{aligned}
&\text{Max} \quad \sum_{o=1}^{t} w_{os}((1-\alpha)y_{os}^{l} + \alpha y_{os}^{m}) \\
&\text{st}: \\
&\sum_{i=1}^{e} v_{is}((1-\alpha)x_{is}^{l} + \alpha x_{is}^{m}) = 1 \\
&\sum_{o=1}^{t} w_{on}((1-\alpha)y_{on}^{l} + \alpha y_{on}^{m}) - \sum_{i=1}^{e} v_{in}((1-\alpha)x_{in}^{l} + \alpha x_{in}^{m}) \leqslant 0 \\
&n = 1,2,\ldots,f\,,\ w_{on}, v_{in} \geqslant \varepsilon\,,\ o = 1,2,\ldots,t\ ,\ i = 1,2,\ldots,e\,;
\end{aligned} \tag{3.9}$$

The values are considered for "α" are 0, 0.25, .5, 0.75, and 1.

If a dummy input is considered in the above models, the models (3.8) and (3.9) can be formulated, respectively as follows:

$$\begin{aligned}
&\text{Max} \sum_{o=1}^{t} w_{o_s}((1-\alpha)y_{os}^{u} + \alpha y_{os^m}) \\
&\text{st}: \\
&\sum_{o=1}^{t} w_{on}((1-\alpha)y_{on}^{u} + \alpha y_{on}^{m}) \leqslant 1\ ; n = 1,2,\ldots,f \\
&w_{on} \geqslant \varepsilon,\ \ i = 1,2,\ldots,e\ \ ; o = 1,2,\ldots,t
\end{aligned} \tag{3.10}$$

$$\begin{aligned}
&\text{Max} \quad \sum_{o=1}^{t} w_{o_s}((1-\alpha)y_{os^l} + \alpha y_{os}^{m}) \\
&\text{st}: \\
&\sum_{o=1}^{t} w_{o_n}((1-\alpha)y_{on^l} + \alpha y_{on}^{m}) \leqslant 1\ ; n = 1,2,\ldots,f \\
&w_{o_n} \geqslant \varepsilon\ ;\ i = 1,2,\ldots,e \quad o = 1,2,\ldots,t
\end{aligned} \tag{3.11}$$

4. A new weight restriction model for supplier selection

4.1. Applying weight restrictions to consider the importance weights of criteria andsub-criteria

To simplify the proposed model for the readers, this module is explained in several steps as below:

Step 1. Preparing fuzzy input data for the importance weights

We also consider the decision makers' opinions about the importance weights of both criteria and sub-criteria. For this purpose, the linguistic variables are used and converted to fuzzy numbers according to Figure 2. The decision makers express their preferences about the relative importance of criteria in comparison with other criteria (wc) and also each sub-criterion in comparison with other sub-criteria in its related criteria group (wsc) as shown in (4.1) and (4.2), respectively.

$$wc = [\tilde{w}c_{hk}]_{3*d} \;\; ; k = 1, \ldots, d \;\; h = 1, 2, 3 \tag{4.1}$$

$$wsc = [\tilde{w}sc_{jk}]_{z*d} \;\; ; k = 1, \ldots, d \;\; j = 1, 2, \ldots, g, g+1, \ldots, p, p+1, \ldots, z-1, z \tag{4.2}$$

Step 2. Calculating the importance weight for each sub-criterion

To calculate the importance weight of each sub-criterion in comparison with all other sub-criteria, the importance weight of each sub-criterion must be multiplied with the importance weight of its related criterion according to each decision maker's preference as shown in equation (4.3).

$$fw = \begin{bmatrix} \tilde{w}sc_{11} * \tilde{w}c_{11} & \tilde{w}sc_{12} * \tilde{w}c_{12} & \ldots & \tilde{w}sc_{1d} * \tilde{w}c_{1d} \\ wsc_{21} * \tilde{w}c_{11} & \tilde{w}sc_{22} * \tilde{w}c_{12} & \ldots & \tilde{w}sc_{2d} * \tilde{w}c_{1d} \\ \vdots & \vdots & \vdots & \vdots \\ \underline{\tilde{w}sc_{g1} * \tilde{w}c_{11}} & \underline{\tilde{w}sc_{g2} * \tilde{w}c_{12}} & \ldots & \underline{\tilde{w}sc_{gd} * \tilde{w}c_{1d}} \\ \tilde{W}_{11} & \tilde{W}_{12} & & \tilde{W}_{1d} \\ \tilde{w}sc_{(g+1)1} * \tilde{w}c_{21} & \tilde{w}sc_{(g+1)2} * \tilde{w}c_{22} & \ldots & \tilde{w}sc_{(g+1)d} * \tilde{w}c_{2d} \\ \tilde{w}sc_{(g+2)1} * \tilde{w}c_{21} & \tilde{w}sc_{(g+2)2} * \tilde{w}c_{22} & \ldots & \tilde{w}sc_{(g+2)d} * \tilde{w}c_{2d} \\ \vdots & \vdots & \vdots & \vdots \\ \underline{\tilde{w}sc_{p1} * \tilde{w}c_{21}} & \underline{\tilde{w}sc_{p2} * \tilde{w}c_{22}} & \ldots & \underline{\tilde{w}sc_{pd} * \tilde{w}c_{2d}} \\ \tilde{W}_{21} & \tilde{W}_{22} & & \tilde{W}_{2d} \\ \tilde{w}sc_{(p+1)1} * \tilde{w}c_{31} & \tilde{w}sc_{(p+1)2} * \tilde{w}c_{32} & \ldots & \tilde{w}sc_{(p+1)d} * \tilde{w}c_{3d} \\ \tilde{w}sc_{(p+2)1} * \tilde{w}c_{31} & \tilde{w}sc_{(p+2)2} * \tilde{w}c_{32} & \ldots & \tilde{w}sc_{(p+2)d} * \tilde{w}c_{3d} \\ \vdots & \vdots & \vdots & \vdots \\ \underline{\tilde{w}sc_{z1} * \tilde{w}c_{31}} & \underline{\tilde{w}sc_{z2} * \tilde{w}c_{32}} & \ldots & \underline{\tilde{w}sc_{zd} * \tilde{w}c_{3d}} \\ \tilde{W}_{31} & \tilde{W}_{32} & & \tilde{W}_{3d} \end{bmatrix} \tag{4.3}$$

Step 3. Aggregating the decision makers' opinions for sub-criteria weights

To reduce the computational burden of the model, the obtained fuzzy weights of sub-criteria, which is shown in equation (4.3) are combined into three groups (economic, environmental, and social). In fact, decision maker's opinion for sub-criteria weights aggregate to decision maker's opinion for criteria weights. To aggregate these fuzzy ratings suppose the q fuzzy numbers are considered as equation (4.4) then the aggregated fuzzy number can be defined as equation (4.5).

$$\tilde{R}_c = (a_c^l, a_c^m, a_c^u), \quad c = 1, 2, \ldots, q \tag{4.4}$$

$$\begin{aligned} &\tilde{R} = (a^l, a^m, a^u) \\ &st. \\ &a^l = \min_p \{a^l\} \quad , a^m = \tfrac{1}{q} \sum_{c=1}^{q} a_c^m \quad , a^u = \max_p \{a^u\} \quad c = 1, \ldots, q \end{aligned} \tag{4.5}$$

Therefore, by applying the equation (4.5), the fuzzy weights matrix (fw) is converted to a matrix which includes "$\tilde{W}$" arrays as presented in equation (4.6).

$$FW = [\tilde{W}_{hk}]_{3*d} \;\; ; k = 1, \ldots, d \;\; h = 1, 2, 3 \tag{4.6}$$

The importance weights are reflected in our proposed model through two next steps.

Step 4. Defuzzification of fuzzy weights

The arrays of fuzzy weights matrix (4.6) are defuzzified to the crisp weights by using the COA method as shown in equation (4.7).

$$CW = [W_{hk}]_{3*d} \;\; ; k = 1, \ldots, d \;\; h = 1, 2, 3 \tag{4.7}$$

Step 5. Calculating the ratio of the crisp weights

$$R_{CW^T} = \begin{bmatrix} \dfrac{W_{11}}{W_{12}} & \dfrac{W_{12}}{W_{13}} & \dfrac{W_{11}}{W_{13}} \\ \dfrac{W_{21}}{W_{22}} & \dfrac{W_{22}}{W_{23}} & \dfrac{W_{21}}{W_{23}} \\ \vdots & \vdots & \vdots \\ \dfrac{W_{d1}}{W_{d2}} & \dfrac{W_{d2}}{W_{d3}} & \dfrac{W_{d1}}{W_{d3}} \end{bmatrix}_{k*3} \tag{4.8}$$

Step 6. Calculating upper and lower bound of pair criteria weights ratio

Step 7. Applying weight constraints in the proposed model

$$A_L \leqslant \frac{w_{n1}}{w_{n2}} \leqslant A_U\,,\;\; B_L \leqslant \frac{w_{n2}}{w_{n3}} \leqslant B_U\,,\;\; C_L \leqslant \frac{w_{n1}}{w_{n3}} \leqslant C_U \;\; n = 1, 2, \ldots, f \tag{4.9}$$

The proposed model is open-ended to adapt any number of supplier selection criteria, supplier selection sub-criteria, and candidate suppliers for today's manufacturing including small, medium and large enterprises. In the next section, a real-life supplier selection is presented.

4.2. Calculate the ratings of the suppliers' performance to apply in the proposed model

Like the First module, second one is also explained in several steps as below:

Step 1. Preparing fuzzy input data for the suppliers' performance

To show the decisions makers' preferences for suppliers' performance with respect to sub-criteria, the linguistic variables are used and converted to fuzzy numbers according to Figure 3.

As it mentioned before, we have 3 criteria ($h = 1, 2, 3$), "z" sub-criteria ($j = 1, 2, \ldots, g, g+1, \ldots, p, p+1, \ldots, z-1, z$), and f suppliers ($n = 1, 2, \ldots, f$) and suppose that a decision committee has $d$decision makers. The decisions makers' preferences for each supplier's performance with respect to sub-criteria are solicited as,

$$\begin{aligned} SP_n &= [\tilde{r}_{jk}]_{z\times d} k = 1, \ldots, d \\ j &= 1, 2, \ldots, g, g+1, \ldots, p, p+1, \ldots, z-1, z n = 1, 2, \ldots, f \end{aligned} \tag{4.10}$$

Step 2. Aggregating the decision makers' opinions fort suppliers' performances

To reduce the computational burden, the fuzzy ratings of supplier's performance in equation (4.10) are divided based on three criteria groups (economic, environmental, and social) similar to similar to the previous sub-sections. In fact, decision makers' opinions about suppliers' performances with respect to sub-criteria are aggregated to suppliers' performance with respect to criteria.

According to equation (4.5), the aggregated fuzzy ratings of supplier's performance changes (4.10) to (4.11). For example, the fuzzy numbers $\tilde{r}_{11}, \tilde{r}_{21,}, \ldots, \tilde{r}_{g1}$ are aggregated to $\tilde{R}_{11}$.

$$SP_n = [\tilde{R}_{hk}]_{3\times d} = \begin{bmatrix} \tilde{r}_{11} & \tilde{r}_{12} & \ldots & \tilde{r}_{1d} \\ \tilde{r}_{21} & \tilde{r}_{22} & \ldots & \tilde{r}_{2d} \\ \vdots & \vdots & \vdots & \vdots \\ \dfrac{\tilde{r}_{g1}}{\tilde{R}_{11}} & \dfrac{\tilde{r}_{g2}}{\tilde{R}_{12}} & \ldots & \dfrac{\tilde{r}_{gd}}{\tilde{R}_{1d}} \\ \tilde{r}_{(g+1)1} & \tilde{r}_{(g+1)2} & \ldots & \tilde{r}_{(g+1)d} \\ \tilde{r}_{(g+2)1} & \tilde{r}_{(g+2)2} & \ldots & \tilde{r}_{(g+2)d} \\ \vdots & \vdots & \vdots & \vdots \\ \dfrac{\tilde{r}_{p1}}{\tilde{R}_{21}} & \dfrac{\tilde{r}_{p2}}{\tilde{R}_{22}} & \ldots & \dfrac{\tilde{r}_{pd}}{\tilde{R}_{2d}} \\ \tilde{r}_{(p+1)1} & \tilde{r}_{(p+1)2} & \ldots & \tilde{r}_{(p+1)d} \\ \tilde{r}_{(p+2)1} & \tilde{r}_{(p+2)2} & \ldots & \tilde{r}_{(p+2)d} \\ \vdots & \vdots & \vdots & \vdots \\ \dfrac{\tilde{r}_{n1}}{\tilde{R}_{31}} & \dfrac{\tilde{r}_{n2}}{\tilde{R}_{32}} & \ldots & \dfrac{\tilde{r}_{nd}}{\tilde{R}_{3d}} \end{bmatrix}, \quad k = 1, \ldots, d \ , h = 1, 2, 3 \tag{4.11}$$

Step 3. Aggregating the decision makers' opinions for each criteria

To aggregate "K" decision makers' opinions for each criterion, equation (4.5) is applied again for every row of the matrix (4.11) as shown in equation (4.12).

$$SP_n = \begin{bmatrix} \tilde{R}_{11} & \tilde{R}_{12} & \ldots & \tilde{R}_{1d} \\ \tilde{R}_{21} & \tilde{R}_{22} & \ldots & \tilde{R}_{2d} \\ \tilde{R}_{31} & \tilde{R}_{32} & \ldots & \tilde{R}3d \end{bmatrix} \begin{matrix} \Rightarrow \\ \Rightarrow \\ \Rightarrow \end{matrix} \begin{bmatrix} \tilde{R}D_{1n} \\ \tilde{R}D_{2n} \\ \tilde{R}D_{3n} \end{bmatrix} = sp_n \tag{4.12}$$

This procedure is repeated for each of "n" suppliers and there is no limitation about the number of suppliers. Finally, we have the fuzzy decision matrix (FD) as,

$$FD = \left[sp_1 \ sp_2 \ \ldots \ sp_f \right]^T = \left[\tilde{R}D_{nh} \right]_{f\times 3} \quad n = 1, 2, \ldots, f \ \ h = 1, 2, 3 \tag{4.13}$$

Step 4. Normalizing the fuzzy decision matrix

Now, the fuzzy decision matrix (FD) must be normalized. Since, all sub-criteria are preferred to be larger-is-better considering$\tilde{R}D_{nh} = \left[rd^l_{nh}, rd^m_{nh}, rd^u_{nh} \right]$, the normalization can be represented as,

$$NFD = \frac{1}{\max\limits_{n}(rd^{u_{nh}})} \left[\tilde{R}D_{nh} \right]_{f\times 3} = \left[\tilde{N}RD_{nh} \right]_{f\times 3} \tag{4.14}$$

The arrays of equation (4.14) are shown in (4.15).

$$\tilde{N}RD_{nh} = (Nrd^l_{nh}, Nrd^m_{nh}, Nrd^u_{nh}) \tag{4.15}$$

Step 5. Converting the fuzzy numbers to upper bound and lower bound sets

According to the α-cut approach, each fuzzy number of the NFD matrix converts to upper bound and lower bound sets which are in the form of crisp number as shown in (4.16) and (4.17).

TABLE 2. The lower and upper bounds for weight ratio of paired criteria.

		Economic/ Environmental	Environmental/ Social	Economic / Economic /
Criteria bounds	Lower Bound	$A_L = \min\limits_k \frac{w_{kh}\ for\ h=1}{w_{kh}\ for\ h=2}$	$B_L = \min\limits_k \frac{w_{kh}\ for\ h=2}{w_{kh}\ for\ h=3}$	$C_L = \min\limits_k \frac{w_{kh}\ for\ h=1}{w_{kh}\ for\ h=3}$
	Upper Bound	$A_U = \max\limits_k \frac{w_{kh}\ for\ h=1}{w_{kh}\ for\ h=2}$	$B_U = \max\limits_k \frac{w_{kh}\ for\ h=2}{w_{kh}\ for\ h=3}$	$C_U = \max\limits_k \frac{w_{kh}\ for\ h=1}{w_{kh}\ for\ h=3}$

$$NRD_{\text{nh(upper)}} = (1-\alpha)Nrd^{u}_{nh} + (\alpha)Nrd^{m}_{nh} \tag{4.16}$$

$$NRD_{\text{nh(lower)}} = (1-\alpha)Nrd^{l}_{nh} + (\alpha)Nrd^{m}_{nh} \tag{4.17}$$

Now, the normalized fuzzy decision matrix (NFD) is divided to two crisp matrixes according to (4.16) and (4.17) as shown in (4.18) and (4.19).

$$NCD_{\text{upper}} = \left[NRD_{\text{nh(upper)}}\right]_{f\times 3} \tag{4.18}$$

$$NCD_{\text{lower}} = \left[NRD_{\text{nh(lower)}}\right]_{f\times 3} \tag{4.19}$$

Step 6. Utilizing supplier's performance as output variables in the proposed model

To develop a fuzzy-DEA method which consider the decision makers' preferences in supplier selection problem, the input and output items must be identified. The results of the previous step as supplier's performance in the form of NCD_{upper} and NCD_{lower} matrices are considered as output variables in models (3.8) and (3.9), respectively. To calculate the relative efficiency of suppliers a dummy input is applied. Therefore, the models (3.8) and (3.9) are replaced with models (3.10) and (3.11), respectively and supplier's performance as output variables pass to the proposed model.

5. Supplier selection in SAPCO Company: a real application

A real-life supplier selection issue is utilized to show the applicability of the proposed model. SAPCO Company[2] is the leading motivator to supply localized auto parts for producing various automobiles. To achieve company's success in the market, there is a major need to evaluate performance rating of potential suppliers. Among existing different groups of supplier in this company, Piston/Cylinder suppliers are chosen for this research. Identifying the supplier selection criteria are based on the perceptions of three decision makers from distinct functional areas (department of purchasing, department of quality, and manufacturing) including DM1, DM2, and DM3, respectively.

To derive the necessary data, the two questionnaires (Appendix-A) have been designed and approved by this committee. From the collected data, finally, eight sub-criteria were selected including "Quality" (Q), "Delivery" (D), "Technology Level" (TL), "After Sales Services" (ASS), "Environmental Management System" (EMS), "Pollution Control" (PC), "Work Safety & Labor Health" (WS&LH), and "Ethics" (E). The results of this process are presented in Table 3 and Table 6, respectively. In addition, decision makers' preference about suppliers' performance are shown in Table 7.

As shown in Table 3, for example, the opinion of second decision maker (DM2) on the relative importance of environmental merits is SI (strong Important) which its related fuzzy number equals to (0.5, 0.667, 0.834) according to Figure 2. Also in Table 6, for example, the opinion of first decision maker (DM1) on the relative

[2] www.sapco.com

Table 3. Decision makers' opinions for criteria weights in SAPCO Company.

		DM1	DM2	DM3
Criteria	Economic	EI(0.667, 0.834, 1)	EI(0.667, 0.834, 1)	SI(0.5, 0.667, 0.834)
	Environmental	MI(0.334, 0.5, 0.667)	SI(0.5, 0.667, 0.834)	EI(0.667, 0.834, 1)
	Social	LMI(0.167, 0.334, 0.5)	MI(0.334, 0.5, 0.667)	MI(0.334, 0.5, 0.667)

Table 4. Decision makers' opinions for sub-criteria weights in SAPCO Company.

		DM1	DM2	DM3
Sub criteria	Q	EI(0.667, 0.834, 1)	EI(0.667, 0.834, 1)	EI(0.667, 0.834, 1)
	D	EI(0.667, 0.834, 1)	SI(0.5, 0.667, 0.834)	SI(0.5, 0.667, 0.834)
	TL	SI(0.5, 0.667, 0.834)	EI(0.667, 0.834, 1)	SI(0.5, 0.667, 0.834)
	ASS	SI(0.5, 0.667, 0.834)	SI(0.5, 0.667, 0.834)	MI(0.334, 0.5, 0.667)
	EMS	SI(0.5, 0.667, 0.834)	EI(0.667, 0.834, 1)	EI(0.667, 0.834, 1)
	PC	LMI(0.167, 0.334, 0.5)	MI(0.334, 0.5, 0.667)	EI(0.667, 0.834, 1)
	WS& LH	MI(0.334, 0.5, 0.667)	SI(0.5, 0.667, 0.834)	LMI(0.167, 0.334, 0.5)
	E	WI(0, 0.167, 0.334)	LMI(0.167, 0.334, 0.5)	SI(0.5, 0.667, 0.834)

importance of WS & LH is moderate Important (MI), which is equal to (0.34, 0.5, 0.67). These Tables show that the economic merits have received more attention than environmental merits and also environmental merits have received more attention than social merits.

The number of candidate suppliers in this case is 5. Decision makers' preferences about suppliers' performance with respect to sub-criteria are shown in Table 7. For example, the opinions of DM1, DM2, and DM3 on the performance of first supplier with respect to "Q" are EP, EP, and EP, respectively. The related fuzzy number to this linguistic rating is (6.67, 8.34, 10.0) according to Figure 3.

5.1. Results and discussion

To show the calculation of case study in simple way for the readers, the order of steps in two modules has been considered here.

Based on Step 1 in 4.1, the inputs from decision makers' preferences (Tabs. 3 and 4), show the fuzzy input data. Based on Steps 2 and 3 in 4.1, the data of Tables 3 and 6 are considered as matrix arrays of (4.1) and (4.2) which are multiplied with each other and then aggregated according to (4.5) and (4.3). The aggregated weights are shown as,

$$FW = \begin{bmatrix} (0.3889\ \ 0.6250\ \ 0.9167) & (0.3889\ \ 0.6250\ \ 0.9167) & (02500\ \ 0.4444\ 0.6944) \\ (0.1667\ \ 0.3333\ \ 0.5556) & (0.2500\ \ 0.4444\ \ 0.6944) & (0.4444\ \ 0.6944\ \ 1.0000) \\ (0.0556\ 0.1667\ \ 0.333) & (0.167\ \ 0.3333\ \ 0.5556) & (0.1111\ \ 0.2500\ 0.4444) \end{bmatrix} \tag{5.1}$$

Based on Step 1 in 4.2, the data of Table 7 are considered as matrix arrays in equation (4.10). Then, based on Step 2 and Step 3 in 4.2, the arrays of Table 5 are aggregated according to equation (4.5), equation (4.11), and equation (4.12). The results for the first supplier are shown in equation (5.2).

$$sp_1 = \begin{bmatrix} (6.6667\ 8.3333\ 10.0000) \\ (3.3333\ 5.0000\ 6.6667) \\ (3.3333\ 5.0000\ 6.6667) \end{bmatrix} \tag{5.2}$$

TABLE 5. Decision makers' opinions with respect to sub-criteria for candidate suppliers.

Sub criteria	DMs	A	B	C	D	E
Q	DM1:	EP(6.67, 8.34, 10)	MP(3.34, 5.0, .67)	MP(3.34, 5.0, .67)	SP(5.0, 6.67, 8.34)	EP(6.67, 8.34, 10)
	DM2:	EP(6.67, 8.34, 10)	MP(3.34, 5.0, .67)	MP(3.34, 5.0, .67)	MP(3.34, 5.0, .67)	SP(5.0, 6.67, 8.34)
	DM3:	EP(6.67, 8.34, 10)	MP(3.34, 5.0, .67)	MP(3.34, 5.0, .67)	EP(6.67, 8.34, 10)	SP(5.0, 6.67, 8.34)
D	DM1:	EP(6.67, 8.34, 10)	MP(3.34, 5.0, .67)	MP(3.34, 5.0, .67)	WP(0.0, 1.67, 3.34)	SP(5.0, 6.67, 8.34)
	DM2:	EP(6.67, 8.34, 10)	MP(3.34, 5.0, .67)	MP(3.34, 5.0, .67)	MP(3.34, 5.0, .67)	LMP(1.67, 3.34, 5)
	DM3:	EP(6.67, 8.34, 10)	MP(3.34, 5.0, .67)	MP(3.34, 5.0, .67)	LMP(1.67, 3.34, 5)	MP(3.34, 5.0, .67)
TL	DM1:	EP(6.67, 8.34, 10)	MP(3.34, 5.0, .67)	MP(3.34, 5.0, .67)	MP(3.34, 5.0, .67)	SP(5.0, 6.67, 8.34)
	DM2:	EP(6.67, 8.34, 10)	MP(3.34, 5.0, .67)	MP(3.34, 5.0, .67)	EP(6.67, 8.34, 10)	EP(6.67, 8.34, 10)
	DM3:	EP(6.67, 8.34, 10)	MP(3.34, 5.0, .67)	MP(3.34, 5.0, .67)	SP(5.0, 6.67, 8.34)	SP(5.0, 6.67, 8.34)
ASS	DM1:	EP(6.67, 8.34, 10)	MP(3.34, 5.0, .67)	MP(3.34, 5.0, .67)	LMP(1.67, 3.34, 5)	MP(3.34, 5.0, .67)
	DM2:	EP(6.67, 8.34, 10)	MP(3.34, 5.0, .67)	MP(3.34, 5.0, .67)	LMP(1.67, 3.34, 5)	MP(3.34, 5.0, .67)
	DM3:	EP(6.67, 8.34, 10)	MP(3.34, 5.0, .67)	MP(3.34, 5.0, .67)	LMP(1.67, 3.34, 5)	MP(3.34, 5.0, .67)
EMS	DM1:	MP(3.34, 5.0, .67)	EP(6.67, 8.34, 10)	MP(3.34, 5.0, .67)	EP(6.67, 8.34, 10)	LMP(1.67, 3.34, 5)
	DM2:	MP(3.34, 5.0, .67)	EP(6.67, 8.34, 10)	MP(3.34, 5.0, .67)	SP(5.0, 6.67, 8.34)	WP(0.0, 1.67, 3.34)
	DM3:	MP(3.34, 5.0, .67)	EP(6.67, 8.34, 10)	MP(3.34, 5.0, .67)	SP(5.0, 6.67, 8.34)	MP(3.34, 5.0, .67)
PC	DM1:	MP(3.34, 5.0, .67)	EP(6.67, 8.34, 10)	MP(3.34, 5.0, .67)	MP(3.34, 5.0, .67)	LMP(1.67, 3.34, 5)
	DM2:	MP(3.34, 5.0, .67)	EP(6.67, 8.34, 10)	MP(3.34, 5.0, .67)	EP(6.67, 8.34, 10)	LMP(1.67, 3.34, 5)
	DM3:	MP(3.34, 5.0, .67)	EP(6.67, 8.34, 10)	MP(3.34, 5.0, .67)	SP(5.0, 6.67, 8.34))	LMP(1.67, 3.34, 5)
WS & LH	DM1:	MP(3.34, 5.0, .67)	MP(3.34, 5.0, .67)	EP(6.67, 8.34, 10)	WP(0.0, 1.67, 3.34)	SP(5.0, 6.67, 8.34)
	DM2:	MP(3.34, 5.0, .67)	MP(3.34, 5.0, .67)	EP(6.67, 8.34, 10)	WP(0.0, 1.67, 3.34)	SP(5.0, 6.67, 8.34)
	DM3:	MP(3.34, 5.0, .67)	MP(3.34, 5.0, .67)	EP(6.67, 8.34, 10)	WP(0.0, 1.67, 3.34)	SP(5.0, 6.67, 8.34)
E	DM1:	MP(3.34, 5.0, .67)	MP(3.34, 5.0, .67)	EP(6.67, 8.34, 10)	MP(3.34, 5.0, .67)	EP(6.67, 8.34, 10)
	DM2:	MP(3.34, 5.0, .67)	MP(3.34, 5.0, .67)	EP(6.67, 8.34, 10)	WP(0.0, 1.67, 3.34)	SP(5.0, 6.67, 8.34)
	DM3:	MP(3.34, 5.0, .67)	MP(3.34, 5.0, .67)	EP(6.67, 8.34, 10)	LMP(1.67, 3.34, 5)	EP(6.67, 8.34, 10)

(Column header row spans: "Suppliers" over A–E.)

This procedure is repeated for other four suppliers and the fuzzy decision matrix (FD) is structured. Then, based on Step 4 in 4.2, it is normalized according to equation (4.14) as shown in equation (5.3).

$$NFD = \begin{bmatrix} (0.6667\ 0.8333\ 1.0000) & (0.3333\ 0.5000\ 0.6667) & (0.3333\ 0.5000\ 0.6667) \\ (0.3333\ 0.5000\ 0.6667) & (0.6667\ 0.8333\ 1.0000) & (0.3333\ 0.5000\ 0.6667) \\ (0.3333\ 0.5000\ 0.6667) & (0.3333\ 0.5000\ 0.6667) & (0.6667\ 0.8333\ 1.0000) \\ (0.3333\ 0.5000\ 0.6667) & (0.5278\ 0.6944\ 0.8611) & (0.0833\ 0.2500\ 0.4167) \\ (0.4444\ 0.6111\ 0.7778) & (0.5278\ 0.6944\ 0.8611) & (0.5556\ 0.7222\ 0.8889) \end{bmatrix} \tag{5.3}$$

Then, based on Step 5 in 4.2, the normalized fuzzy decision matrix (NFD) divide into two crisp matrixes according to (4.18) and (4.19) as shown in (5.4), (5.5).

$$NCD_{\text{upper}} = \begin{bmatrix} (1-\alpha)1.000 + 0.8333\alpha & (1-\alpha)0.6667 + 0.5000\alpha & (1-\alpha)0.6667 + 0.5000\alpha \\ (1-\alpha)0.6667 + 0.5000\alpha & (1-\alpha)1.000 + 0.8333\alpha & (1-\alpha)0.6667 + 0.5000\alpha \\ (1-\alpha)0.6667 + 0.5000\alpha & (1-\alpha)0.6667 + 0.5000\alpha & (1-\alpha)1.000 + 0.8333\alpha \\ (1-\alpha)0.6667 + 0.5000\alpha & (1-\alpha)0.8611 + 0.6944\alpha & (1-\alpha)0.4167 + 0.2500\alpha \\ (1-\alpha)0.7778 + 0.6111\alpha & (1-\alpha)0.5000 + 0.3333\alpha & (1-\alpha)0.8889 + 0.7222\alpha \end{bmatrix} \tag{5.4}$$

$$NCD_{\text{upper}} = \begin{bmatrix} (1-\alpha)0.6667 + 0.8333\alpha & (1-\alpha)0.3333 + 0.5000\alpha & (1-\alpha)0.3333 + 0.5000\alpha \\ (1-\alpha)0.3333 + 0.5000\alpha & (1-\alpha)0.6667 + 0.8333\alpha & (1-\alpha)0.3333 + 0.5000\alpha \\ (1-\alpha)0.3333 + 0.5000\alpha & (1-\alpha)0.3333 + 0.5000\alpha & (1-\alpha)0.6667 + 0.8333\alpha \\ (1-\alpha)0.3333 + 0.5000\alpha & (1-\alpha)0.5278 + 0.6944\alpha & (1-\alpha)0.0833 + 0.2500\alpha \\ (1-\alpha)0.4444 + 0.6111\alpha & (1-\alpha)0.1667 + 0.3333\alpha & (1-\alpha)0.5556 + 0.7222\alpha \end{bmatrix} \tag{5.5}$$

TABLE 6. Weight ratio of paired criteria in SAPCO Company.

		Economic/ Environmental	Environmental/ Social	Economic/ Social
Criteria bounds	Lower Bound	0.6494	1.3158	1.7241
	Upper Bound	1.8289	2.6552	3.4750

TABLE 7. Super efficiency analysis of upper bound values.

		Efficiency					Ranking
		$\alpha = 0$	$\alpha = 0.25$	$\alpha = 0.5$	$\alpha = 0.75$	$\alpha = 1$	
Suppliers	A	1.101347	1.107234	1.113876	1.121310	1.129843	1
	B	1.000000	1.000000	1.000000	1.000000	1.000000	2
	C	0.9706553	0.9689507	0.9670274	0.9648749	0.9624044	3
	D	0.8928412	0.8867993	0.8800356	0.8724113	0.8637281	5
	E	0.9530676	0.9503413	0.9473123	0.9438226	0.9398713	4

TABLE 8. Super-efficiency analysis of lower bound values.

		Efficiency					Ranking
		$\alpha = 0$	$\alpha = 0.25$	$\alpha = 0.5$	$\alpha = 0.75$	$\alpha = 1$	
Suppliers	A	1.180674	1.164533	1.151068	1.139701	1.129843	1
	B	1.000000	1.000000	1.000000	1.000000	1.000000	2
	C	0.9476862	0.9523600	0.9562585	0.9595499	0.9624044	3
	D	0.8125608	0.8286851	0.8422400	0.8537725	0.8637281	5
	E	0.9164067	0.9238069	0.9300420	0.9353639	0.9398713	4

As seen in these tables, the first two suppliers are efficient and other three suppliers are inefficient. The ranking order of five suppliers is A, B, C, E, and D. Having a look at Table 7, it is found that, the economic criteria have been received more attention from the first supplier. That is why; the best supplier is supplier 1 due to the most importance of economic criteria (see Tabs. 3 and 6). From Tables 7 and 8, it can be seen that the upper bound efficiencies are decreased by increasing α and the lower bound efficiencies are increased by increasing α for every supplier. In term of αvariation, it can be clearly seen that the ranking result remain constant for upper and lower bound of efficiency scores. This shows the proposed model is well working.

To show the contribution of this paper in case of open-ended supplier selection model, some additional discussion will be presented as below.

5.2. Validation of the proposed model

The proposed fuzzy-DEA model is validated through comparing its performance by the existing FIS-based supplier selection model [9] in literature. To compare the two models properly, the applied membership functions and linguistic terms regarding to criteria, sub-criteria, and the supplier's performance with respect to sub-criteria must be same in both models. So, the triangular membership functions are applied for the relative importance of criteria, sub-criteria, and the ratings of suppliers' performance with respect to sub-criteria for both models as shown in Figures 2 and 3, respectively.

Utilizing the decisions makers' preferences for criteria, sub-criteria, and suppliers' performance with respect to sub-criteria (Tabs. 3, 4, and 5) in the FIS-based model considering the mentioned membership functions,

TABLE 9. The optimal multipliers of upper bound model ($\alpha = 0.5$).

		Criteria		
		Economic	Environmental	Social
Suppliers	A	0.7536256	0.4120650	0.3131669
	B	0.5399310	0.5758350	0.2694845
	C	0.7536256	0.4120650	0.3131669
	D	0.7536256	0.4733386	0.2168707
	E	0.7536256	0.4120650	0.3131669

TABLE 10. The optimal multipliers of lower bound model ($\alpha = 0.5$).

		Criteria		
		Economic	Environmental	Social
Suppliers	A	1.000059	0.5468090	0.4155715
	B	0.7164869	0.7641314	0.3079946
	C	1.000059	0.5468090	0.4155715
	D	1.000059	0.6178062	0.2877868
	E	1.000059	0.5468090	0.4155715

TABLE 11. Efficiency scores from the FIS- based model.

	Suppliers	Efficiency	Ranking
Suppliers	A	86.7638	1
	B	75.6657	2
	C	75.2408	3
	D	70.6588	5
	E	71.7001	4

inputs for the FIS-based model are obtained as shown in equation 36.

$$\begin{bmatrix} 8.5556 & 7.4444 & 7.4444 & 6.3333 & 4.8889 & 3.5556 & 3.2222 & 2.5556 \\ 5.2222 & 4.5556 & 4.5556 & 3.8889 & 8.0000 & 5.7778 & 3.2222 & 2.5556 \\ 7.4444 & 4.5556 & 6.4815 & 3.8889 & 3.3333 & 2.4444 & 4.2222 & 3.8519 \\ 6.8889 & 3.1111 & 6.0000 & 2.6667 & 6.963 & 4.6667 & 1.2222 & 1.7778 \\ 5.2222 & 4.5556 & 4.5556 & 3.8889 & 4.8889 & 3.5556 & 5.2222 & 4.1111 \end{bmatrix} \tag{5.6}$$

In matrix above, each row presents the suppliers' performance with respect to sub-criteria. For example, the first array (8.5556) shows the rating of first supplier with respect to quality (Q). By executing the FIS-based model, the efficiency scores and ranking order are obtained as shown in Table 11.

As seen in Table 11, the ranking order of five suppliers for the FIS-based model is A, B, C, E, and D, which, are same with the proposed fuzzy-DEA model (Tabs. 7 and 8). It is clear that by normalization the score ranking amount of the FIS-based model (which is between 0−100), these amount are approximately same with those of the proposed fuzzy-DEA model. These results show the validation of the proposed model and comparing the two ranking results presents that the proposed model comes up with the FIS-based model.

5.3. Managerial implications

In these days, managers are more concerned about the life-cycle behaviour and involvement of a product. In this realm, managers and product designer cannot work in isolation but need to sit-together with other disciplines including the purchasing people. Purchasing management has come to play a critical role as a key to optimize the business activities in manufacturing under recent agile improvement of network technology, economic globalization, and growing of outsourcing agenda. Now, a production plant need to fulfil a variety of agenda or criteria under the domains of economic, social, and environmental aspects. These together in long-term performance achievements come to the fold of sustainable manufacturing. Therefore, one of the crucial challenges in manufacturing for purchasing department is supplier evaluation and henceforth their selection considering the sustainable agenda. Supplier selection is an important area of decision making in manufacturing, mainly for large and medium companies– either multinational (MNCs) or local.

DEA is one of the appropriate tools for supplier selection since it can consider several criteria to be optimized simultaneously. However, authors in the related papers in literature, do not consider some points on DEA method. First, they do not take into account the relative importance of input and output criteria. Second, the supplier selection decision is involved a high degree of vagueness and ambiguity. The related data, which divided into inputs and outputs in the conventional DEA models must be numeric and precise. Third, there is a limitation on the number of inputs and outputs (criteria) in accordance with the number of DMUs (suppliers) in DEA technique. If number of DMUs is not large enough, then the likelihood of most or all DMUs receiving efficiency scores at or near 1.0 is great and this limits the discrimination power of the DEA. As a result, selecting suitable supplier becomes too difficult for managers to make this strategic decision. Here, the weight restriction fuzzy DEA model has been proposed which considers all three aforementioned points, simultaneously to incorporate the managers.

6. Conclusions and recommendations for future research

In this paper, the sustainability issue for supplier selection has been located, and the DEA technique and its applications have been focused to develop the decision-making models under uncertainties. The main conclusions of this paper are as follows:

(1) The proposed weight restriction fuzzy-DEA model for supplier selection has been developed by incorporating the sustainability issues in the selection process for manufacturing firms, where the sustainability is a significant concern.
(2) The proposed weight restriction fuzzy-DEA model can be used for companies those are having problems in a supplier selection system when related information is imprecise. In addition, incorporation of relative importance of performance indicators will provide added benefits to the decision model that support manufacturing or service firms in the supplier selection process.
(3) The proposed weight restriction fuzzy-DEA model can be used for multi-criteria decision-making problems with any number of suppliers and indicators for today's manufacturing suitable for small, medium, and large enterprises.
(4) Suppliers' ranking through the efficiency scores obtained under the proposed model is in agreement with the existing FIS-based model. This validates the acceptance of the proposed weight restriction fuzzy-DEA model. The proposed weight restriction fuzzy-DEA model can be for supplier selection considering sustainability aspects in addition to the conventional economic or cost-based aspects.

Although many attempts have been made for the supplier selection, the issue of sustainability has been remained a challenge.

For the future work, systematic model suggested in this paper for supplier selection can be implemented to other problems, such as supply chain evaluation, technology selection, and personnel selection.

APPENDIX

TABLE A1. Relative importance of perfarmance indicators being attached for supplier selection in manufacturing/assembling of company products.

Main Criteria (indicators)	Importance being attached by the company	Sub-criteria (indicators)	Importance being attached by the company
Sustainable Economic aspects	1 2 3 4 5	Economic aspects	
		Constant reduction of manufacturing cost or cost per unit load supply	0 1 2 3 4 5
		Delivery on time, potential for cycle time or lead time reduction	0 1 2 3 4 5
		Specified Quality, quality management system of supplier.	0 1 2 3 4 5
		Technological capability (manufacturing facilities and capabilities, productivity, innovation, knowledge workers, documentation)	0 1 2 3 4 5
		Financial capability (ability for further investment, return on investment (ROI), healthy net present value (NPV)	0 1 2 3 4 5
		Flexibility (variety in raw materials or components, ability to produce/supply under make-to-order or assemble-to-order environments, facility planning, etc.)	0 1 2 3 4 5
		Organization & control (follows standard operating procedure (SOP), clear flow charts with control loops and their execution, etc.)	0 1 2 3 4 5
		Services and communications with the supplier (able to provide after services on time, ensure reliability)	0 1 2 3 4 5
		Any other indicator you consider: please specify	0 1 2 3 4 5
Conserved/preserved Environmental aspects	1 2 3 4 5	Concern about preservation of environment	
		Attainment of sustainable environmentalcompetencies	0 1 2 3 4 5
		Environmental management system (carry out environmental impact assessment (EIA) periodically, reporting to the customer, etc.	0 1 2 3 4 5
		Any other indicator you consider: please specify	0 1 2 3 4 5
Healthy/sound Social aspects	1 2 3 4 5	Ability to develop long-term relationships with customer	
		Social-respondsibilities (following professional/ engineering ethics, help building social institutions, not using child labor, etc.)	0 1 2 3 4 5
		Work safety & labor health	0 1 2 3 4 5
		Any other indicator you consider: please specify	0 1 2 3 4 5

Notes: Not Considered = (0); Weak Important = (3.1); Low Moderate Important = (3.2); Moderate Important = (3.3); Strong Important = (3.4); Extreme Important = (3.5)

Table A2. A supplier's performance for a specified product from sustainable point of view.

Sub-criteria (indicators)	Supplier's performance with respect to sub-criteria
Supply items at reasonable costs or prices over the years	1 2 3 4 5
Delivery performance (consistency in meeting delivery deadlines, order fill rate, perfect delivery rate, labeling)	1 2 3 4 5
Lot rejection rate or rework or scrap rate is normally within the average quality level in the past supplies	1 2 3 4 5
Having technically adequate employee and equipment	1 2 3 4 5
Financial stability (assets and debts, income and earnings, cash flow), Financial capability to reach raw material, semi-finished product and other resources	1 2 3 4 5
Flexibility of order altering	1 2 3 4 5
Organizational management (follows standard operating procedure (SOP), clear flow charts with control loops and their execution, etc.)	1 2 3 4 5
Integrated service capability (response time for customers' request, efficiency of engineering support, fulfilling customers' special requests, customer information service platform)	1 2 3 4 5
Conformance to environmental regulatory standards (promoting level of pollution control)	1 2 3 4 5
Environmental management system (establishment of environmental commitment and policy)	1 2 3 4 5
Social-responsibilities (the interests and rights of employee, the rights of stakeholder, information disclosure, respect for the policy, discrimination)	1 2 3 4 5
Work safety & labor health (health and safety incidents, health and safety practices, child labor, long working hours, flexible working arrangements, job opportunities, research and development, career delvelopment)	1 2 3 4 5

Notes: Weakly preferred = (3.1); Low Moderately preferred = (3.2); moderately preferred = (3.3); strongly preferred = (3.4); extremely preferred = (3.5)

Table A3. Code programming of LINGO software.

```
MODEL:
SETS:
  DMU/B1 B2 B3 B4 B5/:
    EFFICIENCY;

  FACTOR/DMU economic environmental social/;
  DXF(DMU, FACTOR): F;
ENDSETS
DATA:
  NINPUTS = 1;

F=
1 0.8333 0.5 0.5
1 0.5 0.8333 0.5
1 0.5 0.5 0.8333
```

```
1 0.5 0.6944 0.25
1 0.6111 0.3333 0.7222
1 0.1667 0.1667 0.1667
1 0.8333 0.8333 0.8333
;
ENDDATA

SETS:
    DXFXD(DMU,FACTOR): W;
  ENDSETS
    MAX = @SUM(DMU: EFFICIENCY);
    @FOR(DMU(I):
      EFFICIENCY (I) = @SUM(FACTOR(J)|J #GT# NINPUTS:
        F(I, J)* W(I, J));

    @FOR(DMU(K):
      @SUM(FACTOR(J)|J #GT# NINPUTS:
    F(K, J)* W(I, J)) <= 1;
W(K,3)<=(1/.6494)*W(I,2);
W(K,3)>=(1/1.8289)*W(I,2);

W(K,4)<=(1/1.7241)*W(I,2);
W(K,4)>=(1/3.4750)*W(I,2);
W(K,4)<=(1/1.3158)*W(I,3);
W(K,4)>=(1/2.6552)*W(I,3);

);

);
```

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