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Supplier Selection in the Sustainable Supply Chain: The Application of Analytic Hierarchy Process and Fuzzy Data Envelopment Analysis

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Abstract

The development and management of an effective and efficient supply chain involve the selection of the suppliers. Only economic criteria, including cost and delivery, once used to be considered in the process of supplier selection. But, they do not suffice for the evaluation of suppliers anymore due to the rapidly changing environment, and different perspectives are needed to be considered. The present paper aims to present a hybrid method based on fuzzy data envelopment analysis for sustainable supplier selection. At first, the criteria for sustainable supplier selection are derived from the relevant literature. Then, the hierarchy of the criteria and their preferential interrelations are specified by analytic hierarchy process. Eventually, the performance of the suppliers is evaluated using fuzzy data envelopment analysis. The presented DEA model has been inspired by the concept of ideal and anti-ideal decision-making units (DMUs) in the evaluation of cross-efficiency. According to this concept, a DMU is efficient if it is close to the ideal DMU's performance and far from the anti-ideal DMU's performance.

Keywords:
Sustainable Supplier Selection
Data Envelopment Analysis
Cross-Efficiency Evaluation
Analytic Hierarchy Process
Fuzzy Numbers

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INTRODUCTION

Supply chains are the key links connecting the inputs of an organization to its outputs (Kuo et al., 2010). Indeed, the supply chain is an inter-organizational approach encompassing the supplier of the suppliers to the consumer of the consumers (Zhang et al., 2016). The supply chains have rapidly developed in recent years. Since the sheer focus on the economic performance to optimize the costs or capital return cannot ensure the development or sustainability of the supply chain (Hong et al., 2018; Mota et al., 2017), the concepts of *sustainable supply chain management and green supply chain management* have emerged to lay emphasis on the significance of social and environmental concerns along with the economic factors in supply chain planning (Bastas & Liyanage, 2018; Bendul et al., 2017).

Today, many enterprises have progressed considerably owing to the application of the sustainable supply chain (Ding et al., 2018), and the sustainable supply chain management (SSCM) is regarded as a prerequisite for the sustainable success and the establishment of the competitive advantage for the firms (Hong et al., 2018; Moktadir et al., 2018). Sustainable supply chain considers, along with the economic benefits of the business, the social and environmental consequences of the activities and products of the supply chain across the process of the material and service flow between suppliers and customers including the purchase of material and the production, distribution, and sale of the goods (Osiro et al., 2018; Liu & Papageorgiou, 2013; Kuo et al., 2010).

In this regard, it is of crucial importance for the realization of the sustainable supply chain goals to select the supplier pool on the basis of the principles and parameters of sustainability (Buyukozkan & Berkol, 2011) so far as many regard the process of supplier selection as the most important variable in the effective management of the supply chain network (Chang et al., 2011; Wu & Blackhurst, 2009; Gonzalez et al., 2004). So, the selection of sustainable supplier and the effective management of the supplier relations are key factors in enhancing the competitiveness of the enterprises (Banaeian et al., 2018; Chang et al., 2011). Accordingly, procurement manager should evaluate the performance of the suppliers periodically against some key indices and decide on the most appropriate supplier (Sarkis & Dhavale, 2015; Wu & Blackhurst, 2009).

Two issues are especially critical when it comes to the decision on the supplier selection. The first question concerns with what criteria to use and the next concerns with what procedures to follow for the assessment and selection of the suppliers. The selection of supplier(s) has never been an easy task because of the multiplicity of the evaluation criteria (Yang & Chen, 2006; Weber, 1991). This is also because of the fact that each supplier can meet only a part of the purchaser's criteria (Keshavarz et al., 2017; Igarashi et al., 2013). So, their selection requires a structured, systemic approach without which this crucial decision is likely to fail (Hasehmi et al., 2015). Therefore, the selection of the effective supplier needs a capable analysis model and decision support tools to help make a balance between multiple subjective and objective criteria (Bhattacharya et al., 2010; Kahraman et al., 2003) Supplier selection is a multivariate decision-making process that generally concerns with the assessment of supplier performance against a set of criteria. In the past, only economic criteria were included in the evaluations; however, the increased environmental costs and greenhouse gases emission have now embedded the environmental and social criteria within this process, too.

The selection of the right criteria is a major challenge in the supplier evaluation process. Three aspects are of the crucial importance in specifying the criteria for the sustainable supplier selection: economic, environmental, and social. Research shows that various criteria have been involved in supplier selection in economic aspect. In a first attempt, Dickson (1966) identified 23 features preferred by the purchase agents and managers in the US and Canada for the evaluation of suppliers. Weber et al. (1991) reviewed 74 papers that had been published over the period of 1966 to 1990 and concluded that cost/price, delivery, and quality were the most important criteria in the appraisal of the suppliers. According to Ho et al. (2010), quality, delivery, price/cost, manufacturing capability, service, management, technology, research and development, finance, flexibility, reputation, relationship, risk, and safety and environment constituted the criteria most extensively used for supplier selection. Govindan et al. (2015) conducted a literature review in the environmental aspect and found that the environmental management system is mostly used as the environmental criterion followed by green image, environmental performance, design for environment, green competencies, environmental improvement cost, ISO 14000, green product, and so on. As far as the social aspect concerned, the criteria mostly contain discrimination, long working hours, human rights, health and safety, information disclosure, employment practices, and the rights of stakeholders (Osiro et al., 2018; Gold & Awasthi, 2015; Mani et al., 2014; Govindan et al., 2013).

Researchers have used various methods for supplier selection including AHP (Gold & Awasthi, 2015), ANP (Buyukozkan & Cifci, 2011), TOPSIS (Daneshvar, 2014), DEMATEL (Hsu et al., 2013), fuzzy logic (Orji & Wei, 2015; Govindan et al., 2013), VIKOR (Wu et al., 2016b), DEA (Cheng et al., 2017; Karsak & Dursun, 2014; Wu & Blackhurst, 2009), artificial intelligence (Kuo et al., 2010), Bayesian framework (Sarkis & Dhavale, 2015), dynamic programming (Mafakheri et al., 2011), mixed integer programming (MIP) model (Aktin & Gergin, 2016), grey systems theory (Memon et al., 2015), and path analysis (Reuter et al., 2012). Readers can refer to Chai et al. (2013) for a detailed description of the supplier selection support methods.

The present paper employs data envelopment analysis (DEA) (Charnes et al., 1978) for sustainable supplier selection. DEA and its hybrids are widely used for supplier evaluation and selection (Kontis & Vrysagotis, 2011). The traditional procedure to calculate efficiency by DEA is based on self-evaluation, and the optimal set of input and output weights are allocated to decision-making units (DMUs) for their efficiency enhancement. This procedure often assesses several DMUs to be efficient whose discrimination is a difficult task. In these conditions, peer evaluation is recommended. In other words, the performance of a DMU is not evaluated merely on the basis of the optimistic efficiency; rather, the evaluation process should apply the cross-efficiencies derived from the weights determined by the DMUs themselves (Wang et al., 2011). Therefore, our proposed approach uses cross-efficiencies to compare the performance of the suppliers.

Cross-efficiency evaluation was first introduced by Sexton et al. (1986) in which the efficiency score of a DMU is calculated on the basis of the weights of other manufacturing units. Then, this model was examined by Doyler and Green (1994) who proposed aggressive and benevolent formulations for the cross-efficiency. Wang and Chin (2010) suggested alternative models for the DEA cross-efficiency evaluation. Ruiz and Sirvent (2017) evaluated cross-efficiency in fuzzy DEA. Wu et al. (2018) dealt with a hybrid DEA-VIKOR method for the cross-efficiency evaluation of the Chinese banks. Song et al. (2017), Lin et al. (2016), Wu et al. (2016a), and Alcaraz et al. (2013) are some other similar studies. Wang et al. (2011) presented an approach for cross-efficiency evaluation that is based on ideal and anti-ideal DMUs. This is the basis for the approach introduced in this paper for the cross-efficiency evaluation by the concept of ideal and anti-ideal DMUs. We integrated this method with a review of the relevant literature and weight restrictions derived from AHP and used in the sustainable supplier efficiency evaluation. The present study aims to answer these questions: What criteria should be used for the sustainable supplier selection? How can we identify the interrelations and structure of the criteria? How can the importance of criteria be determined? Finally, how can we compare the performance of the suppliers by linguistic data? Our final goal is to develop a comprehensive solution to answer these questions with respect to the sustainable supplier selection. Our solution for the sustainable supplier selection is composed of three phases: (i) reviewing the literature to identify the criteria for the sustainable supplier selection; (ii) organizing the criteria and figuring out their interrelations by analytic hierarchy process (AHP); and (iii) giving weights to the criteria and evaluating the performance of the suppliers by data envelopment analysis (DEA) which eventually leads to the selection of the most competent supplier.

Sustainable supplier selection criteria

After the review of the literature to identify the

Table 1: Sustainable supplier selection criteria and sub-criteria in previous literature

Sustainability dimensions	Sustainable supplier selection criteria	Sustainable supplier selection sub-criteria	Explanation	Related literature
Economic	Cost/Price (profitability of suppliers)	Material cost	The price of the material considering the quality of the material and other services provided by supplier.	(Osiro et al., 2018); (Song et al., 2017); (Wu et al., 2016b); (Subramanian & Gunasekaran, 2015); (Igarashi et al., 2013); (Chang et al., 2011).
		Freight cost	The cost of transportation.	
		After sales service cost	The price of the after sales service.	
	Quality	Rejection rate of the product	Number of rejected supplied goods detected by quality control.	(Osiro et al., 2018); (Song et al., 2017); (Wu et al., 2016b); (Hashemi et al., 2015); (Sarkis & Dhavale, 2015); (Reuter et al., 2012); (Chang et al., 2011).
		Capability of handling abnormal quality	The capability of the supplier in handling abnormal quality problems.	
		Process for internal Quality Audit of Material	One shall ensure that the supplier will make a reasonable number of audits on the quality level offered and is certified to ensure a maximum level of quality to prevent possible failures.	
	Delivery & Service	Lead time flexibility	Flexibility in time between the placement and arrival of order without compromising quality and cost.	(Osiro et al., 2018); (Luthra et al., 2017); (Song et al., 2017); (Kannan et al., 2015); (Paul, 2015); (Chang et al., 2011).
		After sales service	The level of service is given after delivering goods.	
		On-time delivery	The capability to follow the predefined delivery.	
Environmental	Environmental Management System (EMS)	ISO-14001 certification	Whether the supplier has environment-related certification such as ISO14000.	(Osiro et al., 2018); (Song et al., 2017); (Luthra et al., 2017); (Hashemi et al., 2015); (Hsu et al., 2013); (Kuo et al., 2010).
		Environmental Performance Evaluation	Supplier should have environmental policies, planning of environmental objectives, checking and control of environmental activities.	
	Eco-design	Recycle of products when design	Ability to treat the used products or their accessories, to reprocess the materials, and to replace the required new materials when producing new products.	(Osiro et al., 2018); (Luthra et al., 2017); (Song et al., 2017); (Hashemi et al., 2015); (Hsu et al., 2013); (Kuo et al., 2010).
		Re-manufacturing	Detach certain accessories from waste products for future usage.	
	Green Products	Re-use	Ability to re-utilize the used products and their related accessories.	(Osiro et al., 2018); (Fallahpour et al., 2017); (Luthra et al., 2017); (Song et al., 2017); (Hashemi et al., 2015); (Kannan et al., 2015).
		Air emissions/ Waste water	The quantity control and treatment of hazardous emission, such as SO2, NH3, CO and HCl. / The quantity control and the treatment of waste water.	
		Green certification	Supplier must provide green related certification for products.	
	Green Technology	Materials used in the supplied components that reduce the impact on natural resources	The use of materials in the components that have a lower impact on the natural resources.	(Osiro et al., 2018); (Fallahpour et al., 2017); (Sarkis & Dhavale, 2015); (Hashemi et al., 2015); (Kannan et al., 2015); (Buyukozkan & Cifci, 2011).
		Ability to alter process and product for reducing the impact on natural resources	The ability of the supplier to alter the process and product design in order to reduce the impact on the natural resources.	
		Using a modern eco efficient transportation fleet and using green fuels	Supplier should use eco-efficient transportation fleet like energy efficient Vessels and high Euro norms for trucks. And supplier should use green fuels with low sulfur content, and alternative fuels.	
Social	Employee right and welfare	Contract	Supplier should have contract with their employees.	Goren (2018); (Osiro et al., 2018); (Barbosa-Povoa et al., 2017); (Ansari & Kant, 2017); (Kuo et al., 2010).
		Employment insurance	Supplier should provide employment insurance for their employees.	
		Standard working hours	Ordinary hours are a employee's normal and regular hours of work, which do not attract overtime rates.	
	Occupational health and safety	Health insurance at work	Supplier must cover the cost of Employee's health insurance at work	(Goren, 2018); (Osiro et al., 2018); (Song et al., 2017); (Fallahpour et al., 2017); (Feil et al., 2015); (Bai & Sarkis, 2010).
		Training for safety at work	To prevent accidents and protect the health of workers, they must be trained at work.	
		Providing appropriate equipment at work	To prevent accidents and protect the health of workers, they must have appropriate equipment.	

criteria for sustainable supplier selection, we specified 10 criteria (25 sub-criteria) in economic, social, and environmental dimensions.

Table 1 summarizes the sustainable supplier selection criteria and sub-criteria drawing the greatest attention in the previous literature. It is important to point out that Table 1 is not an ultimate or complete list of sustainable supplier selection criteria. If necessary, the group decision can adopt new criteria to satisfy the specific needs of the stakeholders.

Criteria organization using AHP

After the criteria for sustainable supplier selection were identified from the review of the literature in Section 2, the second phase of the research solution is to organize the criteria and determine their interdependence using the principles of analytic hierarchy process (AHP). AHP was presented by Saaty (1980) to evaluate the options and select them on the basis of a set of selected criteria. This is a widely accepted and adopted MADM method. AHP is a vigorous technique that organizes the decision-making problem as a hierarchy composed of several levels to figure out a structured, yet simple, solution for it. AHP has helped analysts select the best decision out of numerous decisions (Saaty, 1996). The technique requires the application of pairwise comparison matrices between the elements of the same level that are scored in the range of 1-9 (1 = equally preferred, 9 = extremely preferred) and uses eigenvector to give weights to criteria (and sub-criteria). Then, these criteria are organized in an AHP-derived hierarchical graph with respect to the interrelations between different criteria and sub-criteria. Readers can refer to Brunelli (2015) for a more detailed description of the AHP technique.

The results of this section are presented in Table 2. It can be observed that the criteria and sub-criteria derived from the review of the literature are tabulated in columns 1 and 2. Also, the sub-criteria have been divided into input-type (I) and output-type (O) in column 3. Finally, the weights pertaining to different criteria have been specified in column 4 for a given supplier k. At this step, the decisions were made with the aid of four academic professors who were familiar with the supply chain. The decision makers expressed their preferences for the values of criteria (or sub-criteria) with principles that are much easier to be built than the allocation of numerical weights. This preferential ranking is done with a scale at three levels:

more important, equally important, and less important. In this scale, if the input criteria v_{1k} and v_{2k} for the supplier k are equally important, the difference between their weights will be considered to be zero ($v_{1k} - v_{2k}=0$); if v_{1k} is more important than v_{2k}, then we will have $v_{1k}-v_{2k}>0$; and the opposite is $v_{1k}-v_{2k}<0$. For example, according to the preferences of the decision-making group, “quality is more important than cost”; so, we will have $u_{1k}+u_{2k}+u_{3k}-v_{1k}-v2k-v_{3k}>0$; or “environmental management system and eco-design are more important than green products, green technology, and green transportation”; so, the relation $u_{4k}+u_{5k}+u_{6k}+u_{7k}-u_{8k}-u_{9k}-u_{10k}-u_{1k}-u_{12k}-u_{13k}>0$ holds true. Some other preferences are given below:

- *Delivery & service is more important than cost.*
- *Eco-design is more important than environmental management system.*
- *Green product is more important than green technology and green transportation, and green technology is more important than green transportation.*
- *Employee right and welfare is more important than occupation health and safety.*
- *Economic dimension is more important than environmental and social dimensions.*

Similarly, the preferences of the sub-criteria were identified by the decision-making group. All these relationships will be used in limiting the weights of inputs and outputs of the suppliers against obtaining the hypothetical values in DEA.

The conversion of fuzzy supplier inputs-outputs to crisp numbers

Most sustainable supplier selection criteria are qualitative in nature. For example, it is easier to measure ‘quality’ as to be moderate or very good than to give it a numerical value. However, in order to be able to use them in quantitative methods like DEA, we have to convert them to crisp numbers. A triangular fuzzy number $\tilde{M}=(a,m,b)$ can be converted to a crisp number M by Equation (1).

Table 2: Criteria and sub-criteria for the selection of the sustainable supplier and their respective weights

Criteria	Sub-criteria	Type	Weight (*Supplier k*)
Cost/Price (profitability of suppliers) (C1)	Material cost (C1.1)	I	v_{1k}
	Freight cost (C1.2)	I	v_{2k}
	After sales service cost (C1.3)	I	v_{3k}
Quality (C2)	Rejection rate of the product (C2.1)	O	u_{1k}
	Capability of handling abnormal quality (C2.2)	O	u_{2k}
	Process for internal Quality Audit of Material (C2.3)	O	u_{3k}
Delivery & Service (C3)	Lead time flexibility (C3.1)	I	v_{4k}
	After sales service (C3.2)	I	v_{5k}
	On-time delivery (C3.3)	I	v_{6k}
Environmental Management System (EMS) (C4)	ISO-14001 certification (C4.1)	O	u_{4k}
	Environmental Performance Evaluation (C4.2)	O	u_{5k}
Eco-design (C5)	Recycle of products when design (C5.1)	O	u_{6k}
	Re-manufacturing (C5.2)	O	u_{7k}
Green Products (C6)	Re-use (C6.1)	O	u_{8k}
	Air emissions/ Waste water (C6.2)	O	u_{9k}
	Green certification (C6.3)	O	u_{10k}
Green Technology (C7)	Materials used in the supplied components that reduce the impact on natural resources (C7.1)	O	u_{11k}
	Ability to alter process and product for reducing the impact on natural resources (C7.2)	O	u_{12k}
Green Transportation (C8)	Using a modern eco efficient transportation fleet & using green fuels (C8.1)	O	u_{13k}
Employee right and welfare (C9)	Contract (C9.1)	O	u_{14k}
	Employment insurance (C9.2)	O	u_{15k}
	Standard working hours (C9.3)	O	u_{16k}
Occupational health and safety (C10)	Health insurance at work (C10.1)	O	u_{17k}
	Training for safety at work (C10.2)	O	u_{18k}
	Providing appropriate equipment at work (C10.3)	O	u_{19k}

$$M = (a+4m+b)/6 \tag{1}$$

For example, the crisp output M for a triangular fuzzy value $\tilde{M}=(1,1,3)$ is as below:

$$M=(1+4*1+3)/6=1.33 \tag{2}$$

The linguistic variables applied to the criteria of sustainable supplier selection and the relevant crisp values derived from Equation (1) are presented in Table 3. After the crisp values are derived for different criteria of sustainable supplier selection, they can be readily included in the next phase of DEA.

Table 3: Linguistic variables and their crisp values

Linguistic Variable	Triangular fuzzy number (TFN)	Crisp number
Very low (VL)	(1, 1, 3)	1.33
Low (L)	(1, 3, 5)	3
Medium (M)	(3, 5, 7)	5
High (H)	(5, 7, 9)	7
Very high (VH)	(7, 9, 9)	8.67

Cross-efficiency evaluation by ideal and anti-ideal DMUs

Cross-efficiency evaluation is a technique of DEA in which each DMU has multiple efficiency scores (obtained by self-evaluation or peer-evaluation) which are averaged to reflect the overall performance of the DMU. Then, the DMUs are compared to one another and ranked in terms of the average cross-efficiencies.

Assume n suppliers in which each supplier S_j $(j=1,2,\ldots,n)$ uses m inputs x_{ij} $(i=1,2,\ldots,m)$ and s outputs y_{rj} $(r=1,2,\ldots,s)$. For a given supplier k, the relative efficiency score is defined using CCR model as Equation (3).

$$
\begin{aligned}
& Max\theta_{kk} = \frac{\sum_{r=1}^{s} u_{rk} y_{rk}}{\sum_{i=1}^{m} v_{ik} x_{ik}}, \\
& s.t. \\
& \theta_{jk} = \frac{\sum_{r=1}^{s} u_{rk} y_{rj}}{\sum_{i=1}^{m} v_{ik} x_{ij}} \leq 1, \quad j=1,2,\ldots,n, \\
& u_{rk} \geq 0, \quad r=1,2,\ldots,s, \\
& v_{ik} \geq 0, \quad i=1,2,\ldots,m.
\end{aligned}
\tag{3}
$$

where u_{rk} represents the weight of rth output value and v_{ik} represents the weight of ith input from the kth supplier. The goal of the above model is to define a set of input and output weights that are the most appropriate for the supplier *k*. Using Charnes et al. (1978)'s conversion, Equation (3) can be converted to the following linear program.

$$
\begin{aligned}
& Max\ \theta_{kk} = \sum_{r=1}^{s} u_{rk} y_{rk}, \\
& s.t. \\
& \sum_{i=1}^{m} v_{ik} x_{ik} = 1, \\
& \sum_{r=1}^{s} u_{rk} y_{rj} - \sum_{i=1}^{m} v_{ik} x_{ij} \leq 0, \\
& j=1,2,\ldots,n, \\
& u_{rk} \geq 0, \quad r=1,2,\ldots,s, \\
& v_{ik} \geq 0, \quad i=1,2,\ldots,m.
\end{aligned}
\tag{4}
$$

Let's suppose that u_{rk}^* and v_{ik}^* denote the optimum solution for Equation (4). The optimum efficiency or CCR efficiency that is obtained by solving Equation (4) with u_{rk}^* and v_{ik}^* is represented by θ_{kk}^*. This efficiency indicates the self-evaluation of the supplier k. The cross-efficiency of the supplier k with respect the peer j is represented by θ_{jk} in which $\theta_{jk}=(\sum_{r=1}^{s} u_{rk}^* y_{rj})/(\sum_{i=1}^{m} v_{ik}^* x_{ij})$. Equation (4) is solved for each supplier k and produces n input weights and n output weights. Each supplier k will have *(n-1)* cross-efficiencies plus one optimum efficiency. Together, these efficiencies form the cross-efficiency matrix as shown in Table 4 in which $\theta_{kk}=\theta_{kk}^*$ $(k=1,2,\ldots,n)$ is the optimum efficiencies of n suppliers.

The DEA model that is presented here for the evaluation of the cross-efficiency has been inspired by the concept of ideal and anti-ideal DMUs which is often used in multiple criteria decision-making (Mirhedayatian et al., 2013; Sun et al., 2013; Wang et al., 2011; Hatami-Marbini et al., 2010). An ideal DMU consumes minimum inputs and produces maximum outputs whilst an anti-ideal DMU consumes maximum inputs and produces minimum outputs. A DMU is said to be efficient when its performance is close to the performance of the ideal DMU and far from that of the anti-ideal DMU. These distances to the ideal and anti-ideal DMU are the basis to calculate the closeness coefficient ratio (CC_k) for the supplier k. Our goal is to maximize CC (Equation (7)) for all suppliers. According to these conceptions, the following formulations are introduced.

Inputs and outputs of an ideal DMU (Ideal Sustainable Supplier, ISS):

$$
\begin{aligned}
& y_i^{Max} = \underset{r}{Max}\{y_{rj}\}, \quad r=1,2,\ldots,s, \\
& x_i^{min} = \underset{j}{min}\{x_{ij}\}, \quad i=1,2,\ldots,m.
\end{aligned}
\tag{5}
$$

Inputs and outputs of an anti-ideal DMU (Anti-Ideal Sustainable Supplier, AISS):

$$
\begin{aligned}
& y_i^{min} = \underset{r}{min}\{y_{rj}\}, \quad r=1,2,\ldots,s, \\
& x_i^{Max} = \underset{j}{Max}\{x_{ij}\}, \quad i=1,2,\ldots,m.
\end{aligned}
\tag{6}
$$

Table 4: Cross-efficiency matrix for n DMUs

Target supplier	**1**	**2**	**...**	**n**	**Average cross-efficiency**
1	θ_{11}	θ_{12}	...	θ_{1n}	$\frac{1}{n}\sum_{k=1}^{n}\theta_{1k}$
2	θ_{21}	θ_{22}	...	θ_{2n}	$\frac{1}{n}\sum_{k=1}^{n}\theta_{2k}$
$\vdots$	$\vdots$	$\vdots$	$\ddots$	$\vdots$	$\vdots$
n	θ_{n1}	θ_{n2}	...	θ_{nn}	$\frac{1}{n}\sum_{k=1}^{n}\theta_{nk}$

Here, the distance between the supplier k and ISS is denoted by d(k,ISS) and its distance from AISS is denoted by d(k,AISS). These distances are calculated by Equation (7).

$$\begin{aligned} d(k,ISS) &= \sum_{r=1}^{s} u_{rk}\,(y_r^{Max} - y_{rk}) \\ &\quad + \sum_{i=1}^{m} v_{ik}(x_{ik} \\ &\quad - x_i^{min}), \\ d(k,AISS) &= \sum_{r=1}^{s} u_{rk}\,(y_{rk} - y_r^{min}) \\ &\quad + \sum_{i=1}^{m} v_{ik}(x_i^{Max} \\ &\quad - x_{ik}), \\ &k=1,2,\ldots,n. \end{aligned} \tag{7}$$

CC_k for the supplier k with respect to ISS and AISS is derived from Equation (8).

$$CC_k = d(k,AISS)/d(k,ISS)+d(k,AISS)$$

$$= \frac{\sum_{r=1}^{s} u_{rk}\,(y_{rk} - y_r^{min}) + \sum_{i=1}^{m} v_{ik}\left(x_i^{Max} - x_{ik}\right)}{\sum_{r=1}^{s} u_{rk}\,(y_r^{Max} - y_{rk}) + \sum_{i=1}^{m} v_{ik}\left(x_{ik} - x_i^{min}\right) + \sum_{r=1}^{s} u_{rk}\,(y_{rk} - y_r^{min}) + \sum_{i=1}^{m} v_{ik}\left(x_i^{Max} - x_{ik}\right)},$$

$$k=1,2,\ldots,n. \tag{8}$$

We aim to maximize CC_k for the supplier k so that it is as close to ISS performance and as far from AISS performance as possible. The higher the RC value is, the more efficient the supplier will be. The weights u_{rk} and v_{ik} that help the supplier k to realize this target is calculated by Equation (9).

$$\begin{aligned} &\text{Max} \\ &RC_k = \frac{\sum_{r=1}^{s} u_{rk}\,(y_{rk} - y_r^{min}) + \sum_{i=1}^{m} v_{ik}\left(x_i^{Max} - x_{ik}\right)}{\sum_{r=1}^{s} u_{rk}\,(y_{rk} - y_r^{min}) + \sum_{i=1}^{m} v_{ik}\left(x_i^{Max} - x_{ik}\right) + \sum_{r=1}^{s} u_{rk}\,(y_r^{Max} - y_{rk}) + \sum_{i=1}^{m} v_{ik}\left(x_{ik} - x_i^{min}\right)} \\ &s.t. \\ &\sum_{r=1}^{s} u_{rk} y_{rj} - \sum_{i=1}^{m} v_{ik}\, x_{ij} \le 0, \\ &j = 1,2,\ldots,n, \\ &u_{rk} \ge 0, \quad r = 1,2,\ldots,s, \\ &v_{ik} \ge 0, \quad i = 1,2,\ldots,m. \end{aligned} \tag{9}$$

Equation (9) can be rephrased to linear form as below:

$$\begin{aligned} &Max \sum_{r=1}^{s} u_{rk}\,(y_{rk} - y_r^{min}) + \sum_{i=1}^{m} v_{ik}(x_i^{Max} - x_{ik}) \\ &s.t. \\ &\sum_{r=1}^{s} u_{rk}\,(y_{rk} - y_r^{min}) + \sum_{i=1}^{m} v_{ik}(x_i^{Max} - x_{ik}) \\ &+ \sum_{r=1}^{s} u_{rk}\,(y_r^{Max} - y_{rk}) + \sum_{i=1}^{m} v_{ik}(x_{ik} - x_i^{min}) = 1 \\ &\sum_{r=1}^{s} u_{rk} y_{rk} - \theta_{kk}^{*} \sum_{i=1}^{m} v_{ik}\, x_{ik} = 0, \quad j = 1,2,\ldots,n, \\ &\sum_{r=1}^{s} u_{rk} y_{rj} - \sum_{i=1}^{m} v_{ik}\, x_{ij} \le 0, \quad u_{rk} \ge 0, \quad r = 1,2,\ldots,s, \\ &\qquad v_{ik} \ge 0, \quad i = 1,2,\ldots,m, \end{aligned} \tag{10}$$

Equation (10) is simplified as below:

$$\begin{aligned} &Max \sum_{r=1}^{s} u_{rk}\,(y_{rk} - y_r^{min}) + \sum_{i=1}^{m} v_{ik}(x_i^{Max} - x_{ik}) \\ &s.t. \\ &\sum_{r=1}^{s} u_{rk}\,(y_r^{Max} - y_r^{min}) + \sum_{i=1}^{m} v_{ik}(x_i^{Max} - x_i^{min}) = 1 \\ &\sum_{r=1}^{s} u_{rk} y_{rk} - \theta_{kk}^{*} \sum_{i=1}^{m} v_{ik}\, x_{ik} = 0, \quad j = 1,2,\ldots,n, \\ &\qquad u_{rk} \ge 0, \quad r = 1,2,\ldots,s, \\ &\sum_{r=1}^{s} u_{rk} y_{rj} - \sum_{i=1}^{m} v_{ik}\, x_{ij} \le 0, \quad v_{ik} \ge 0, \quad i = 1,2,\ldots,m, \end{aligned} \tag{11}$$

Numerical application of proposed method

This section uses the proposed fuzzy DEA method to select a sustainable supplier out of four suppliers. Table 5 presents the linguistic evaluation for the three suppliers in terms of the criteria derived from the literature review.

Table 5: Ranking of suppliers in terms of performance

Criteria	Criteria type	Supplier linguistic ratings			
		S1	S2	S3	S4
(C1.1)	**I**	L	VH	H	L
(C1.2)	**I**	VL	H	H	M
(C1.3)	**I**	H	M	M	L
(C2.1)	O	H	M	L	M
(C2.2)	O	VL	H	VH	L
(C2.3)	O	L	VH	VH	L
(C3.1)	I	L	VH	VH	VL
(C3.2)	I	VL	M	H	VL
(C3.3)	**I**	L	H	VH	M
(C4.1)	O	VL	M	M	VL
(C4.2)	O	L	M	M	L
(C5.1)	O	L	H	M	VL
(C5.2)	O	M	H	VH	L
(C6.1)	O	M	M	H	L
(C6.2)	O	L	H	M	VL
(C6.3)	O	L	H	H	L
(C7.1)	O	L	H	M	M
(C7.2)	O	M	VH	H	L
(C8.1)	O	VL	L	L	VL
(C9.1)	**O**	M	M	H	H
(C9.2)	**O**	M	H	H	VH
(C9.3)	**O**	L	M	M	M
(C10.1)	O	L	M	H	H
(C10.2)	O	M	H	H	M
(C10.3)	O	M	VH	VH	VL

Table 6: Crisp performance of ideal and anti-ideal sustainable suppliers

Criteria	Crisp ratings				Ideal & Anti-Ideal Sustainable Suppliers	
	S1	S2	S3	S4	ISS	AISS
(C1.1)	3	8.67	7	3	3	8.67
(C1.2)	1.33	7	7	5	1.33	7
(C1.3)	7	5	5	3	3	7
(C2.1)	7	5	3	5	7	3
(C2.2)	1.33	7	8.67	3	8.67	1.33
(C2.3)	3	8.67	8.67	3	8.67	3
(C3.1)	3	8.67	8.67	1.33	1.33	8.67
(C3.2)	1.33	5	7	1.33	1.33	7
(C3.3)	3	7	8.67	5	3	8.67
(C4.1)	1.33	5	5	1.33	5	1.33
(C4.2)	3	5	5	3	5	3
(C5.1)	3	7	5	1.33	7	1.33
(C5.2)	5	7	8.67	3	8.67	3
(C6.1)	5	5	7	3	7	3
(C6.2)	3	7	5	1.33	7	1.33
(C6.3)	3	7	7	3	7	3
(C7.1)	3	7	5	5	7	3
(C7.2)	5	8.67	7	3	8.67	3
(C8.1)	1.33	3	3	1.33	3	1.33
(C9.1)	5	5	7	7	7	5
(C9.2)	5	7	7	8.67	8.67	5
(C9.3)	3	5	5	5	5	3
(C11.1)	3	5	7	7	7	3
(C10.2)	5	7	7	5	7	5
(C10.3)	5	8.67	8.67	1.33	8.67	1.33

The crisp numbers for the fuzzy evaluations shown in Table 5 are presented in Table 6. Two last columns in Table 6 show the ideal and anti-ideal (sustainable suppliers) solution for different criteria derived from the literature review. As can be seen, ideal solution – i.e. ideal sustainable supplier (ISS) – consumes the minimum inputs to produce the maximum outputs ($ISS=(X^{min},Y^{Max})$) whereas the opposite holds true for anti-ideal solution – i.e. the anti-ideal sustainable supplier ($AISS=(X^{Max},Y^{min})$).

Equation (4) is employed to find out the optimum efficiencies for four suppliers. The results will be as $\theta_{11}^*=1$, $\theta_{22}^*=1$, $\theta_{33}^*=1$, and $\theta_{44}^*=1$. Accordingly, it can be said that the four suppliers are efficient, but their performances cannot be distinguished. Therefore, the fuzzy DEA method is applied to evaluate their cross-efficiency. This method is based on maximization of the distance from anti-ideal solution (sustainable supplier) and minimization of the distance to the ideal solution using Equation (11). Column 2 in Table 7 presents the input-output weights derived for four suppliers. As can be seen, few criteria are involved in overall decision-making (C1.1, C1.2, C2.1, C3.1, C3.3, C5.1, C5.2, C6.1 and C10.1). Column 3 contains the weights derived when the restriction on weight is extremely positive (>0). Therefore, all weights of the input and output criteria are assumed as $>\varepsilon$ in which $\varepsilon = 0.0001$. It is evident that the weight of criteria obtained here (Column 3) differs from that obtained by our presented model (Column 2). Therefore, our model yields different results depending on the weights (strictly zero or nine). So, the decision makers should be cautious when interpreting the weighting results and apply the weight value restriction that is applicable to their problem.

Table 7: Input-output weights

Criteria	**Weights**							
	$u_{rk}\geq 0, r=1,2,\ldots,s$ $u_{rk}\geq 0, r=1,2,\ldots,s$				$u_{rk}\geq \varepsilon . r=1,2,\ldots,s$ $v_{ik}\geq \varepsilon . i=1,2,\ldots,m$ $\varepsilon=0.0001$			
	S1	**S2**	**S3**	**S4**	**S1**	**S2**	**S3**	**S4**
(C1.1)	0	0.6851	0.5728	0	0.0001	0.3580	0.0001	0.0001
(C1.2)	0	0.5728	0	0	0.0001	0.0001	0.0001	0.0001
(C1.3)	0	0	0	0	0.0001	0.0001	0.0001	0.0001
(C2.1)	0	0	0	0.2890	0.0110	0.3201	0.0001	0.0136
(C2.2)	0	0	0	0	0.0001	0.0001	0.0001	0.0001
(C2.3)	0	0	0	0	0.0001	0.0001	0.0635	0.0001
(C3.1)	0.2890	0	0.6851	0	0.2694	0.0001	0.0001	0.0001
(C3.2)	0	0	0	0	0.0001	0.0001	0.0001	0.0001
(C3.3)	0.2890	0.5728	0	0	0.0210	0.5260	0.0001	0.0001
(C4.1)	0	0	0	0	0.0001	0.0001	0.0001	0.0001
(C4.2)	0	0	0	0	0.0001	0.0001	0.7860	0.0001
(C5.1)	0	0	0	0.1645	0.0001	0.0001	0.0001	0.2100
(C5.2)	0	0.5728	0	0	0.5241	0.0001	0.0001	0.0001
(C6.1)	0	0	0	0.2890	0.0001	0.0501	0.0001	0.0001
(C6.2)	0	0	0	0	0.0013	0.0001	0.0531	0.0001
(C6.3)	0	0	0	0	0.0001	0.0001	0.0001	0.0001
(C7.1)	0	0	0	0	0.0001	0.0001	0.0001	0.0001
(C7.2)	0	0	0	0	0.0001	0.0001	0.0001	0.0001
(C8.1)	0	0	0	0	0.0001	0.0001	0.0001	0.0001
(C9.1)	0	0	0	0	0.0001	0.0001	0.0001	0.0001
(C9.2)	0	0	0	0	0.0056	0.0001	0.0001	0.0001
(C9.3)	0	0	0	0	0.0001	0.0001	0.0001	0.0001
(C10.1)	0	0.5728	0.5728	0	0.0001	0.0001	0.0023	0.0001
(C10.2)	0	0	0	0	0.0001	0.0386	0.0001	0.0001
(C10.3)	0	0	0	0	0.0001	0.0001	0.0001	0.0001

Table 8 summarizes the results on average cross-efficiency obtained from Equation (8). It can be observed that Supplier 2 has the best performance followed by Suppliers 3, 4, and 1 in the next ranks, respectively.

Table 8: Cross-efficiency results

	S1	S2	S3	S4	Average cross-efficiency	Rank
S1	1	0.126	0.201	0.658	0.496	4
S2	0.425	1	0.910	0.539	0.718	1
S3	0.38	0.9	1	0.527	0.701	2
S4	0.763	0.328	0.299	1	0.597	3

We did another experiment to explore the impact of preferential relations derived from AHP on the input-output weights, the results of cross-efficiency, and the resulting ranking. Table 9 shows the DEA-derived input-output weights after eliminating the input-output weight restriction. The input-output weights for four suppliers are shown in Column 2 of Table 9. It can be seen that very few criteria are involved in overall decision making (C1.1, C1.2, C2.1, C3.1, C3.3, C5.1, C5.2, C6.1, and C10.1). Column 3 contains the weights obtained when the weight restriction is extremely positive (>0). Therefore, all weights of the input and output criteria are considered as >ε where $\varepsilon = 0.0001$. It is evident that the weights of the criteria obtained here (Column 3) differ from those obtained from our proposed model (Column 2). Also, as can be seen, the results are different from Table 7 (considering AHP-derived input-output weight restrictions).

Table 10 shows the results of cross-efficiency without AHP weight restriction. The comparison of Tables 8 and 10 reveals that Supplier 4 and 1 are ranked differently although the best supplier does not change. This implies that the final results of our model are sensitive to weight restrictions. However, the results are more realistic when AHP weight restrictions are included because input-output weights are context-dependent in the real world and should, therefore, be matched with decision maker's preferences.

Table 9: Input-output weights (without inputs-output weight restrictions)

Criteria	Weights							
	$u\_{rk}\geq 0, r=1,2,\ldots,s$ $v\_{ik}\geq 0, i=1,2,\ldots,m$				$u\_{rk}\geq \varepsilon, r=1,2,\ldots,s$ $v\_{ik}\geq \varepsilon, i=1,2,\ldots,m$ $\varepsilon=0.0001$			
	S1	**S2**	**S3**	**S4**	**S1**	**S2**	**S3**	**S4**
(C1.1)	0	0.002	0	0	0.0001	0.002	0.0002	0.0002
(C1.2)	0	0	0.213	0	0.0001	0.0001	0.0001	0.0001
(C1.3)	0	0	0	0	0.0374	0.0274	0.0001	0.0105
(C2.1)	0	0	0.1592	0.3201	0.0110	0.0001	0.0592	0.0002
(C2.2)	0	0.5293	0	0	0.0001	0.7521	0.0001	0.0001
(C2.3)	0	0	0	0	0.0001	0.0001	0.0635	0.0001
(C3.1)	0	0	0	0	0.2694	0.0001	0.0001	0.0001
(C3.2)	0.4239	0	0	0	0.0001	0.0001	0.0001	0.0001
(C3.3)	0	0	0	0	0.0210	0.3801	0.0075	0.0001
(C4.1)	0	0.3280	0.1893	0	0.0001	0.0001	0.0001	0.0001
(C4.2)	0	0	0	0	0.0002	0.0001	0.0001	0.0001
(C5.1)	0	0	0	0	0.0001	0.0001	0.5214	0.3211
(C5.2)	0	0	0	0	0.0295	0.0001	0.0001	0.0001
(C6.1)	0.0268	0	0	0	0.0001	0.0501	0.0001	0.0001
(C6.2)	0	0	0	0	0.0002	0.0001	0.0014	0.0001
(C6.3)	0	0	0	0	0.0001	0.0002	0.0001	0.0001
(C7.1)	0	0.4236	0	0	0.0251	0.0001	0.0001	0.0001
(C7.2)	0	0	0	0	0.0001	0.0001	0.0001	0.0001
(C8.1)	0	0	0	0	0.0001	0.0056	0.0001	0.0001
(C9.1)	0	0	0	0.2193	0.0001	0.0001	0.0001	0.0002
(C9.2)	0	0	0	0	0.0014	0.0001	0.0001	0.0001
(C9.3)	0	0	0	0	0.0001	0.0002	0.0001	0.0001
(C10.1)	0.1260	0	0	0	0.0001	0.0001	0.0003	0.0001
(C10.2)	0	0	0	0	0.0001	0.0014	0.0001	0.0002
(C10.3)	0	0	0	0	0.0001	0.0001	0.0001	0.0001

Table 10: Cross-efficiency results (without inputs-output weight restrictions)

	S1	S2	S3	S4	Average cross-efficiency	Rank
S1	1	0.243	0.278	0.7	0.555	4
S2	0.459	1	0.982	0.586	0.756	1
S3	0.401	0.902	1	0.563	0.716	2
S4	0.687	0.273	0.232	1	0.548	3

CONCLUSION

Due to the growing worldwide awareness of sustainability, stringent government directions, and increasing community knowledge, organizations cannot neglect sustainability concerns in business. In order to increase business performance and competitive advantage, sustainability-focused supplier selection is a crucial decision in industrial supply chains.

The present paper presented a hybrid method based on AHP and fuzzy DEA for sustainable supplier selection. The criteria for this selection are derived and organized from literature (and/or consultation with experts/decision-making panel) and AHP. Fuzzy DEA is, also, employed to calculate the cross-efficiencies using the concept of ideal and anti-ideal DMUs out of the linguistic input-output data so as to be used in the selection of the sustainable supplier. The strengths of the suggested method are its capability in organizing the criteria, rationalizing input-output weights for a certain supplier by preferential relations derived from AHP principles, and using qualitative data for the inputs and outputs of the supplier by DEA method. The major limitation is that when the weight values are strictly positive, different results are obtained for the weights of the output criteria. Therefore, decision-makers should be cautious when interpreting the weighting results and apply the weight value restriction that is applicable to their problem. It is recommended to make a comparison between the presented method and other standard cross-efficiency methods in future research. Also, the impact of defuzzification technique should be studied on cross-efficiency results.

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