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A flexible cross-efficiency fuzzy data envelopment analysis model for sustainable sourcing

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ABSTRACT

Sustainable sourcing is a recent priority for firms considering customer behavior and societal norms with respect to the supply chain. Customer attitudes, particularly in the developed countries, are affected by the perceived sustainability of products or services regarding environmental, social and economic aspects. Seeking to maximize their market shares, firms frequently require an effective sourcing approach in supply chain management (SCM) by selecting sustainable suppliers (sourcing) and by enforcing standards through continuous supplier evaluations (monitoring) as well as by contract adjustments (retention). Most existing sourcing methodologies are either cost-oriented or ad hoc, without the tools and techniques necessary to deal with sustainability. In this paper, we propose a product-based framework for sustainable supplier sourcing considering different sustainability, operational and organizational criteria based on the type of outsourced products in the evaluation process. We develop a flexible cross-efficiency evaluation methodology based on data envelopment analysis (DEA) for identifying supplier performance. This research also uses fuzzy set theory to tackle the vagueness of information that is often present in the information-gathering step. We present a case study from the semiconductor industry to demonstrate the applicability of the proposed model and the efficacy of the procedures and algorithms.

1. Introduction

Due to the depletion of natural resources, climate change, carbon emission and global warming, sustainability has generally been considered a key factor assuring the economic and social survival of organizations. Increasingly, this has also been a criterion to increase competitiveness in markets with a high awareness of socio-environmental conditions (Dao et al., 2011). Even companies in emerging markets struggling with social and ecological challenges often incorporate sustainability practices into their strategic plans to improve their social responsibility.

Sustainability, as defined by the World Commission on Environment and Development (WCED), is an approach to meet present needs as well as to deal with the possible impacts on the lives of future generations (WCED, 1987). The Global Reporting Initiative (GRI, 2010) describes sustainability on a number of different dimensions such as economic, environment, society, product responsibility, human rights, and labor practices. The GRI report is commonly used as a tool to inform external and internal stakeholders about the sustainable performance of organizations (Baskaran et al., 2012). Sourcing from emerging markets plays a crucial role when companies outsource part of their activities or cooperate with suppliers. However, many companies in emerging markets face difficulties and challenges in sustainability because of a lack of many important factors such as legal implementation,

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knowledge, an educated labor force, technology, infrastructure and capital. Therefore, outsourcing firms need to carefully screen and select suppliers on the basis of multiple criteria, including sustainability. Though the incorporation of the sustainability dimensions into decision-making process is a difficult task, it is particularly important for the companies to develop sustainable supply chain management (SCM) practices to integrate operational, organizational and sustainability viewpoints (Roth et al., 2008).

The literature shows an absence of supplier assessment decision support systems that integrate sustainability criteria with conventional criteria such as price, quality, flexibility, etc. Furthermore, the implications of using sustainability criteria are difficult to define and measure due to their inherent vagueness and impreciseness (Phillis and Andriantiatsaholiniaina, 2001). In particular, information describing sustainability may be either unquantifiable or cost prohibitive. Using crisp values for imprecise and subjective information may lead to an oversimplification of the sustainable evaluation problem, just like using the mean valuation and ignoring the variance for a random variable. Fuzzy sets theory can represent ambiguous, uncertain or imprecise information as a formal mathematical framework to formalize inaccuracies inherent in decision-making (Zadeh, 1965).

In this study, we propose a four-phase analytical framework for supplier evaluation using sustainability criteria and apply fuzzy sets theory to allow for imprecise estimates in uncertain environments. In phase 1, we adopt the Kraljic portfolio Kraljic (1983) to classify the potential suppliers into four groups: strategic suppliers, bottleneck suppliers, routine suppliers and leverage suppliers. In phase 2, we identify operational, organizational and sustainability criteria based on the industry under consideration. In phase 3, a flexible fuzzy cross-efficiency method is developed to evaluate suppliers in relation to the criteria selected in the previous phase. In phase 4, we group suppliers into three classes: preferred suppliers, approved suppliers, and phase-out suppliers.

The remainder of this paper is organized as follows: Section 2 reviews the relevant literature on supplier selection in SCM. Section 3 mathematically reviews DEA and cross-efficiency models. Sections 4 and 5 present the proposed methodology as well as a new framework for sustainable supplier performance assessment. In Section 6, we present a case study to show the applicability of the framework. Finally, in section 7, we present concluding remarks and suggest directions for future research.

2. Literature review

This section is divided into three sub-sections, composed of (*i*) SCM and sustainability, (*ii*) supplier evaluation criteria, and (*iii*) supplier evaluation methods, to provide a comprehensive overview of the existing literature.

2.1. SCM and sustainability

SCM is the term popularized in the early 1980s describing the planning and control of materials, financial and information flows, and the logistics activities internally within a company and also externally between companies (Cooper et al., 1997). Among the recent extensions to SCM, risk management (Colicchia and Strozzi, 2012), performance evaluation (Agrell and Hatami-Marbini, 2013), and supply chain integration (Fabbe-Costes and Jahre, 2007) within a supply chain have drawn much attention in a vast body of literature. Different definitions of risk management in a supply chain context are proposed in the literature. Supply chain risk management can be defined as "*the variation in the distribution of possible supply chain outcomes, their likelihoods, and their subjective values*" (Jüttner et al., 2003). Performance evaluation of a supply chain by means of frontier analysis is a foremost tool to ensure productivity, competitiveness and profitability of the chain, but the evaluation requires the consideration of the specificities of the network character of the assessed units (Agrell and Hatami-Marbini, 2013). Supply chain integration is an effective approach for improving performance that develops seamless connections between the various actors, stages, and functions within a supply chain to maximize customer satisfaction.

Lately, increasing environmental, economic and social sustainability costs of supply chain networks as well as increasing consumer pressure for eco-friendly products and services have led many organizations to make an attempt to design a sustainable SCM (Baskaran et al., 2012).

Sustainability is a new watchword by which firms and stakeholders in SCM can evaluate the impacts from societal (people) and ecological (planet) perspectives. Shrivastava (1995, p. 955) defines sustainability as "*the potential for reducing long-term risks associated with resource depletion, fluctuations in energy costs, product liabilities, and pollution and waste management.*" To arrive at sustainability, we need to balance three pillars: social, environmental and economic factors in a uniform harmony as depicted in Fig. 1 (Elkington, 1998).

Fig. 1 shows the region of sustainability at the intersection of social, environmental, and economic performance where it can positively affect the natural environment and society, but also yield long-term economic benefits and competitive advantages for the firm (Carter and Rogers, 2008). Business sustainability has been defined as "*the creation of resilient organizations through integrated economic, social and environmental systems*".

Sustainable SCM (SSCM) is then the strategic, transparent integration and achievement of an organization's social, environmental and economic goals in the systemic coordination of key inter-organizational business processes for improving the long-term performance of the supply chains (Carter and Rogers, 2008). An alternative definition of SSCM by Ahi and Searcy (2013) is "*the creation of coordinated supply chains through the voluntary integration of*

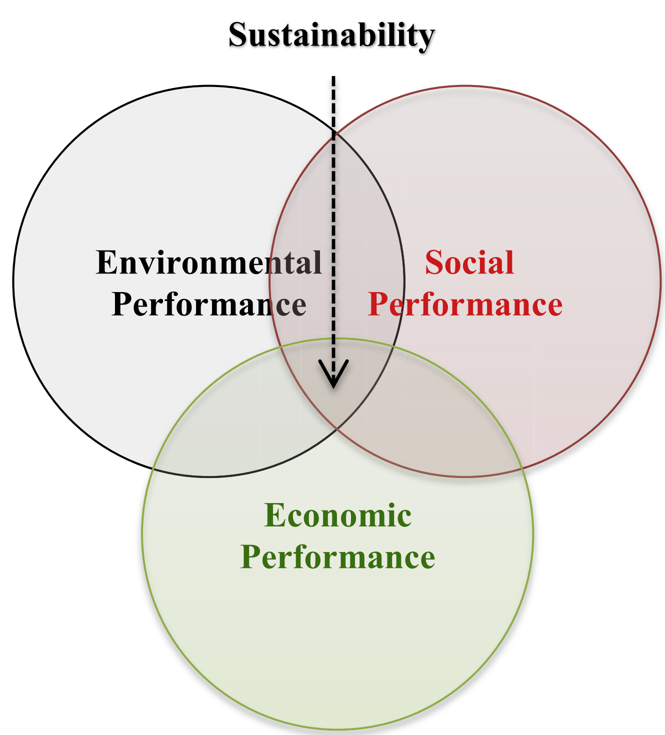

Fig. 1. Sustainability - the triple bottom line.

economic, environmental, and social considerations with key inter-organizational business systems designed to efficiently and effectively manage the material, information, and capital flows associated with the procurement, production, and distribution of products or services in order to meet stakeholder requirements and improve the profitability, competitiveness, and resilience of the organization over the short and long-term". Three pillars of sustainability have been explicitly addressed in some definitions of SSCM although these aspects cannot be found in many definitions in the literature (Ahi and Searcy, 2013).

2.2. Supplier evaluation criteria

Numerous authors have used a variety of criteria to assess suppliers in order to improve performance and competitiveness of manufacturers (Kumar et al., 2006; Shin et al., 2000). Dickson (1966) introduced 23 important criteria such as quality, delivery, performance, warranty and claim policy, production facilities and capacity, net price, and technical capabilities for supplier evaluation based on a questionnaire survey. The purchasing managers of about 300 commercial organizations were asked to determine the most important supplier selection criteria. According to Dickson (1966), quality, delivery and performance history are the three most important criteria whereas Weber et al. (1991) proposed a number of criteria for supplier assessment such as price, delivery, quality, productive capability, location, technical capability, management organization, reputation, industry position, financial stability, performance history, and maintainability. A recent literature review from 2000 to 2008 in Govindan et al. (2013) shows that the most popular criterion is quality, followed by delivery, price/cost, manufacturing capability, and service. Ho et al. (2010)'s literature review shows that the most popular criterion is quality, followed by delivery, price/cost, manufacturing capability, service, management, technology, research and development, finance, flexibility, reputation, relationship, risk, and safety and environment. Contrary to common belief, the authors concluded that price/cost is not the most widely used criterion.

Firms often need to include sustainability for their managerial decision-making such as supplier evaluation due to financial considerations, fairness to suppliers and customers, corporate reputation, social change, good human relations and inter-organizational learning (Baskaran et al., 2012). Rodriguez et al. (2006) considered the necessity of implementing sustainability programs rather than symbolic efforts to receive certification. In a study about Dutch firms, Graafland and van de Ven (2006) documented no significant relationship between management's strategic and moral view of sustainability aspects and actual sustainability practice with respect to supplier selection. In another review, Seuring (2013) also confirmed that the social dimension in the field of sustainable supplier selection has not been given much attention from a practical standpoint. Some examples in the literature dealing with these issues are: "ethical sourcing" (Blowfield, 2000; Roberts, 2003), "socially responsible buying" (SRB) (Maignan et al., 2002) or "purchasing responsibility" (Carter, 2005; Carter and Jennings, 2004; Hutchins and Sutherland, 2008).

2.3. Supplier evaluation methods

Supplier performance management using mathematical modeling is a rich field, using conventional tools such as linear and mixed-integer programming (Baskaran et al., 2012). Chou and Chang (2008) proposed a strategy-aligned fuzzy approach for selecting suppliers from the strategic management viewpoint. Chen et al. (2006) and Hatami-Marbini and Tavana (2011) used linguistic values and a fuzzy MCDM model to carry out supplier selection. The fuzzy analytic hierarchy process (AHP) and fuzzy technique for order preference by similarity to ideal solution (TOPSIS) are the most common methods for selecting the best suppliers (e.g. Bottani and Rizzi, 2006; Chan, 2003; Liu and Hai, 2005; and Göl and Çatay, 2007). Talluri and Narasimhan (2004) utilized DEA-based models for strategic sourcing. The combination of TOPSIS/AHP and DEA methods has been also proposed by several researchers (e.g., Tone, 1989; Sinuany-Stern et al., 2000; Sueyoshi, 2001; Escobar and Moreno-Jiménez, 2002; Wang et al., 2009). Using a process of supplier evaluation using DEA, the presence of dual-role factors among performance factors were theoretically discussed by Toloo and Barat (2015). Toloo and Nalchigar (2011) proposed a DEA model for withstanding the supply base by selecting suppliers in the presence of cardinal, ordinal, or bounded data. Given that their approach suffered from some drawbacks, the integrated mixed integer programming-DEA model was developed by Toloo (2014) for finding the most efficient supplier with cardinal and ordinal data. The literature review of MCDM approaches for supplier evaluation for the 2000–2008 period, done by Ho et al. (2010), showed that DEA was the most used approach, followed by mathematical programming, AHP, case-based reasoning (CBR), the analytic network process (ANP), fuzzy set theory, simple multi-attribute rating technique (SMART), and the genetic algorithm (GA).

3. Performance evaluation

The origins of frontier analysis can be traced back to Farrell (1957), but the field developed largely through the linear programming (LP) formulation introduced by Charnes et al. (1978) called data envelopment analysis (DEA). DEA is a non-parametric method that spans a minimal hull around a reference set of observations (called decision-making units, DMUs) using LP and a minimal set of assumptions.

3.1. Original DEA models

Consider n DMUs with m inputs and s outputs. Let $x_{ij}(i=1,2,...,m)$ and $y_{rj}(r=1,2,...,s)$ be the input and output values of DMU$_j$ ($j = 1, \dots, n$). The radial technical input-efficiency measure of DMU$_k$ is formulated in the dual formulation as follows:

$$\begin{aligned}
&\theta_{kk} = \max \frac{\sum_{r=1}^{s} u_{rk} y_{rk}}{\sum_{i=1}^{m} v_{ik} x_{ik}}, \\
&s.t. \frac{\sum_{r=1}^{s} u_{rk} y_{rj}}{\sum_{i=1}^{m} v_{ik} x_{ij}} \le 1, \quad j = 1, \dots, n, \\
&u_{rk}, v_{ik} \ge 0, \quad r = 1, \dots, s; i = 1, \dots, m.
\end{aligned} \tag{1}$$

where u_{rk} and v_{ik} are the weights associated with outputs and inputs, respectively. The first set of constraints does not allow all the DMUs to arrive at an efficiency greater than one. The total flexibility of weights allows each DMU to maximize self-efficiency. The efficiency score varies within [0,1]. DMU$_k$ is said to be *efficient* if θ_{kk}=1 and there exists at least one set of optimal weights, with $u^*_{rk} > 0$ and $v^*_{ik} > 0$; otherwise DMU$_k$ is called *inefficient*. The non-linear model (1) can be converted to the following LP problem using Charnes and Cooper (1962)'s method:

$$\begin{aligned}
&\theta_{kk} = \max \sum_{r=1}^{s} u_{rk} y_{rk}, \\
&s.t. \sum_{i=1}^{m} v_{ik} x_{ik} = 1, \\
&\sum_{r=1}^{s} u_{rk} y_{rj} - \sum_{i=1}^{m} v_{ik} x_{ij} \le 0, \quad j = 1, \dots, n, \\
&u_{rk}, v_{ik} \ge 0, \quad r = 1, \dots, s; i = 1, \dots, m.
\end{aligned} \tag{2}$$

Model (2) refers to the input oriented constant returns-to-scale (CRS) model.

3.2. Cross-efficiency model

The conventional DEA is not able to discriminate between efficient units. To produce a full ranking, Sexton at al. (1986) introduced the cross-efficiency model, extended by Doyle and Green (1994, 1995), to evaluate all the DMUs through both self and peer-evaluations. The self-evaluation evaluates the efficiencies of the DMUs with the most favorable weights so that each of them can achieve its best possible relative efficiency, while the peer-evaluation evaluates the efficiency of each DMU with the weights specified by the other DMUs. The advantage of the cross-efficiency evaluation is to guarantee a unique ranking for the DMUs even irrespective of scale and dimensionality (Doyle and Green, 1995). However, the disadvantage of applying cross-efficiency scores is the uniqueness of the input and output weights obtained from model (2) that makes the cross-efficiency analysis arbitrary and limits its applicability (Talluri and Narasimhan, 2004). To deal with this limitation, we here review the formulation developed by Doyle and Green (1994).

Denote the optimal solutions to model (2) by u^*_{rk} (r=1,2,...,s) and v^*_{ik} (i=1,2,...,m) which represent the relative importance weights of the s outputs and m inputs. Then,$\theta^*_{kk} = \max\ \sum_{r=1}^{s} u^*_{rk} y_{rk}$, is referred to as the CRS-efficiency of DMU$_k$ that presents its best relative efficiency.

Also, $\theta^*_{kj} = \sum_{r=1}^{s} u^*_{rk} y_{rj} / \sum_{i=1}^{m} v^*_{ik} x_{ij}$ is referred to as a cross-efficiency value of DMU$_j$, representing the peer evaluation of DMU$_k$ compared to DMU$_j$ ($j = 1, \ldots, j \neq k$). For convenience, DMU$_k$ is also referred to as a target DMU.

Model (2) is solved n times, one for each target DMU. As a consequence, there will be n sets of input and output weights for the n DMUs and each DMU has one CRS-efficiency value as well as (n-1) cross-efficiency values. The n efficiency values are averaged to form an estimate for the overall performance of the DMU. Based on their average cross-efficiency values, the n DMUs can be compared or ranked. However, model (2) is often found producing multiple optimal solutions. To deal with this problem, Sexton et al. (1986) suggested introducing a secondary goal to optimize the input and output weights while keeping unchanged the CRS-efficiency of the target DMU. The most commonly used secondary goals suggested by Doyle and Green (1994) are formulated as follows:

$$
\begin{aligned}
&\varphi_{kk} = \min\ \sum_{r=1}^{s} u_{rk} \left(\sum_{j=1, j \neq k}^{n} y_{rj} \right), \\
&s.t. \sum_{i=1}^{m} v_{ik} \left(\sum_{j=1, j \neq k}^{n} x_{ij} \right) = 1, \\
&\sum_{r=1}^{s} u_{rk} y_{rk} - \theta^*_{kk} \sum_{i=1}^{m} v_{ik} x_{ik} = 0, \\
&\sum_{r=1}^{s} u_{rk} y_{rj} - \sum_{i=1}^{m} v_{ik} x_{ij} \leq 0, \quad j = 1, \ldots, n, j \neq k, \\
&u_{rk}, v_{ik} \geq 0, \quad r = 1, \ldots, s; i = 1, \ldots, m.
\end{aligned} \tag{3}
$$

and

$$
\begin{aligned}
&\phi_{kk} = \max\ \sum_{r=1}^{s} u_{rk} \left(\sum_{j=1, j \neq k}^{n} y_{rj} \right), \\
&s.t. \sum_{i=1}^{m} v_{ik} \left(\sum_{j=1, j \neq k}^{n} x_{ij} \right) = 1, \\
&\sum_{r=1}^{s} u_{rk} y_{rk} - \theta^*_{kk} \sum_{i=1}^{m} v_{ik} x_{ik} = 0, \\
&\sum_{r=1}^{s} u_{rk} y_{rj} - \sum_{i=1}^{m} v_{ik} x_{ij} \leq 0, \quad j = 1, \ldots, n, j \neq k, \\
&u_{rk}, v_{ik} \geq 0, \quad r = 1, \ldots, s; i = 1, \ldots, m.
\end{aligned} \tag{4}
$$

Models (3) and (4) are known as the *aggressive* and *benevolent* formulations, respectively, for cross-efficiency evaluation. The aggressive model (3) aims at minimizing the cross efficiencies of all other DMUs whereas the benevolent model (4) aims at maximizing the cross-efficiencies of all other DMUs to some extent.

4. Methodology

In this section, we first introduce a novel version of cross-efficiency evaluation that enables the decision maker to identify his/her aggressive and benevolent level in distinct situations. We then propose an evaluation process for measuring the efficiency of a group of DMUs by means of cross-efficiency scores when the input and output data are fuzzy.

4.1. Cross-efficiency model based on DM's preference

Cross-efficiency goes beyond the pure self-appraisal in the conventional DEA model and evaluates each unit using the average of the efficiency scores of the other (*n-1*) scores arising from the optimal peer multipliers.

Recalling the notation in Section 2, the features of models (3) and (4), we propose the following LP model:

$$
\begin{aligned}
&\max\ \ w_1 \sum_{r=1}^{s} u_{rk} \left(\sum_{j=1, j \neq k}^{n} y_{rj} \right) - w_2 \sum_{r=1}^{s} u_{rk} \left(\sum_{j=1, j \neq k}^{n} y_{rj} \right) \\
&s.t. \sum_{i=1}^{m} v_{ik} \left(\sum_{j=1, j \neq k}^{n} x_{ij} \right) = 1, \\
&\sum_{r=1}^{s} u_{rk} y_{rk} - \widehat{\theta}^*_{kk} \sum_{i=1}^{m} v_{ik} x_{ik} = 0, \\
&\sum_{r=1}^{s} u_{rk} y_{rj} - \sum_{i=1}^{m} v_{ik} x_{ij} \leq 0, \quad j = 1, \ldots, n, j \neq k, \\
&u_{rk}, v_{ik} \geq 0, \quad r = 1, \ldots, s; i = 1, \ldots, m.
\end{aligned} \tag{5}
$$

where w_1 and w_2 are the user-specified weights reflecting the preference from the benevolent and aggressive viewpoints, respectively. Note that the weights are designed to sum to unity, i.e., $w_1+w_2=1$. If $w_1=1$, model (5) is transformed into the benevolent model (4) and if $w_2=1$ model (5) is converted into the aggressive model (3). The cross-efficiency score is called *moderate* when $w_1=w_2=0.5$.

4.2. Fuzzy cross-efficiency model

The conventional DEA models are limited to use precise measurements of both the inputs and outputs. However, as discussed above the evaluation of multidimensional performance, such as in supplier selection, is often contingent on using incomplete and poorly defined linguistic variables. Ad hoc scalarization of such variables naturally would undermine the confidence in the obtained results, as it masks the underlying uncertainty in the reference set. Some researchers have proposed various methods for coping with the impreciseness and ambiguity in DEA. One remedy suggested is to use fuzzy logic and fuzzy sets to represent ambiguous or imprecise information such as linguistic variables[1] in DEA (Hatami-Marbini et al., 2010, 2011a). A short overview of fuzzy sets is provided in Appendix I.

Let us consider n DMUs, each of which uses m different

[1] A linguistic variable is a variable such as *very small, small, medium, large* and *very large,* measured by words or sentences in natural languages (Zadeh, 1975). Zadeh (1975) showed how the linguistic variable concept can be extended to envelop a true collection of natural language of terms. A linguistic variable makes an attempt to approximate a phenomenon that is too complex and ill-defined to be measured in conventional quantitative ways.

trapezoidal fuzzy inputs $\tilde{x}_{ij}=(x_{ij}^{m1},x_{ij}^{m2},x_{ij}^{l},x_{ij}^{u})$ to generate s different trapezoidal fuzzy outputs $\tilde{y}_{rj}=(y_{rj}^{m1},y_{rj}^{m2},y_{rj}^{l},y_{rj}^{u})$. The generic fuzzy CRS model with fuzzy data can be expressed as:

$$\begin{aligned}
&\theta_{kk}=\max\ \sum\nolimits_{r=1}^{s}u_{rk}\tilde{y}_{rk},\\
&s.t.\sum\nolimits_{i=1}^{m}v_{ik}\tilde{x}_{ik}=1,\\
&\sum\nolimits_{r=1}^{s}u_{rk}\tilde{y}_{rj}-\sum\nolimits_{i=1}^{m}v_{ik}\tilde{x}_{ij}\le 0,\quad j=1,\dots,n,\\
&u_{rk},v_{ik}\ge 0,\quad r=1,\dots,s;i=1,\dots,m.
\end{aligned}\tag{6}$$

Based on the recent fuzzy DEA review by Emrouznejad et al. (2014), there are six categories in the literature to solve the fuzzy DEA model (6), namely, the tolerance approach, the α-level based approach (see e.g., Hatami-Marbini et al., 2011c, 2013c; Saati et al., 2013), the fuzzy ranking approach (see e.g., Emrouznejad et al., 2011; Hatami-Marbini et al., 2011b), the possibility approach (see e.g., Lertworasirikul et al., 2003), fuzzy arithmetic (see e.g., Hatami-Marbini et al., 2015), and fuzzy random/type-2 fuzzy sets (see e.g., Tavana et al., 2012, 2014).

Given that the $\alpha-$level based approach is one of the most popular fuzzy DEA models along with providing due flexibility for the analyst to set their own acceptable possibility levels (Hatami-Marbini et al., 2011c), in this paper, we apply the $\alpha-$level based approach suggested by Saati et al. (2002) to solve model (6). The basic idea is to generate a possibilistic programming problem that is converted into an interval-programming problem by means of the $\alpha-$level. This method defines a decision variable in the interval for all the inputs and outputs of DMUs with the aim of not only satisfying the set of constraints, but also maximizing the efficiency value rather than comparing the equality (or inequality) of two intervals. However, we point out that the $\alpha-$level based model is not computationally efficient since the number of LP models needed to be solved is $n.\mathrm{p}(\alpha)$ where $\mathrm{p}(\alpha)$ is the number of α-levels and each established model includes $2n(m+s)$ additional constraints. For a given α, the resulting interval-programming problem is formulated as the following crisp LP model:

$$\begin{aligned}
&\max\ \widehat{\theta}_{kk}^{\alpha}=\sum\nolimits_{r=1}^{s}\overline{y}_{rk}\\
&s.t.\sum\nolimits_{i=1}^{m}\overline{x}_{ik}=1,\\
&\sum\nolimits_{r=1}^{s}\overline{y}_{rj}-\sum\nolimits_{i=1}^{m}\overline{x}_{ij}\le 0,\ j=1,\dots,n,\\
&v_{ik}\left(\alpha x_{ij}^{m1}+(1-\alpha)x_{ij}^{l}\right)\le\overline{x}_{ij}\le v_{ik}\left(\alpha x_{ij}^{m2}+(1-\alpha)x_{ij}^{u}\right),\quad i=1,\dots,m;j=1,\dots,n,\\
&u_{rk}\left(\alpha y_{rj}^{m1}+(1-\alpha)y_{rj}^{l}\right)\le\overline{y}_{rj}\le u_{rk}\left(\alpha y_{rj}^{m2}+(1-\alpha)y_{rj}^{u}\right),\quad r=1,\dots,s;j=1,\dots,n,\\
&u_{rk},v_{ik}\ge 0,\quad r=1,\dots,s;i=1,\dots,m.
\end{aligned}\tag{7}$$

where α varies between $[0,1]$. A DMU$_k$ is said to be [radial technical] *input-efficient* if $\widehat{\theta}_{kk}^{\alpha*}=1$ for an α-level, otherwise DMU$_k$ is classified as an *inefficient* DMU for an α-level. It is needless to consider the left-hand-side of the first constraint as a fuzzy number, $\tilde{1}$, since this assumption leads to a number of additional constrains that are ultimately redundant (for further discussion, see Saati et al. (2002, p.261)). It should be noted that we obtain the optimal multipliers on inputs and outputs for each α. Analogous to the conventional cross-efficiency technique, we make use of peer evaluation instead of self-evaluation for a given α, so-called a *primary goal*, so as to calculate the cross-efficiency scores where input and output data are characterized by fuzzy numbers. The possible existence of the non-uniqueness of u_{rk} and v_{ik} may lead to distinctive cross-efficiency scores when solving model (6). To deal with this problem, we develop the fuzzy form of model (5) where the *secondary goal* based on the DM's preference is to optimize input and output weights while keeping unchanged the CRS efficiency of a certain DMU as represented below:

$$\begin{aligned}
&\max\ w_1\sum\nolimits_{r=1}^{s}u_{rk}\left(\sum\nolimits_{j=1,j\ne k}^{n}\tilde{y}_{rj}\right)-w_2\sum\nolimits_{r=1}^{s}u_{rk}\left(\sum\nolimits_{j=1,j\ne k}^{n}\tilde{y}_{rj}\right)\\
&s.t.\quad\sum\nolimits_{i=1}^{m}v_{ik}\left(\sum\nolimits_{j=1,j\ne k}^{n}\tilde{x}_{ij}\right)=1,\\
&\sum\nolimits_{r=1}^{s}u_{rk}\tilde{y}_{rk}-\widehat{\theta}_{kk}^{\alpha*}\sum\nolimits_{i=1}^{m}v_{ik}\tilde{x}_{ik}=0,\\
&\sum\nolimits_{r=1}^{s}u_{rk}\tilde{y}_{rj}-\sum\nolimits_{i=1}^{m}v_{ik}\tilde{x}_{ij}\le 0,\quad j=1,\dots,n,j\ne k,\\
&u_{rk},v_{ik}\ge 0,\quad r=1,\dots,s;i=1,\dots,m,
\end{aligned}\tag{8}$$

where $\widehat{\theta}_{kk}^{\alpha*}$ is the radial technical input-efficiency score of DMU$_k$ for an α-level calculated by model (7). The fuzzy inputs and outputs can be represented as a bounded interval for different α levels and the fuzzy model (8) is then transformed into the following model:

$$\begin{aligned}
&\max\ w_1\sum\nolimits_{r=1}^{s}u_{rk}\left(\sum\nolimits_{j=1,j\ne k}^{n}\left(\alpha y_{rj}^{m1}+(1-\alpha)y_{rj}^{l},\alpha y_{rj}^{m2}+(1-\alpha)y_{rj}^{u}\right)\right)-w_2\sum\nolimits_{r=1}^{s}u_{rk}\left(\sum\nolimits_{j=1,j\ne k}^{n}\left(\alpha y_{rj}^{m1}+(1-\alpha)y_{rj}^{l},\alpha y_{rj}^{m2}+(1-\alpha)y_{rj}^{u}\right)\right)\\
&s.t.\sum\nolimits_{i=1}^{m}v_{ik}\left(\sum\nolimits_{j=1,j\ne k}^{n}\left(\alpha x_{ij}^{m1}+(1-\alpha)x_{ij}^{l},\alpha x_{ij}^{m2}+(1-\alpha)x_{ij}^{u}\right)\right)=1,\\
&\sum\nolimits_{r=1}^{s}u_{rk}\left(\alpha y_{rk}^{m1}+(1-\alpha)y_{rk}^{l},\alpha y_{rk}^{m2}+(1-\alpha)y_{rk}^{u}-\widehat{\theta}_{kk}^{\alpha*}\right)\sum\nolimits_{i=1}^{m}v_{ik}\left(\alpha x_{ik}^{m1}+(1-\alpha)x_{ik}^{l},\alpha x_{ik}^{m2}+(1-\alpha)x_{ik}^{u}\right)=0,\\
&\sum\nolimits_{r=1}^{s}u_{rk}\left(\alpha y_{rj}^{m1}+(1-\alpha)y_{rj}^{l},\alpha y_{rj}^{m2}+(1-\alpha)y_{rj}^{u}\right)-\sum\nolimits_{i=1}^{m}v_{ik}\left(\alpha x_{ij}^{m1}+(1-\alpha)x_{ij}^{l},\alpha x_{ij}^{m2}+(1-\alpha)x_{ij}^{u}\right)\le 0,\quad j=1,\dots,n,j\ne k\\
&u_{rk},v_{ik}\ge 0,\quad r=1,\dots,s;i=1,\dots,m.
\end{aligned}\tag{9}$$

We then define the interval variable transformations $\widehat{y}_{rj}$ and $\widehat{x}_{ij}$ as follows:

$$\widehat{y}_{rj} = \left(\alpha y_{rj}^{m1} + (1-\alpha)y_{rj}^{l}, \alpha y_{rj}^{m2} + (1-\alpha)y_{rj}^{u}\right), \quad i = 1,\dots,m; j = 1,\dots,n$$

$$\widehat{x}_{ij} = \left(\alpha x_{ij}^{m1} + (1-\alpha)x_{ij}^{l}, \alpha x_{ij}^{m2} + (1-\alpha)x_{ij}^{u}\right), \quad r = 1,\dots,s; j = 1,\dots,n$$

and these variables are substituted in model (9) to derive the following model:

$$\begin{aligned}
&\max\ w_1\sum_{r=1}^{s}\sum_{j=1,j\neq k}^{n} u_{rk}\widehat{y}_{rj} - w_2\sum_{r=1}^{s}\sum_{j=1,j\neq k}^{n} u_{rk}\widehat{y}_{rj}\\
&s.t. \sum_{i=1}^{m}\sum_{j=1,j\neq k}^{n} v_{ik}\widehat{x}_{ij} = 1,\\
&\sum_{r=1}^{s} u_{rk}\widehat{y}_{rk} - \widehat{\theta}_{kk}^{\alpha*}\sum_{i=1}^{m} v_{ik}\widehat{x}_{ik} = 0,\\
&\sum_{r=1}^{s} u_{rk}\widehat{y}_{rj} - \sum_{i=1}^{m} v_{ik}\widehat{x}_{ij} \le 0, \quad j = 1,\dots,n, j\neq k,\\
&\alpha x_{ij}^{m1} + (1-\alpha)x_{ij}^{l} \le \widehat{x}_{ij} \le \alpha x_{ij}^{m2} + (1-\alpha)x_{ij}^{u}, \quad i = 1,\dots,m; j = 1,\dots,n,\\
&\alpha y_{rj}^{m1} + (1-\alpha)y_{rj}^{l} \le \widehat{y}_{rj} \le \alpha y_{rj}^{m2} + (1-\alpha)y_{rj}^{u}, \quad r = 1,\dots,s; j = 1,\dots,n,\\
&u_{rk}, v_{ik} \ge 0, \quad r = 1,\dots,s; i = 1,\dots,m.
\end{aligned} \tag{10}$$

The above model is transformed into the LP model (11) using the variable transformations $\overline{y}_{rj} = u_{rk}\widehat{y}_{rj}$ $(r = 1, \dots, s;\ j = 1, \dots, n)$ and $\overline{x}_{ij} = v_{ik}\widehat{x}_{ij}$ $(i = 1, \dots, m;\ j = 1, \dots, n)$.

$$\begin{aligned}
&\max\ w_1\sum_{r=1}^{s}\sum_{j=1,j\neq k}^{n} \overline{y}_{rj} - w_2\sum_{r=1}^{s}\sum_{j=1,j\neq k}^{n} \overline{y}_{rj}\\
&s.t. \sum_{i=1}^{m}\sum_{j=1,j\neq k}^{n} \overline{x}_{ij} = 1,\\
&\sum_{r=1}^{s} \overline{y}_{rk} - \widehat{\theta}_{kk}^{\alpha*}\sum_{i=1}^{m} \overline{x}_{ik} = 0,\\
&\sum_{r=1}^{s} \overline{y}_{rj} - \sum_{i=1}^{m} \overline{x}_{ij} \le 0, \quad j = 1,\dots,n, j\neq k,\\
&v_{ik}\left(\alpha x_{ij}^{m1} + (1-\alpha)x_{ij}^{l}\right) \le \overline{x}_{ij} \le v_{ik}\left(\alpha x_{ij}^{m2} + (1-\alpha)x_{ij}^{u}\right), \quad i = 1,\dots,m; j = 1,\dots,n,\\
&u_{rk}\left(\alpha y_{rj}^{m1} + (1-\alpha)y_{rj}^{l}\right) \le \overline{y}_{rj} \le u_{rk}\left(\alpha y_{rj}^{m2} + (1-\alpha)y_{rj}^{u}\right), \quad r = 1,\dots,s; j = 1,\dots,n,\\
&u_{rk}, v_{ik} \ge 0,\ r = 1,\dots,s; i = 1,\dots,m.
\end{aligned} \tag{11}$$

In summary, the proposed fuzzy cross-efficiency method is implemented using the following six steps:

Step 1. Determine a given α-level.

Step 2. Calculate the efficiency, $\widehat{\theta}_{kk}^{\alpha*}$, of all the DMUs for the pre-specified α using model (7).

Step 3. Determine the value of w_1 and w_2 on the basis of the DM's preference.

Step 4. Calculate the optimal input and output weights, v_{ik}^{*} and u_{rk}^{*}, for the pre-specified α using model (11).

Step 5. Obtain the fuzzy cross-efficiency matrix for the pre-specified α-level by the following equation:

$$\tilde{\theta}_{kj}^{\alpha} = \frac{\sum_{r=1}^{s} u_{rk}^{*}\tilde{y}_{rj}}{\sum_{i=1}^{m} v_{ik}^{*}\tilde{x}_{ij}}, \ k,j = 1,\dots,n. \tag{12}$$

Step 6. Calculate the fuzzy efficiency scores of all the DMUs for the pre-specified α by the following equation:

$$\bar{\tilde{\theta}}_{j}^{\alpha} = \frac{\sum_{j=1,j\neq k}^{n}\tilde{\theta}_{kj}^{\alpha}}{n-1}, \quad j = 1,\dots,n. \tag{13}$$

The ranking of fuzzy numbers is a crucial procedure for making a proper decision in fuzzy environments (Cheng, 1998). However, this is inherently an intricate task and in some cases such as those involving overlapping fuzzy numbers, different ranking methods can give rise to different rankings. The centroid-based and distance minimization techniques are the most frequently used methods for ordering fuzzy numbers (Wang et al., 2006; Hatami-Marbini et al., 2013a, 2013b). Asady and Zendehnam (2007) proposed a defuzzification method based on the nearest points of the fuzzy numbers that produces very realistic results while maintaining the basic properties. In this study, we defuzzify the fuzzy efficiency score resulted from our proposed fuzzy cross-efficiency method to a crisp value by the method proposed by Asady and Zendehnam (2007) to enhance the interpretability of the results and give better insight into supplier performance.

5. Proposed sustainable sourcing framework

In this section, we introduce a four-phase framework to evaluate the performance of a set of potential suppliers as follows:

Phase 1: This phase categorizes the current suppliers into the four groups based on the Kraljic portfolio purchasing model (Kraljic, 1983) which entails two variables: profit impact and degree of supply risk. These variables yield a Kraljic matrix that enables us to characterize four different types of suppliers; i) strategic suppliers, ii) bottleneck suppliers, iii) leverage suppliers, and iv) routine suppliers as presented in Fig. 2.

Strategic suppliers have a significant value to the firm since the supply risk's degree and the profit impact are both high, for instance gearboxes for automobile manufacturers and turbines for the chemical industry. We therefore give priority to strategic products due to the fact that there exist a limited number of potential suppliers to be purchased. *Bottleneck suppliers* (low profit impact, high supply risk) present a dominant influence position for the products that have a moderate impact on the financial results and a crucial impact on their supply for a firm. *Leverage products* (high profit impact, low supply risk) consider a relatively large share of the end product's cost price associated with a relatively low supply risk in which there exist a wide variety of suppliers. *Routine suppliers* (low profit impact, low supply risk) are related to

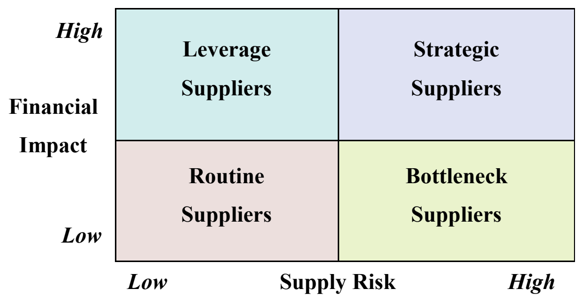

Fig. 2. Supplier classification based on the Kralijc portfolio.

the products that have a small value per unit. In addition, routine products consume 80% of the purchasing department's time with less than 20% of the purchasing turnover (i.e., a rule of thumb) (Caniels and Gelderman, 2005). In reality, some companies outsource thousands of products and services. We perform this phase to determine the critical outsourced products in terms of profit impact and supply risk so as to evaluate the performance of their suppliers.

Phase 2: The second phase defines quantitative and qualitative evaluation criteria for each group of suppliers in terms of operational, organizational and sustainable aspects. In referring to the literature, we opt for {quality, cost, financial situation, flexibility, delivery} and {relationship, technology, culture} for the operational and organizational criteria, respectively. In consideration of the specific features of each supplier group defined in Phase 1, it necessitates a different combination of operational and organizational criteria for evaluation of suppliers. The operational criteria for strategic, leverage, bottleneck and routine suppliers are {quality, cost, financial situation, flexibility}, {quality, cost, flexibility}, {quality, cost, financial situation}, and {quality, cost, delivery}, respectively, and the organizational criteria for those suppliers are {relationship, technology, culture}, {technology, culture}, {relationship} and {culture}, respectively. The sustainable aspect of our supplier evaluation includes {social, environment and economic} criteria regardless of supplier classification. In addition, we introduce some relevant indicators to represent each criterion of the operational, organizational aspects as shown in Figs. 3 and 4. The characteristics of each supplier group lead us to consider a mix of indicators to introduce the criteria as represented in Table 1. The definitions of those indicators that are considered in evaluating suppliers are given in Appendix II.

As shown in Fig. 1, the sustainability criteria include an integration of economic, environmental and social dimensions (Gauthier, 2005). However, in existing studies in SCM, researchers often focused only on environmental and economic dimensions (Bai and Sarkis, 2010). In addition, Seuring (2013) showed that there exist 23 articles on sustainable SCM modeling with the focus on both environmental and economic issues while only two articles including Clift (2003) and Foran et al. (2005) considered all three dimensions of sustainability. Put differently, no research has been independently conducted in SCM that takes into account the social dimension. However, unethical activities such as discrimination and child labor can lead to considerable damage to the reputation, market share and competitiveness of the outsourcing firm. For example, chocolate manufacturers, Nestlé and Cadbury, were accused of using child slavery in the cocoa industry (Dahan and Gittens, 2010). Another such case occurred in 2003, when the South Coast Air Quality Management District (AQMD) sued British Petroleum (PB) for $319 million as penalties for thousands of air pollution violations during an 8-year period. To extract the criteria and indicators of sustainability, we exploit the Global Reporting Initiative (GRI, 2010) as a reliable reference (see Fig. 5) in order to obtain the appropriate environmental, social and economic criteria to evaluate suppliers. The definitions of the indicators of operational, organizational and sustainable aspects that are considered in evaluating suppliers are given in Appendix II.

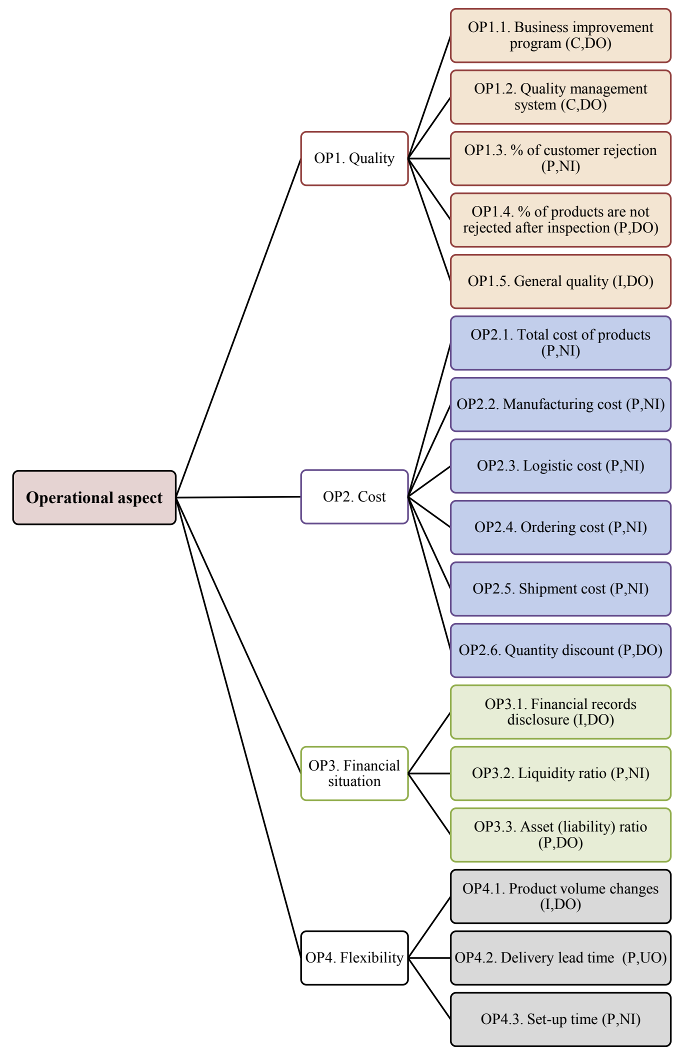

Fig. 3. Criteria and indicators of the operational aspect.

Phase 3: The third phase evaluates the performance efficiency of suppliers using the DEA-based model presented in the previous section. The cross efficiency as a DEA-based model is a powerful mathematical technique that has been developed based on the profit-cost ratio for measuring the relative efficiency of entities (suppliers) with multi-inputs and multi-outputs. In other words, the efficiency of each entity is defined as a quotient of the weighted sum of outputs to the weighted sum of inputs. Therefore, each entity wishes to minimize its inputs and maximize its outputs for the purpose of increasing the efficiency (profit-cost ratio). As a consequence, we can identify the input or output roles of the indicators associated with each criterion. Note that the outputs and inputs always belong to one of the following groups:

- Undesirable output (UO): The goal is to be minimized.
- Desirable output (DO): The goal is to be maximized.
- Normal input (NI): The goal is to be minimized.
- Desirable input (DI): The goal is to be maximized.

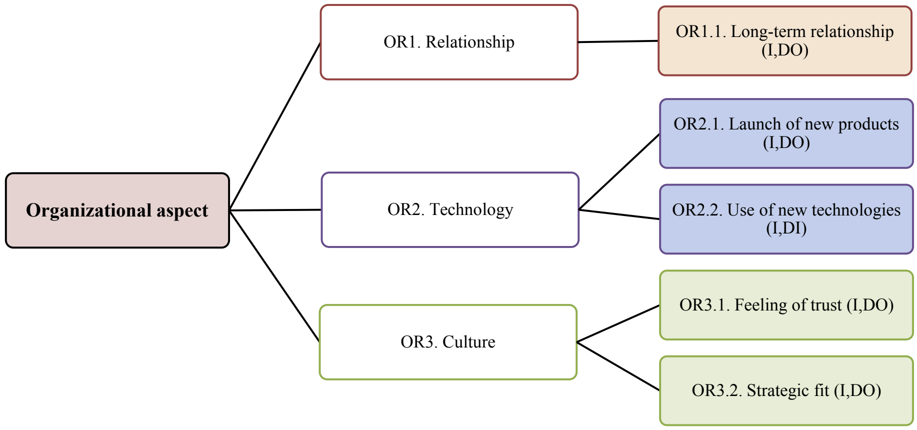

Fig. 4. Criteria and indicators of the organizational aspect.

Table 1
Indicators of each supplier group.

Supplier group	Indicators						
	Operational aspect				Organizational aspect		
	Quality	Cost	Financial situation	Flexibility	Relationship	Technology	Culture
Strategic	OP1.1 OP1.2 OP1.3 OP1.4	OP2.1 OP2.2 OP2.3 OP2.5	OP3.1 OP3.2 OP3.3	OP4.1 OP4.2	OR1.1	OR2.1 OR2.2	OR3.1 OR3.2
Leverage	OP1.2 OP1.3 OP1.4	OP2.1 OP2.2 OP2.3 OP2.4 OP2.5 OP2.6	–	OP4.1 OP4.2 OP4.3	–	OR2.2	OR3.1
Bottleneck	OP1.2 OP1.4	OP2.1	OP3.1 OP3.2 OP3.3	–	OR1.1	–	–
Routine	OP1.5	OP2.1 OP2.3	–	OP4.2	–	–	OR3.1

The sustainability sub-criteria can be classified as inputs or outputs as shown in Table 2. Some indicators may only be imprecisely determined using linguistic variables from experts or decision-makers. In this study, we apply fuzzy logic to deal with the impreciseness. Furthermore, some indicators are characterized by categorical variables (discrete valued or binary) (Agrell et al., 2005). In this regard, "I", "C" and "P" in Figs. 3 and 4 stand for *imprecise*, *categorical* and *precise* indicators, respectively, "UO" and "DO" stand for *undesirable output* and *desirable output* factors, respectively, and "NI" and "DI" stand for *normal input* and *desirable input* factors, respectively. For example, (C, DO) for OP1.2., implies that the indictor is a categorical desirable output. The last three columns of Table 2 present the type of the sustainability sub-criteria.

Phase 4: This phase groups suppliers into three classes; *preferred*, *approved* and *phase-out* suppliers based on the performance measures obtained from Phase 3. *Preferred suppliers* are a group of suppliers that are appropriate for long-term strategic relationships. *Approved suppliers* are potential candidates for medium-term contracting that may be rejected in the long run because of their inefficiencies. Finally, the *phase-out suppliers* should be replaced by alternative suppliers when possible. This classification provides helpful insights and information to managers and decision-makers with respect to the suppliers' assessment. The four-phase framework is summarized in Fig. 6.

6. Case study

In this section, we present a case study to demonstrate the applicability of the proposed method in the semiconductor industry. The semiconductor industry is a rapidly growing cornerstone industry. As the use of semiconductors devices and components becomes more prevalent across different types of industries, the environmental and social externalities associated with semiconductor manufacturing are likely to increase all over.

Performance on a variety of sustainability issues, such as mitigating greenhouse gas emissions during manufacturing, managing energy consumption and improving energy efficiency during manufacturing, minimizing product lifecycle impacts through innovative in design and business practices, and managing the supply chain, will drive competitiveness in the semiconductor industry.

The framework presented in Section 5 was used to help Semicon Technologies,[2] a large manufacturer of semiconductor equipment, memory chips, microprocessors and microcontrollers located in a developing country in the Middle East. Semicon is being called

[2] Some of the names and data presented in this study are changed to protect the anonymity of the company.

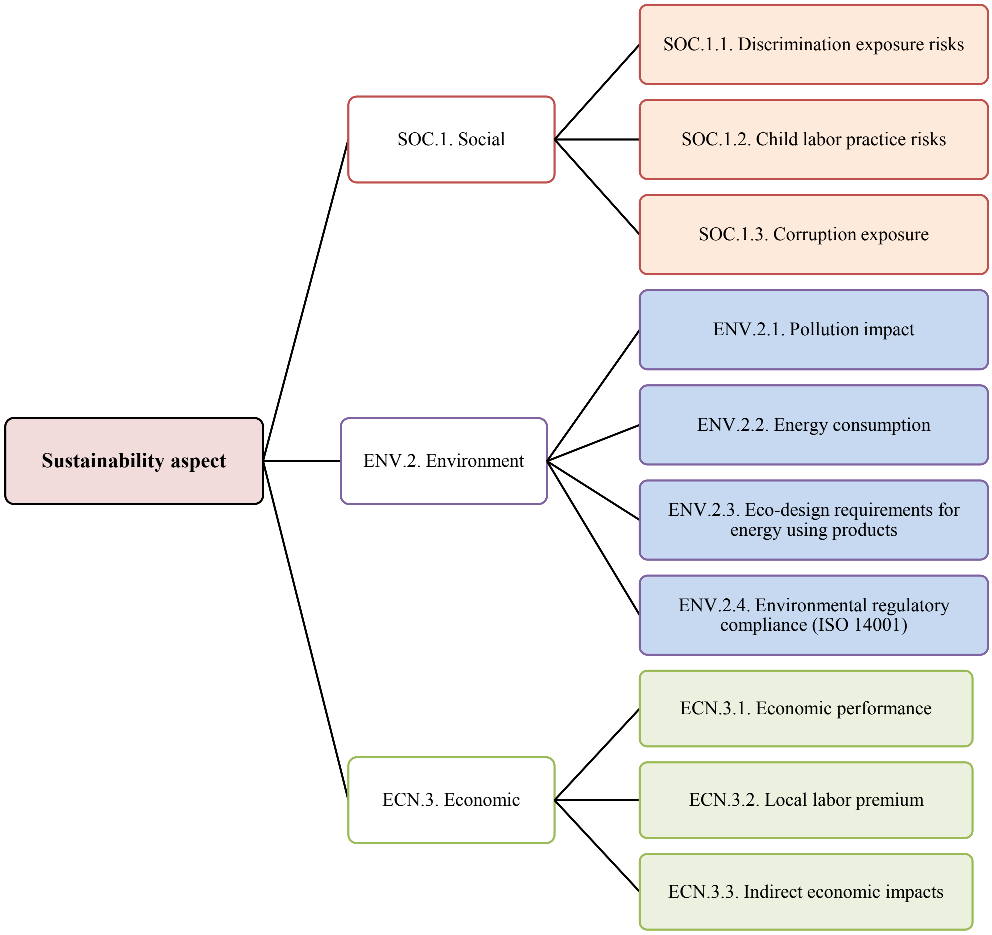

Fig. 5. Criteria and indicators of sustainability.

Table 2
Sustainability criteria.

Dimension	Sub-criterion	Input		Output		Precise	Imprecise	Categorical
		NI	DI	DO	UO			
SOC.1.Social	SOC.1.1	✓					✓	
	SOC.1.2	✓					✓	
	SOC.1.3	✓					✓	
ENV.2.Environment	ENV.2.1				✓	✓		
	ENV.2.2	✓				✓		
	ENV.2.3		✓				✓	
	ENV.2.4		✓					✓
ECN.3. Economic	ECN.3.1			✓		✓		
	ECN.3.2			✓		✓		
	ECN.3.3			✓			✓	

upon to take responsibility for the ways their operations impact the society and the environment. They are asked to apply sustainability principles to their operations since it is no longer acceptable for Semicon to experience economic prosperity in isolation from the stakeholders affected by its actions. Semicon must focus its attention on both increasing its bottom line and being a good corporate citizen.

In this case, we focus on supplier selection through the supply chain as a way to improve performance on a variety of sustainability issues. We consider an example of 12 suppliers in the leverage category that supply Semicon with silicon wafers. The names of these suppliers are not given in the paper in order to protect the anonymity of the companies. The companies supply products that are used in the manufacture of semiconductors such as single crystal silicon wafers, epitaxial silicon wafers and silicon ingots as well as a wide variety of materials such as silicon, gallium arsenate, sapphire and silicon carbide. The operational, organizational and sustainability characteristics of each company has a critical impact on its ability to provide the highest quality product at the most competitive price while providing excellent customer service. The companies are located in a variety of geographical regions in the world, and some of these locations may provide competitive advantages depending on their proximity to sources of raw materials and distribution channels. The characteristics of

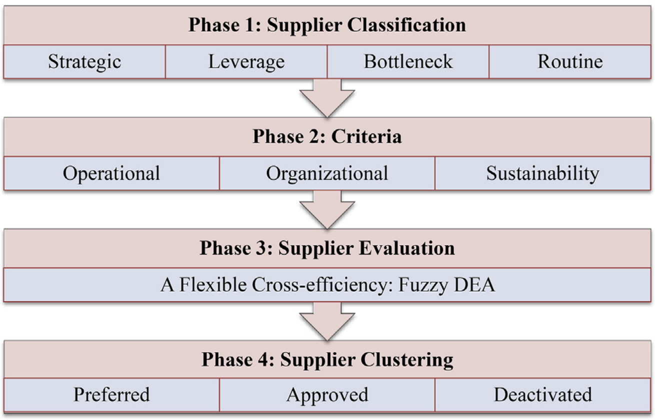

Fig. 6. Proposed framework for supplier evaluation.

the suppliers on the various sustainability criteria may also be a function of the location since societal and environmental norms as well as economic conditions can differ greatly from region to region.

In this section, we show the applicability of the proposed framework to this case where the 12 suppliers in the leverage category are evaluated in the presence of 13 inputs and 11 outputs (see Fig. 6).

Phases 1 and 2: According to Table 1 for the leverage suppliers and sustainability, the assessment criteria can be summarized as follows:

- **Operational aspect:** {OP1.2, OP1.3, OP1.4}, {OP2.1, OP2.2, OP2.3, OP2.4, OP2.5, OP2.6}, and {OP4.1, OP4.2, OP4.3} as the surrogates for Quality, Cost and Flexibility.
- **Organizational aspect: {**OR2.2} and {OR3.1} as the surrogates for Technology and Culture.
- **Sustainability aspect: {**SOC.1.1, SOC.1.2, SOC.1.3}, {ENV. 2.1, ENV. 2.2, ENV. 2.3, ENV. 2.4}, and {ECN. 3.1, ECN. 3.2, ECN. 3.3} as the surrogates for the Social, Environment and Economic dimensions.

The normal inputs, desirable outputs, desirable inputs, and undesirable outputs are defined as {OP2.1, OP2.2, OP2.3, OP2.4, OP2.5, OP4.3, SOC.1.1, SOC.1.2, SOC.1.3, ENV.2.2}, {OP1.2, OP1.3, OP1.4, OP2.6, OR3.1, OP4.1, ECN. 3.1, ECN. 3.2, ECN. 3.3}, {OR2.2, ENV. 2.3, ENV. 2.4}, and {OP4.2, ENV. 2.1}, respectively. In this study, {OR2.2, OR3.1, OP4.1, SOC.1.1, SOC.1.2, SOC.1.3, ENV. 2.3, ECN. 3.3} are imprecise and subjective data can be represented in the form of linguistic variables.

The linguistic terms used to express these factors are:

- OR3.1: Very unreliable (VU), Unreliable (U), Somewhat reliable (SR), Reliable (R), Very reliable (VR)
- OR2.2: Very high use of new technology (VHT), High use of new technology (HT), Some use of new technology, (ST) Little use of new technology (LT), Very little use of new technology (VLT)
- OP4.1: Very high volatility in product volume change (VHC), High volatility in product volume change (HC), Some volatility in product volume change (SC), Little volatility in product volume change (LC), Very little volatility in product volume change (VLC)
- SOC.1.1: Very high evidence of discrimination (VHD), High evidence of discrimination (HD), Some evidence of discrimination (SD), Little evidence of discrimination (LD), Very little evidence of discrimination (VLD)
- SOC.1.2: Very high evidence of child labor (VHL), High evidence of child labor (HL), Some evidence of child labor (SL), Little evidence of child labor (LL), Very little evidence of child labor (VLL)
- SOC.1.3: Very high evidence of corruption (VHCo), High evidence of corruption (HCo), Some evidence of corruption (SCo), Little evidence of corruption (LCo), Very little evidence of corruption (VLCo)
- ENV.2.3: Very high energy eco-design (VHE), High energy eco-design (HE), Some energy eco-design (SE), Little energy eco-design (LE), Very little energy eco-design (VLE)
- ECN.3.3: Very high indirect economic impact (VHI), High indirect economic impact (HI), Some indirect economic impact (SI), Little indirect economic impact (LI), Very little indirect economic impact (VLE).

The linguistic variables and their associated triangular fuzzy numbers (TFN) are summed up in Table 3. Table 4 presents the data for the 13 input criteria (10 normal inputs and 3 desirable inputs) for each supplier. Similarly, Table 5 presents the data for the 11 output criteria (9 desirable outputs and 2 undesirable outputs). For some of the criteria there is a small variation between the suppliers whereas for some other criteria there is a significant amount of variation in the data between them. Thus many of the suppliers are similar on certain characteristics but dissimilar on other characteristics. For example, for OP2.1 and OP2.2 (the total cost of products and the manufacturing cost, respectively), the variation relative to the mean (i.e. the coefficient of variation) is relatively small, whereas for OP2.5 (the shipment cost) it is relatively high. This could reflect large differences in transportation costs since the suppliers are located in different locations around the world. The same can be said for some of the linguistic variables. For example, there seems to be a relatively modest variation among the suppliers for SOC 1.2 (level of discrimination), since most of the suppliers are measured as having either very little, little or some level of discrimination. On the other hand, other linguistic variables (such as OR2.2, the use of new technologies) have a relatively larger amount of variation between the suppliers. Generally speaking, there seems to be more relative variation between the suppliers for the output criteria compared to the input criteria, particularly for those that are measured by quantitative or precise data. Thus the ability to optimize specific operational, organizational or sustainability performance variables with a given set of inputs can vary significantly from supplier to supplier. This may reflect in large part the particular product or product mix that is being sourced.

Overall, the data in Tables 4 and 5 indicate that each supplier is unique in its operational, organizational and sustainability criteria

Table 3
Linguistic variables and their associated triangular fuzzy numbers.

OR3.1	OR2.2	OP4.1	SOC.1.1	SOC.1.2	SOC.1.3	ENV.2.3	ECN.3.3	TFN
VU	VHT	VHC	VHD	VHL	VHCo	VHE	VHI	(0, 0, 20, 35)
U	HT	HC	HD	HL	HCo	HE	HI	(20, 35, 35, 50)
SR	ST	SC	SD	SL	SCo	SE	SI	(35, 50, 50, 65)
R	LT	LC	LD	LL	LCo	LE	LI	(50, 65, 65, 80)
VR	VLT	VLC	VLD	VLL	VLCo	VLE	VLE	(65, 80, 100, 100)

Table 4
Inputs for 12 suppliers.

Suppliers	Normal Inputs										Desirable Inputs		
	OP2.1 (1000$)	OP2.2 (1000$)	OP2.3 (1000$)	OP2.4 (1000$)	OP2.5 (1000$)	OP4.3 (minutes)	SOC.1.1	SOC.1.2	SOC.1.3	ENV. 2.2 (%)	OR2.2	ENV. 2.3	ENV. 2.4
1	1159	712	542	116	109	64	LD	VLL	LCo	86	ST	LE	0
2	1045	845	538	175	121	28	LD	VLL	HCo	48	LT	LE	0
3	1345	737	547	157	211	66	LD	LL	VLCo	86	LT	HE	1
4	1185	601	445	155	173	51	VLD	SL	HCo	61	HT	LE	1
5	1074	636	423	179	56	68	VLD	SL	VLCo	40	HT	SE	1
6	1430	674	374	155	277	53	LD	VLL	SCo	49	ST	VLE	0
7	1043	727	367	109	54	20	VLD	LL	LCo	46	LT	HE	1
8	1445	690	480	143	239	49	SD	VLL	VLCo	74	ST	SE	0
9	1089	723	382	109	149	45	HD	SL	SCo	77	LT	VLE	0
10	1079	691	414	150	278	29	SD	LL	LCo	23	HT	SE	0
11	1451	640	422	199	197	64	SD	VLL	VLCo	86	HT	VLE	0
12	1173	839	478	168	270	28	HD	LL	VLCo	48	ST	SE	0

Table 5
Outputs for 12 suppliers.

Suppliers	Desirable Outputs									Undesirable Outputs	
	OP1.2	OP1.3 (%)	OP1.4 (%)	OP2.6 (%)	OR3.1	OP4.1	ECN. 3.1	ECN. 3.2 (ratio)	ECN. 3.3	OP4.2 (days)	ENV. 2.1 (grams)
1	0	32	51	24	VU	HC	25	1.22	SI	7	364
2	1	69	67	19	R	SC	56	1.37	HI	3	479
3	1	78	46	16	VU	HC	59	1.85	SI	9	147
4	0	83	31	22	SR	LC	55	1.88	SI	13	146
5	1	82	36	1	U	VHC	51	1.68	HI	11	325
6	0	28	12	12	R	HC	20	1.35	LI	11	440
7	0	38	7	18	U	VLC	75	1.21	VLE	10	216
8	1	91	83	4	VR	LC	69	1.51	VLE	12	355
9	1	23	84	12	U	VLC	59	1.04	SI	4	273
10	1	78	18	23	SR	SC	49	1.89	HI	13	889
11	0	32	51	24	SR	VLC	25	1.22	LI	7	364
12	1	69	67	19	VR	SC	56	1.37	LI	3	479

which reflects its various characteristics such as location, product mix, operational plan, organizational structure and culture, and focus on various societal, environmental and economic concerns.

Note that ENV. 2.4 and OP1.2 are measured by means of categorical variables (binary). Studies in the existing literature often consider the desirable outputs and normal inputs and simply ignore the undesirable outputs and desirable inputs which is equivalent to having missing data and could generate misleading results. The present application is composed of three desirable inputs {OR2.2, ENV. 2.3, ENV 2.4} and two undesirable outputs {OP4.2, ENV. 2.1}. There exist several approaches to cope with these types of factors, particularly undesirable outputs, in performance evaluation. Three main approaches to modeling undesirable outputs have been characterized by Dyckhoff and Allen (2001); (1) utilizing the reciprocal of the undesirable output where the undesirable output is modelled as being desirable (Scheel, 2001), (2) utilizing a multi-criteria approach where the undesirable output is modeled as an input (Reinhard et al., 2000), and (3) utilizing the translation property in BCC and additive DEA models (Ali and Seiford, 1990) where a positive scalar is added to the reciprocal additive transformation of the undesirable output. According to Gomes and Lins (2008), the selection of one of these methods is arbitrary, although the common approach models an undesirable output as an input or utilizes the reciprocal. We use the second approach in this study to model the undesirable outputs as normal inputs (and the desirable inputs as desirable outputs).

Phase 3: As earlier described in detail, the proposed cross-efficiency approach in this study contains six steps to measure the fuzzy efficiency and categorize the suppliers. In Step 1, we consider five α-levels {0, 0.25, 0.5, 0.75, 1} in order to incorporate managerial preferences or expert opinions in the process of performance evaluation. In Step 2, model (7), that is based on the conventional DEA model, is solved for each pre-specified α to obtain the efficiency of all the suppliers, $\widehat{\theta}^{\alpha*}_{kk}$, $k = 1,2, \ldots 12$. The efficiency scores of all the suppliers equals 1, indicating a lack of discrimination since we have insufficient units, that is, the number of inputs and outputs is high relative to the number of units. Step 2 is based on the fact that using fuzzy DEA itself is inadequate, particularly in supplier evaluation when the number of assessment criteria is relatively greater than the number of suppliers at large. In Step 3, we define the weights associated with the benevolent and aggressive components of the objective function in model (11). Our results derived from Equation (12) are based on three scenarios: (1) $w_1 > w_2$, (2) $w_1 < w_2$, and (3) $w_1 = w_2 = 0.5$. The results show that the fuzzy efficiency scores are identical for all w_1 and w_2 under these scenarios. Scenarios 1 and 2 are used by a benevolent and aggressive decision-maker, respectively, while scenario 3 is appropriate for those cases where the decision-maker is neutral. Steps 4 and 5 lead to the fuzzy cross-efficiency matrix for the pre-specified α-level. Tables 6–10 present the fuzzy cross-efficiency matrices, θ^{α}_{kj} ($j = 1, \ldots,12$; $k = 1, \ldots,12$), for scenario 2 for five α-levels {0, 0.25, 0.5, 0.75, 1}. For instance, the fuzzy cross-efficiency value of DMU_2 which represents the peer evaluation of DMU_3 compared to DMU_2 for $\alpha = 0$ is θ^{0}_{23}=(0.20,0.26,0.27,0.36). In addition, the fuzzy cross-efficiency value converges toward a precise number by increasing the value α from 0 to 1. It should be noted that the diagonal of Tables (matrices) 6–10 presents the fuzzy [relatively] efficiencies, and the remaining cells are the cross-efficiencies. For instance, the first cell of Table 6 as $\theta^{0}_{11} = (0.55,0.77,0.78,1.00)$ shows the fuzzy efficiency score of Supplier 1 obtained from model (8).

In the last step, Equation (13) is used to obtain the average of all $\theta^{\alpha}_{kj}(j = 1, \ldots,12)$ with the exception of the jth supplier (the supplier under evaluation) as the fuzzy cross-efficiency score for the kth supplier. Tables 11–13 represent the results, $\overline{\theta}^{\alpha}_{k}(k = 1, \ldots,12)$, for the

Table 6
Fuzzy cross-efficiency matrix in scenario 2 for α=0.

Suppliers	1	2	3	4	5	6	7	8	9	10	11	12
1	(0.55,0.77,0.78,1.00)	(0.03,0.04,0.18,0.34)	(0.13,0.18,0.20,0.27)	(0.03,0.04,0.05,0.06)	(0.04,0.05,0.05,0.06)	(0.03,0.04,0.22,0.42)	(0.04,0.05,0.05,0.07)	(0.03,0.04,0.18,0.34)	(0.12,0.20,0.23,0.37)	(0.02,0.03,0.18,0.30)	(0.15,0.29,0.29,0.47)	(0.03,0.04,0.16,0.29)
2	(0.70,0.90,0.91,1.12)	(0.44,0.67,0.67,1.00)	(0.20,0.26,0.27,0.36)	(0.06,0.08,0.08,0.12)	(0.06,0.07,0.07,0.08)	(0.56,0.85,0.86,1.28)	(0.06,0.07,0.07,0.08)	(0.35,0.50,0.50,0.71)	(0.21,0.28,0.33,0.47)	(0.58,0.74,0.75,0.92)	(0.26,0.41,0.41,0.60)	(0.29,0.42,0.42,0.60)
3	(0.45,0.59,0.59,0.74)	(0.03,0.04,0.16,0.29)	(0.74,0.83,0.87,1.02)	(0.40,0.40,0.47,0.54)	(0.47,0.48,0.48,0.49)	(0.03,0.04,0.20,0.37)	(0.42,0.43,0.43,0.44)	(0.04,0.05,0.19,0.34)	(0.14,0.26,0.26,0.42)	(0.03,0.03,0.18,0.30)	(0.16,0.29,0.29,0.47)	(0.04,0.05,0.16,0.29)
4	(0.32,0.50,0.50,0.68)	(0.35,0.57,0.58,0.92)	(0.83,0.94,0.99,1.17)	(0.65,0.79,0.79,1.00)	(0.57,0.58,0.58,0.60)	(0.43,0.73,0.73,1.17)	(0.52,0.53,0.53,0.54)	(0.23,0.32,0.37,0.54)	(0.37,0.56,0.56,0.82)	(0.38,0.53,0.54,0.69)	(0.31,0.40,0.47,0.66)	(0.19,0.27,0.31,0.46)
5	(0.49,0.79,0.81,1.12)	(0.13,0.22,0.26,0.41)	(0.68,0.74,0.81,0.96)	(0.41,0.42,0.49,0.57)	(0.93,0.95,0.97,1.00)	(0.17,0.28,0.33,0.52)	(0.87,0.88,0.89,0.92)	(0.14,0.22,0.26,0.42)	(0.04,0.05,0.20,0.39)	(0.29,0.48,0.48,0.69)	(0.03,0.03,0.17,0.31)	(0.12,0.19,0.22,0.35)
6	(0.33,0.45,0.48,0.58)	(0.36,0.54,0.54,0.78)	(0.15,0.20,0.22,0.28)	(0.04,0.05,0.06,0.08)	(0.02,0.03,0.03,0.04)	(0.46,0.69,0.69,1.00)	(0.02,0.03,0.03,0.04)	(0.32,0.48,0.48,0.68)	(0.12,0.20,0.23,0.36)	(0.54,0.70,0.71,0.87)	(0.15,0.28,0.28,0.45)	(0.27,0.40,0.40,0.56)
7	(1.00,1.33,1.35,1.69)	(0.17,0.31,0.32,0.51)	(0.82,0.92,1.00,1.15)	(0.50,0.58,0.59,0.70)	(1.00,1.03,1.05,1.08)	(0.21,0.39,0.40,0.65)	(0.94,0.97,0.98,1.00)	(0.15,0.24,0.28,0.44)	(0.42,0.59,0.73,0.87)	(0.29,0.47,0.48,0.67)	(0.40,0.49,0.71,0.83)	(0.13,0.20,0.24,0.38)
8	(0.34,0.47,0.47,0.61)	(0.37,0.45,0.64,0.73)	(0.21,0.26,0.30,0.37)	(0.05,0.05,0.07,0.08)	(0.05,0.05,0.06,0.06)	(0.47,0.58,0.82,0.94)	(0.05,0.05,0.06,0.06)	(0.49,0.68,0.84,1.00)	(0.28,0.35,0.41,0.56)	(0.56,0.68,0.85,0.86)	(0.39,0.58,0.58,0.83)	(0.41,0.57,0.70,0.84)
9	(0.69,0.88,0.93,1.10)	(0.20,0.36,0.37,0.60)	(0.23,0.30,0.34,0.43)	(0.06,0.08,0.08,0.11)	(0.06,0.07,0.07,0.08)	(0.24,0.45,0.46,0.75)	(0.06,0.07,0.07,0.08)	(0.15,0.24,0.28,0.44)	(0.47,0.67,0.83,1.00)	(0.21,0.34,0.34,0.47)	(0.40,0.49,0.70,0.81)	(0.13,0.21,0.24,0.37)
10	(0.19,0.31,0.31,0.43)	(0.23,0.37,0.37,0.55)	(0.13,0.18,0.18,0.24)	(0.03,0.05,0.05,0.07)	(0.03,0.03,0.03,0.04)	(0.30,0.47,0.47,0.70)	(0.03,0.03,0.03,0.04)	(0.27,0.43,0.43,0.65)	(0.22,0.34,0.34,0.51)	(0.54,0.77,0.77,1.00)	(0.27,0.44,0.44,0.66)	(0.23,0.36,0.36,0.55)
11	(0.30,0.45,0.49,0.62)	(0.21,0.29,0.34,0.49)	(0.16,0.21,0.25,0.31)	(0.04,0.04,0.05,0.07)	(0.04,0.05,0.05,0.06)	(0.27,0.37,0.43,0.63)	(0.04,0.05,0.05,0.06)	(0.28,0.44,0.45,0.67)	(0.33,0.41,0.58,0.67)	(0.28,0.40,0.40,0.52)	(0.48,0.68,0.84,1.00)	(0.23,0.37,0.38,0.57)
12	(0.31,0.43,0.43,0.55)	(0.37,0.45,0.64,0.73)	(0.21,0.27,0.29,0.37)	(0.04,0.05,0.06,0.07)	(0.04,0.04,0.05,0.05)	(0.47,0.57,0.82,0.93)	(0.04,0.04,0.05,0.05)	(0.55,0.79,0.98,1.20)	(0.23,0.36,0.36,0.53)	(0.72,0.88,1.09,1.10)	(0.33,0.53,0.54,0.83)	(0.46,0.66,0.81,1.00)
Mean	(0.47,0.65,0.66,0.84)	(0.22,0.33,0.40,0.58)	(0.26,0.27,0.28,0.30)	(0.15,0.17,0.19,0.22)	(0.22,0.23,0.23,0.24)	(0.29,0.43,0.52,0.76)	(0.19,0.20,0.21,0.22)	(0.23,0.34,0.40,0.59)	(0.23,0.33,0.39,0.54)	(0.35,0.48,0.55,0.67)	(0.26,0.38,0.44,0.63)	(0.19,0.28,0.33,0.48)

Table 7
Fuzzy cross-efficiency matrix in scenario 2 for α=0.25.

Suppliers	1	2	3	4	5	6	7	8	9	10	11	12
1	(0.65,0.84,0.85,1.05)	(0.03,0.04,0.20,0.37)	(0.03,0.04,0.04,0.05)	(0.03,0.04,0.04,0.06)	(0.04,0.05,0.05,0.06)	(0.03,0.04,0.24,0.46)	(0.04,0.05,0.05,0.07)	(0.03,0.04,0.19,0.36)	(0.16,0.27,0.27,0.38)	(0.02,0.03,0.03,0.04)	(0.16,0.30,0.30,0.49)	(0.03,0.04,0.16,0.30)
2	(0.63,0.81,0.81,1.00)	(0.48,0.74,0.74,1.11)	(0.04,0.05,0.05,0.06)	(0.06,0.08,0.08,0.12)	(0.06,0.07,0.07,0.08)	(0.61,0.93,0.93,1.41)	(0.06,0.07,0.07,0.08)	(0.36,0.52,0.52,0.74)	(0.40,0.55,0.55,0.71)	(0.74,0.75,0.75,0.76)	(0.27,0.42,0.42,0.63)	(0.30,0.44,0.44,0.63)
3	(0.20,0.33,0.33,0.46)	(0.03,0.04,0.18,0.32)	(0.93,0.96,0.97,1.01)	(0.42,0.43,0.50,0.57)	(0.47,0.49,0.49,0.50)	(0.03,0.04,0.21,0.40)	(0.43,0.43,0.44,0.45)	(0.04,0.05,0.19,0.36)	(0.14,0.23,0.23,0.32)	(0.50,0.51,0.51,0.52)	(0.16,0.30,0.30,0.48)	(0.04,0.05,0.17,0.31)
4	(0.54,0.70,0.70,0.86)	(0.38,0.63,0.63,1.01)	(1.00,1.01,1.05,1.10)	(0.69,0.84,0.84,1.07)	(0.58,0.59,0.59,0.61)	(0.47,0.79,0.79,1.28)	(0.52,0.53,0.53,0.54)	(0.24,0.33,0.38,0.57)	(0.26,0.33,0.33,0.40)	(0.05,0.05,0.05,0.06)	(0.32,0.42,0.49,0.69)	(0.20,0.28,0.33,0.48)
5	(0.66,0.93,0.94,1.23)	(0.15,0.24,0.28,0.45)	(0.70,0.70,0.73,0.75)	(0.44,0.44,0.52,0.60)	(0.93,0.96,0.97,1.01)	(0.18,0.30,0.35,0.57)	(0.87,0.89,0.90,0.92)	(0.14,0.23,0.27,0.43)	(0.03,0.03,0.13,0.22)	(0.84,0.85,0.86,0.88)	(0.03,0.03,0.17,0.32)	(0.12,0.20,0.23,0.37)
6	(0.46,0.57,0.71,0.72)	(0.40,0.59,0.60,0.86)	(0.03,0.04,0.04,0.05)	(0.04,0.05,0.05,0.07)	(0.02,0.03,0.03,0.04)	(0.50,0.75,0.76,1.10)	(0.02,0.03,0.03,0.04)	(0.34,0.50,0.50,0.71)	(0.12,0.20,0.20,0.28)	(0.04,0.05,0.05,0.06)	(0.16,0.29,0.29,0.47)	(0.28,0.42,0.42,0.59)
7	(0.44,0.74,0.75,1.05)	(0.18,0.34,0.35,0.56)	(0.88,0.90,0.93,0.97)	(0.53,0.62,0.63,0.74)	(0.99,1.03,1.04,1.08)	(0.22,0.43,0.43,0.70)	(0.95,0.97,0.98,1.01)	(0.15,0.25,0.29,0.46)	(0.39,0.48,0.60,0.61)	(0.05,0.06,0.07,0.08)	(0.42,0.51,0.74,0.86)	(0.13,0.21,0.25,0.39)
8	(0.30,0.42,0.43,0.55)	(0.41,0.50,0.71,0.81)	(0.06,0.07,0.07,0.08)	(0.05,0.05,0.07,0.08)	(0.05,0.05,0.06,0.06)	(0.51,0.63,0.90,1.02)	(0.05,0.05,0.06,0.06)	(0.51,0.71,0.88,1.05)	(0.26,0.34,0.34,0.41)	(0.56,0.57,0.58,0.58)	(0.41,0.60,0.61,0.87)	(0.43,0.60,0.74,0.88)
9	(0.75,0.93,1.15,1.16)	(0.21,0.39,0.40,0.65)	(0.06,0.07,0.07,0.08)	(0.05,0.08,0.08,0.11)	(0.06,0.07,0.07,0.08)	(0.26,0.49,0.50,0.82)	(0.06,0.07,0.07,0.08)	(0.15,0.25,0.29,0.45)	(0.65,0.80,0.99,1.00)	(0.58,0.59,0.59,0.60)	(0.41,0.51,0.73,0.84)	(0.13,0.21,0.25,0.39)
10	(0.26,0.37,0.37,0.47)	(0.26,0.41,0.41,0.60)	(0.02,0.03,0.03,0.03)	(0.03,0.05,0.05,0.07)	(0.03,0.03,0.03,0.04)	(0.32,0.51,0.51,0.76)	(0.03,0.03,0.03,0.04)	(0.28,0.45,0.45,0.68)	(0.17,0.24,0.24,0.31)	(0.96,0.98,0.98,1.01)	(0.28,0.45,0.45,0.69)	(0.24,0.38,0.38,0.57)
11	(0.59,0.72,0.90,0.91)	(0.23,0.32,0.38,0.54)	(0.04,0.05,0.06,0.06)	(0.03,0.04,0.05,0.07)	(0.04,0.05,0.05,0.06)	(0.29,0.40,0.47,0.68)	(0.04,0.05,0.05,0.06)	(0.29,0.46,0.47,0.70)	(0.44,0.54,0.68,0.69)	(0.03,0.04,0.04,0.05)	(0.50,0.71,0.88,1.05)	(0.24,0.39,0.40,0.59)
12	(0.28,0.39,0.39,0.50)	(0.40,0.49,0.70,0.80)	(0.04,0.05,0.05,0.06)	(0.04,0.05,0.06,0.07)	(0.04,0.04,0.05,0.05)	(0.51,0.63,0.89,1.02)	(0.04,0.04,0.05,0.05)	(0.58,0.83,1.02,1.26)	(0.39,0.54,0.54,0.69)	(0.72,0.73,0.74,0.75)	(0.34,0.56,0.56,0.87)	(0.48,0.70,0.86,1.06)
Mean	(0.46,0.63,0.68,0.81)	(0.24,0.36,0.44,0.64)	(0.26,0.27,0.28,0.30)	(0.16,0.18,0.19,0.23)	(0.22,0.23,0.23,0.24)	(0.31,0.47,0.57,0.83)	(0.20,0.20,0.21,0.22)	(0.24,0.35,0.42,0.61)	(0.25,0.34,0.37,0.46)	(0.38,0.38,0.39,0.40)	(0.27,0.40,0.46,0.66)	(0.20,0.29,0.34,0.50)

Table 8
Fuzzy cross-efficiency matrix in scenario 2 for α=0.5.

Suppliers	1	2	3	4	5	6	7	8	9	10	11	12
1	(0.94,0.98,0.98,1.02)	(0.04,0.04,0.22,0.36)	(0.03,0.04,0.04,0.05)	(0.03,0.04,0.04,0.06)	(0.04,0.05,0.05,0.07)	(0.37,0.55,0.55,0.79)	(0.04,0.05,0.05,0.07)	(0.03,0.04,0.19,0.37)	(0.16,0.27,0.27,0.38)	(0.02,0.03,0.03,0.04)	(0.16,0.31,0.31,0.51)	(0.04,0.04,0.17,0.28)
2	(0.73,0.76,0.76,0.79)	(0.69,0.89,0.90,1.10)	(0.04,0.05,0.05,0.06)	(0.06,0.08,0.08,0.12)	(0.06,0.07,0.08,0.09)	(0.50,0.76,0.76,1.15)	(0.06,0.07,0.07,0.08)	(0.37,0.54,0.55,0.77)	(0.40,0.56,0.56,0.72)	(0.74,0.75,0.75,0.77)	(0.28,0.44,0.44,0.65)	(0.54,0.69,0.70,0.86)
3	(0.46,0.48,0.48,0.50)	(0.04,0.04,0.19,0.31)	(0.93,0.97,0.98,1.02)	(0.45,0.45,0.53,0.61)	(0.50,0.52,0.52,0.54)	(0.15,0.24,0.28,0.44)	(0.43,0.44,0.44,0.45)	(0.03,0.05,0.20,0.37)	(0.14,0.23,0.23,0.33)	(0.50,0.51,0.51,0.52)	(0.17,0.31,0.31,0.50)	(0.04,0.04,0.15,0.24)
4	(0.73,0.74,0.76,0.78)	(0.24,0.34,0.34,0.44)	(0.99,1.01,1.05,1.10)	(0.73,0.89,0.89,1.14)	(0.61,0.63,0.63,0.66)	(0.53,0.82,0.82,1.27)	(0.52,0.53,0.53,0.55)	(0.24,0.34,0.40,0.59)	(0.26,0.33,0.33,0.41)	(0.05,0.05,0.05,0.06)	(0.34,0.43,0.51,0.71)	(0.19,0.26,0.26,0.34)
5	(0.10,0.11,0.12,0.14)	(0.16,0.27,0.27,0.38)	(0.70,0.71,0.74,0.77)	(0.46,0.47,0.55,0.64)	(0.92,0.96,0.98,1.03)	(0.24,0.34,0.40,0.59)	(0.88,0.89,0.90,0.93)	(0.14,0.24,0.28,0.45)	(0.03,0.03,0.14,0.22)	(0.84,0.86,0.86,0.88)	(0.03,0.03,0.18,0.34)	(0.13,0.21,0.21,0.29)
6	(0.29,0.31,0.31,0.32)	(0.34,0.44,0.44,0.55)	(0.03,0.04,0.04,0.05)	(0.04,0.05,0.05,0.07)	(0.03,0.03,0.04,0.04)	(0.52,0.74,0.92,1.10)	(0.02,0.03,0.03,0.04)	(0.35,0.52,0.52,0.74)	(0.12,0.20,0.20,0.28)	(0.04,0.05,0.05,0.06)	(0.16,0.30,0.30,0.49)	(0.26,0.34,0.34,0.42)
7	(0.99,1.01,1.06,1.11)	(0.18,0.30,0.31,0.42)	(0.89,0.90,0.94,0.98)	(0.56,0.65,0.66,0.78)	(0.97,1.01,1.03,1.08)	(0.19,0.35,0.36,0.57)	(0.95,0.98,0.99,1.01)	(0.16,0.25,0.30,0.48)	(0.39,0.48,0.60,0.61)	(0.05,0.06,0.07,0.08)	(0.43,0.53,0.77,0.90)	(0.15,0.24,0.24,0.33)
8	(0.15,0.15,0.16,0.17)	(0.43,0.52,0.64,0.65)	(0.06,0.07,0.07,0.08)	(0.05,0.05,0.07,0.08)	(0.05,0.06,0.06,0.07)	(0.25,0.34,0.40,0.57)	(0.05,0.05,0.06,0.06)	(0.53,0.74,0.92,1.10)	(0.26,0.34,0.34,0.41)	(0.56,0.57,0.58,0.59)	(0.42,0.62,0.63,0.91)	(0.33,0.40,0.50,0.50)
9	(0.45,0.46,0.48,0.50)	(0.31,0.50,0.51,0.71)	(0.06,0.07,0.07,0.08)	(0.05,0.07,0.08,0.11)	(0.06,0.07,0.08,0.09)	(0.58,0.83,1.03,1.24)	(0.06,0.07,0.07,0.08)	(0.16,0.25,0.30,0.47)	(0.65,0.80,0.99,1.01)	(0.58,0.59,0.59,0.60)	(0.43,0.53,0.76,0.88)	(0.25,0.40,0.41,0.56)
10	(0.54,0.56,0.56,0.57)	(0.22,0.31,0.31,0.40)	(0.02,0.03,0.03,0.03)	(0.03,0.05,0.05,0.06)	(0.03,0.04,0.04,0.05)	(0.26,0.42,0.42,0.62)	(0.03,0.03,0.03,0.04)	(0.29,0.47,0.47,0.71)	(0.17,0.24,0.24,0.31)	(0.97,0.99,0.99,1.01)	(0.29,0.47,0.47,0.72)	(0.17,0.24,0.24,0.31)
11	(0.71,0.73,0.73,0.75)	(0.33,0.46,0.47,0.60)	(0.04,0.05,0.06,0.06)	(0.03,0.04,0.05,0.06)	(0.04,0.05,0.05,0.06)	(0.41,0.50,0.72,0.82)	(0.04,0.05,0.05,0.06)	(0.30,0.48,0.49,0.74)	(0.44,0.55,0.68,0.69)	(0.03,0.04,0.04,0.05)	(0.52,0.74,0.92,1.10)	(0.26,0.36,0.37,0.47)
12	(0.48,0.50,0.50,0.51)	(0.84,1.04,1.29,1.31)	(0.04,0.05,0.05,0.06)	(0.04,0.05,0.06,0.07)	(0.04,0.05,0.05,0.06)	(0.24,0.33,0.39,0.56)	(0.04,0.04,0.05,0.05)	(0.60,0.87,1.07,1.33)	(0.39,0.54,0.54,0.69)	(0.72,0.73,0.74,0.75)	(0.35,0.58,0.58,0.91)	(0.65,0.80,0.99,1.01)
Mean	(0.51,0.53,0.54,0.56)	(0.28,0.39,0.45,0.56)	(0.26,0.27,0.29,0.30)	(0.16,0.18,0.20,0.24)	(0.22,0.23,0.23,0.25)	(0.34,0.50,0.56,0.78)	(0.20,0.21,0.21,0.22)	(0.24,0.37,0.43,0.64)	(0.25,0.34,0.38,0.46)	(0.38,0.39,0.39,0.40)	(0.28,0.41,0.48,0.68)	(0.21,0.29,0.33,0.42)

Table 9
Fuzzy cross-efficiency matrix in scenario 2 for α=0.75.

Suppliers	1	2	3	4	5	6	7	8	9	10	11	12
1	(0.95,0.98,0.99,1.03)	(0.04,0.04,0.05,0.06)	(0.39,0.52,0.57,0.77)	(0.03,0.04,0.04,0.05)	(0.04,0.05,0.05,0.06)	(0.39,0.57,0.57,0.82)	(0.04,0.05,0.05,0.07)	(0.03,0.04,0.20,0.38)	(0.16,0.27,0.27,0.38)	(0.02,0.03,0.03,0.04)	(0.17,0.32,0.32,0.53)	(0.03,0.04,0.17,0.28)
2	(0.74,0.77,0.77,0.80)	(0.97,0.99,0.99,1.02)	(0.71,0.90,0.94,1.21)	(0.04,0.05,0.05,0.06)	(0.05,0.06,0.07,0.08)	(0.52,0.80,0.80,1.21)	(0.06,0.07,0.07,0.08)	(0.39,0.57,0.57,0.81)	(0.40,0.56,0.56,0.72)	(0.74,0.76,0.76,0.77)	(0.29,0.45,0.45,0.68)	(0.54,0.70,0.70,0.86)
3	(0.47,0.48,0.49,0.50)	(0.56,0.57,0.57,0.58)	(0.76,0.91,0.97,1.21)	(0.87,0.88,0.89,0.91)	(0.50,0.52,0.53,0.55)	(0.15,0.25,0.29,0.46)	(0.43,0.44,0.44,0.45)	(0.03,0.05,0.20,0.38)	(0.14,0.23,0.24,0.33)	(0.51,0.51,0.52,0.53)	(0.17,0.32,0.32,0.52)	(0.04,0.04,0.15,0.24)
4	(0.73,0.74,0.76,0.79)	(0.03,0.04,0.04,0.05)	(0.78,0.97,1.02,1.31)	(0.97,0.99,0.99,1.02)	(0.61,0.64,0.64,0.67)	(0.55,0.85,0.86,1.33)	(0.52,0.54,0.54,0.55)	(0.25,0.35,0.41,0.61)	(0.26,0.33,0.33,0.41)	(0.05,0.05,0.05,0.06)	(0.35,0.45,0.53,0.74)	(0.19,0.26,0.27,0.34)
5	(0.10,0.11,0.12,0.14)	(0.51,0.52,0.52,0.53)	(0.67,0.79,0.90,1.14)	(0.63,0.64,0.64,0.66)	(0.92,0.97,0.98,1.05)	(0.25,0.35,0.41,0.61)	(0.88,0.90,0.91,0.93)	(0.15,0.25,0.29,0.47)	(0.03,0.03,0.14,0.22)	(0.85,0.86,0.87,0.89)	(0.03,0.03,0.18,0.35)	(0.13,0.21,0.21,0.30)
6	(0.30,0.31,0.31,0.32)	(0.03,0.03,0.04,0.04)	(0.43,0.58,0.63,0.81)	(0.03,0.04,0.04,0.05)	(0.02,0.03,0.03,0.04)	(0.54,0.77,0.96,1.15)	(0.02,0.03,0.03,0.04)	(0.37,0.54,0.54,0.77)	(0.12,0.20,0.20,0.28)	(0.04,0.05,0.05,0.06)	(0.17,0.31,0.32,0.51)	(0.26,0.34,0.34,0.42)
7	(0.99,1.00,1.06,1.11)	(0.04,0.05,0.05,0.06)	(0.80,0.98,1.11,1.35)	(0.83,0.85,0.86,0.87)	(0.96,1.01,1.03,1.09)	(0.19,0.36,0.37,0.60)	(0.96,0.98,0.99,1.02)	(0.16,0.26,0.31,0.49)	(0.39,0.49,0.60,0.61)	(0.05,0.06,0.07,0.08)	(0.45,0.55,0.80,0.93)	(0.15,0.24,0.24,0.33)
8	(0.15,0.16,0.16,0.17)	(0.47,0.48,0.48,0.49)	(0.69,0.83,0.95,1.13)	(0.06,0.07,0.07,0.08)	(0.05,0.05,0.06,0.06)	(0.25,0.35,0.41,0.59)	(0.05,0.05,0.06,0.06)	(0.55,0.77,0.96,1.15)	(0.27,0.34,0.34,0.42)	(0.57,0.57,0.58,0.59)	(0.44,0.65,0.66,0.95)	(0.33,0.41,0.50,0.51)
9	(0.45,0.47,0.48,0.50)	(0.94,0.96,0.97,0.98)	(0.74,0.92,1.04,1.28)	(0.06,0.07,0.08,0.08)	(0.06,0.07,0.07,0.08)	(0.60,0.86,1.07,1.30)	(0.06,0.07,0.07,0.08)	(0.16,0.26,0.31,0.49)	(0.65,0.81,1.00,1.01)	(0.58,0.59,0.60,0.60)	(0.44,0.54,0.79,0.91)	(0.25,0.40,0.41,0.56)
10	(0.55,0.57,0.57,0.59)	(0.43,0.44,0.44,0.45)	(0.53,0.71,0.71,0.93)	(0.02,0.02,0.02,0.03)	(0.03,0.03,0.03,0.04)	(0.27,0.43,0.43,0.65)	(0.03,0.03,0.03,0.04)	(0.30,0.49,0.49,0.75)	(0.17,0.24,0.24,0.31)	(0.97,0.99,0.99,1.02)	(0.30,0.49,0.49,0.75)	(0.17,0.24,0.24,0.31)
11	(0.72,0.74,0.75,0.77)	(0.05,0.06,0.06,0.07)	(0.48,0.61,0.71,0.88)	(0.04,0.05,0.05,0.06)	(0.04,0.05,0.05,0.06)	(0.42,0.52,0.75,0.85)	(0.04,0.05,0.05,0.06)	(0.31,0.50,0.51,0.77)	(0.45,0.55,0.68,0.69)	(0.03,0.04,0.04,0.05)	(0.54,0.77,0.96,1.15)	(0.26,0.36,0.37,0.47)
12	(0.49,0.50,0.51,0.52)	(0.94,0.96,0.96,0.98)	(0.39,0.52,0.57,0.77)	(0.04,0.05,0.05,0.06)	(0.04,0.05,0.05,0.05)	(0.25,0.35,0.40,0.58)	(0.04,0.04,0.05,0.05)	(0.63,0.91,1.12,1.39)	(0.39,0.54,0.54,0.70)	(0.73,0.74,0.74,0.75)	(0.37,0.60,0.61,0.96)	(0.66,0.81,1.00,1.01)
Mean	(0.52,0.53,0.54,0.57)	(0.37,0.38,0.38,0.39)	(0.26,0.27,0.29,0.31)	(0.24,0.25,0.25,0.26)	(0.22,0.23,0.24,0.25)	(0.35,0.52,0.58,0.82)	(0.20,0.21,0.21,0.22)	(0.25,0.38,0.45,0.67)	(0.25,0.34,0.38,0.46)	(0.38,0.39,0.39,0.40)	(0.29,0.43,0.50,0.71)	(0.22,0.30,0.33,0.42)

Table 10
Fuzzy cross-efficiency matrix in scenario 2 for α=1.

Supplier	1	2	3	4	5	6	7	8	9	10	11	12
1	(0.98,0.99,1.00,1.02)	(0.04,0.04,0.05,0.06)	(0.03,0.04,0.04,0.05)	(0.03,0.04,0.04,0.05)	(0.04,0.05,0.05,0.07)	(0.40,0.59,0.59,0.85)	(0.04,0.05,0.05,0.07)	(0.03,0.04,0.21,0.40)	(0.16,0.27,0.27,0.38)	(0.02,0.03,0.03,0.04)	(0.17,0.33,0.33,0.55)	(0.03,0.04,0.17,0.28)
2	(0.82,0.83,0.83,0.85)	(0.98,1.00,1.00,1.02)	(0.09,0.10,0.10,0.11)	(0.04,0.05,0.05,0.06)	(0.11,0.12,0.12,0.13)	(0.54,0.83,0.83,1.26)	(0.06,0.07,0.07,0.08)	(0.40,0.59,0.59,0.84)	(0.40,0.56,0.56,0.72)	(0.75,0.76,0.76,0.78)	(0.30,0.47,0.47,0.70)	(0.54,0.70,0.70,0.87)
3	(0.47,0.48,0.49,0.50)	(0.56,0.57,0.57,0.59)	(0.98,0.99,1.00,1.02)	(0.87,0.89,0.90,0.92)	(0.47,0.48,0.48,0.49)	(0.16,0.26,0.30,0.48)	(0.43,0.44,0.44,0.45)	(0.03,0.04,0.21,0.40)	(0.14,0.23,0.24,0.33)	(0.51,0.52,0.52,0.53)	(0.18,0.33,0.33,0.54)	(0.04,0.04,0.15,0.25)
4	(0.72,0.73,0.73,0.74)	(0.03,0.04,0.04,0.05)	(0.98,1.00,1.00,1.03)	(0.98,1.00,1.00,1.02)	(0.53,0.54,0.55,0.56)	(0.57,0.89,0.89,1.39)	(0.53,0.54,0.54,0.55)	(0.26,0.36,0.43,0.63)	(0.26,0.33,0.33,0.41)	(0.05,0.05,0.05,0.06)	(0.36,0.47,0.55,0.77)	(0.19,0.27,0.27,0.34)
5	(0.09,0.10,0.11,0.12)	(0.51,0.52,0.52,0.53)	(0.71,0.72,0.72,0.74)	(0.63,0.64,0.65,0.66)	(0.97,0.99,1.00,1.03)	(0.26,0.36,0.43,0.63)	(0.89,0.90,0.91,0.94)	(0.15,0.25,0.30,0.49)	(0.03,0.03,0.14,0.22)	(0.85,0.86,0.87,0.89)	(0.02,0.03,0.19,0.36)	(0.13,0.21,0.21,0.30)
6	(0.30,0.31,0.31,0.31)	(0.03,0.03,0.04,0.04)	(0.03,0.04,0.04,0.04)	(0.03,0.04,0.04,0.05)	(0.02,0.03,0.03,0.04)	(0.56,0.81,1.00,1.20)	(0.02,0.03,0.03,0.04)	(0.38,0.56,0.56,0.80)	(0.12,0.20,0.20,0.28)	(0.04,0.05,0.05,0.06)	(0.17,0.32,0.33,0.53)	(0.26,0.34,0.35,0.42)
7	(0.98,1.00,1.01,1.03)	(0.04,0.05,0.05,0.06)	(0.84,0.86,0.87,0.88)	(0.84,0.86,0.87,0.88)	(0.98,1.00,1.01,1.03)	(0.20,0.37,0.38,0.62)	(0.96,0.99,1.00,1.02)	(0.16,0.27,0.32,0.51)	(0.40,0.49,0.60,0.61)	(0.05,0.06,0.07,0.08)	(0.46,0.57,0.83,0.97)	(0.15,0.24,0.25,0.34)
8	(0.14,0.15,0.15w,0.16)	(0.47,0.48,0.49,0.49)	(0.12,0.13,0.13,0.14)	(0.06,0.07,0.07,0.08)	(0.08,0.08,0.09,0.09)	(0.26,0.36,0.42,0.61)	(0.05,0.05,0.06,0.06)	(0.57,0.81,1.00,1.20)	(0.27,0.34,0.34,0.42)	(0.57,0.58,0.58,0.59)	(0.46,0.68,0.68,0.99)	(0.33,0.41,0.50,0.51)
9	(0.51,0.52,0.53,0.54)	(0.94,0.96,0.97,0.99)	(0.14,0.15,0.16,0.16)	(0.06,0.07,0.08,0.08)	(0.10,0.11,0.12,0.12)	(0.62,0.90,1.11,1.35)	(0.06,0.07,0.07,0.08)	(0.17,0.27,0.32,0.50)	(0.66,0.81,1.00,1.02)	(0.58,0.59,0.60,0.61)	(0.46,0.56,0.82,0.95)	(0.25,0.40,0.41,0.56)
10	(0.54,0.55,0.55,0.55)	(0.43,0.44,0.44,0.45)	(0.05,0.06,0.06,0.06)	(0.02,0.02,0.02,0.03)	(0.05,0.06,0.06,0.07)	(0.28,0.45,0.45,0.67)	(0.03,0.03,0.03,0.04)	(0.31,0.51,0.51,0.78)	(0.17,0.24,0.24,0.31)	(0.98,1.00,1.00,1.02)	(0.31,0.51,0.51,0.79)	(0.17,0.24,0.24,0.31)
11	(0.73,0.74,0.75,0.76)	(0.05,0.05,0.06,0.07)	(0.04,0.05,0.05,0.06)	(0.04,0.05,0.05,0.06)	(0.04,0.05,0.05,0.06)	(0.44,0.54,0.78,0.89)	(0.04,0.05,0.05,0.06)	(0.32,0.52,0.53,0.80)	(0.45,0.55,0.68,0.69)	(0.03,0.04,0.04,0.05)	(0.56,0.80,1.00,1.20)	(0.26,0.37,0.37,0.47)
12	(0.52,0.53,0.53,0.54)	(0.94,0.96,0.97,0.99)	(0.09,0.10,0.10,0.11)	(0.04,0.05,0.05,0.06)	(0.07,0.07,0.07,0.08)	(0.26,0.36,0.42,0.60)	(0.04,0.04,0.05,0.05)	(0.65,0.95,1.18,1.47)	(0.16,0.27,0.27,0.38)	(0.73,0.74,0.75,0.76)	(0.38,0.63,0.63,1.00)	(0.66,0.81,1.00,1.02)
Mean	(0.53,0.54,0.54,0.56)	(0.37,0.38,0.38,0.39)	(0.29,0.29,0.30,0.31)	(0.24,0.25,0.26,0.27)	(0.23,0.24,0.24,0.25)	(0.36,0.54,0.60,0.85)	(0.20,0.21,0.21,0.22)	(0.26,0.40,0.47,0.69)	(0.25,0.35,0.38,0.46)	(0.38,0.39,0.39,0.40)	(0.30,0.45,0.52,0.74)	(0.22,0.30,0.33,0.42)

Table 11
Fuzzy efficiency and its defuzzified point of 12 suppliers for each α (w1<w2).

Supplier	$\alpha = 0$		$\alpha = 0.25$		$\alpha = 0.5$		$\alpha = 0.75$		$\alpha = 1$	
	Eff.	Np	Eff.	Np	Eff.	Np	Eff.	Np	Eff.	Np
1	(0.465,0.647,0.661,0.840)	0.65299	(0.464,0.627,0.680,0.810)	0.64515	(0.512,0.527,0.537,0.558)	0.53354	(0.516,0.532,0.543,0.565)	0.5388	(0.530,0.540,0.544,0.555)	0.54214
2	(0.223,0.332,0.400,0.578)	0.3833	(0.243,0.363,0.438,0.635)	0.41992	(0.284,0.389,0.454,0.556)	0.42071	(0.366,0.376,0.380,0.390)	0.37811	(0.368,0.378,0.382,0.392)	0.38004
3	(0.263,0.273,0.282,0.296)	0.27835	(0.263,0.273,0.283,0.299)	0.27947	(0.263,0.273,0.285,0.302)	0.28093	(0.264,0.274,0.288,0.306)	0.28281	(0.285,0.294,0.298,0.308)	0.29629
4	(0.150,0.169,0.186,0.224)	0.18227	(0.157,0.176,0.194,0.233)	0.19003	(0.164,0.183,0.202,0.243)	0.19789	(0.241,0.250,0.254,0.263)	0.25224	(0.242,0.252,0.256,0.265)	0.2535
5	(0.215,0.225,0.229,0.240)	0.22721	(0.215,0.227,0.231,0.242)	0.22884	(0.216,0.229,0.233,0.246)	0.23126	(0.218,0.233,0.237,0.253)	0.23531	(0.227,0.236,0.240,0.249)	0.23803
6	(0.289,0.434,0.521,0.760)	0.50111	(0.312,0.471,0.567,0.829)	0.54475	(0.337,0.498,0.556,0.784)	0.54377	(0.349,0.517,0.578,0.818)	0.56554	(0.362,0.537,0.600,0.851)	0.58777
7	(0.194,0.203,0.206,0.216)	0.20487	(0.195,0.204,0.207,0.217)	0.20571	(0.196,0.205,0.208,0.217)	0.20656	(0.197,0.206,0.209,0.218)	0.2074	(0.198,0.206,0.210,0.219)	0.20824
8	(0.226,0.341,0.400,0.586)	0.38831	(0.235,0.354,0.417,0.611)	0.40424	(0.243,0.368,0.433,0.637)	0.42058	(0.252,0.382,0.451,0.665)	0.43736	(0.261,0.397,0.468,0.692)	0.45458
9	(0.226,0.329,0.387,0.541)	0.37081	(0.251,0.341,0.374,0.456)	0.35562	(0.252,0.342,0.376,0.458)	0.35694	(0.253,0.343,0.377,0.460)	0.35827	(0.254,0.345,0.379,0.461)	0.35959
10	(0.353,0.482,0.545,0.671)	0.51274	(0.375,0.384,0.388,0.397)	0.38605	(0.377,0.386,0.390,0.399)	0.38782	(0.378,0.388,0.392,0.401)	0.38959	(0.380,0.389,0.393,0.403)	0.39136
11	(0.259,0.384,0.444,0.629)	0.42891	(0.268,0.399,0.461,0.656)	0.44606	(0.278,0.414,0.479,0.683)	0.46362	(0.288,0.430,0.498,0.711)	0.4816	(0.298,0.446,0.516,0.740)	0.50002
12	(0.188,0.281,0.329,0.478)	0.31896	(0.196,0.293,0.343,0.501)	0.3333	(0.214,0.294,0.327,0.419)	0.3137	(0.215,0.296,0.329,0.421)	0.31499	(0.215,0.297,0.330,0.423)	0.31627

Table 12
Fuzzy efficiency and its defuzzified point of 12 suppliers for each α (w1>w2).

Supplier	$\alpha = 0$		$\alpha = 0.25$		$\alpha = 0.5$		$\alpha = 0.75$		$\alpha = 1$	
	Eff.	Np	Eff.	Np	Eff.	Np	Eff.	Np	Eff.	Np
1	(0.909,1.015,1.020,1.128)	1.01796	(0.832,1.039,1.085,1.279)	1.05872	(0.754,0.990,1.098,1.375)	1.05431	(0.763,0.983,1.085,1.343)	1.04334	(0.801,0.960,1.034,1.239)	1.00836
2	(0.898,1.022,1.068,1.186)	1.04337	(0.841,1.034,1.082,1.245)	1.05063	(0.630,0.898,1.003,1.423)	0.98833	(0.695,0.937,1.022,1.376)	1.00764	(0.796,0.959,1.032,1.247)	1.00849
3	(0.683,0.864,0.975,1.274)	0.94898	(0.874,1.036,1.077,1.215)	1.05053	(0.740,0.984,1.104,1.460)	1.07191	(0.696,0.956,1.068,1.461)	1.04531	(0.796,0.959,1.033,1.250)	1.00925
4	(0.803,1.015,1.098,1.285)	1.05033	(0.786,1.032,1.123,1.335)	1.0689	(0.835,0.980,1.024,1.146)	0.99634	(0.760,0.968,1.030,1.294)	1.01293	(0.789,0.959,1.023,1.239)	1.00248
5	(0.916,1.071,1.116,1.243)	1.08665	(0.823,0.973,1.019,1.140)	0.98901	(0.708,0.975,1.085,1.399)	1.04211	(0.710,0.973,1.051,1.403)	1.03415	(0.801,0.968,1.031,1.242)	1.01068
6	(0.871,1.070,1.120,1.288)	1.08724	(0.834,1.049,1.094,1.283)	1.06492	(0.852,0.996,1.033,1.156)	1.00933	(0.729,0.952,1.020,1.340)	1.01016	(0.796,0.962,1.030,1.257)	1.01144
7	(0.850,1.015,1.060,1.202)	1.03163	(0.805,1.005,1.055,1.243)	1.02703	(0.740,0.950,1.026,1.293)	1.00216	(0.723,0.952,1.019,1.345)	1.00956	(0.799,0.968,1.028,1.245)	1.01009
8	(0.797,0.966,1.019,1.155)	0.98405	(0.809,0.961,1.031,1.186)	0.99679	(0.837,0.956,0.996,1.103)	0.97288	(0.719,0.952,1.039,1.373)	1.02043	(0.795,0.959,1.028,1.247)	1.00743
9	(0.782,0.975,1.057,1.243)	1.01406	(0.846,1.002,1.044,1.181)	1.0184	(0.634,0.903,0.966,1.327)	0.95737	(0.757,0.950,1.012,1.270)	0.99745	(0.801,0.971,1.029,1.251)	1.01292
10	(0.860,0.970,1.008,1.112)	0.98765	(0.827,0.999,1.059,1.208)	1.02339	(0.731,0.996,1.099,1.407)	1.05799	(0.734,0.963,1.059,1.350)	1.02649	(0.797,0.958,1.032,1.243)	1.00721
11	(0.838,1.069,1.133,1.330)	1.09253	(0.850,1.033,1.079,1.234)	1.04898	(0.755,0.972,1.051,1.361)	1.03502	(0.752,0.953,1.024,1.312)	1.0105	(0.796,0.960,1.025,1.246)	1.00683
12	(0.819,1.099,1.188,1.432)	1.13450	(0.803,0.991,1.046,1.199)	1.00964	(0.842,0.984,1.034,1.163)	1.00563	(0.703,0.925,1.010,1.333)	0.99278	(0.801,0.961,1.034,1.239)	1.00883

Table 13
Fuzzy efficiency and its defuzzified point of 12 suppliers for each α (w1 = w2 = 0.5).

Supplier	$\alpha = 0$		$\alpha = 0.25$		$\alpha = 0.5$		$\alpha = 0.75$		$\alpha = 1$	
	Eff.	Np	Eff.	Np	Eff.	Np	Eff.	Np	Eff.	Np
1	(0.766,0.924,0.979,1.102)	0.94281	(0.741,0.912,0.972,1.105)	0.93257	(0.706,0.869,0.926,1.052)	0.88834	(0.674,0.819,0.870,0.983)	0.83667	(0.802,0.849,0.864,0.904)	0.83667
2	(0.512,0.521,0.525,0.535)	0.52308	(0.513,0.523,0.527,0.537)	0.52499	(0.512,0.523,0.528,0.539)	0.52585	(0.521,0.531,0.535,0.544)	0.53259	(0.758,0.815,0.849,0.916)	0.53259
3	(0.427,0.484,0.487,0.544)	0.48554	(0.439,0.502,0.506,0.570)	0.50402	(0.454,0.527,0.531,0.604)	0.52883	(0.434,0.638,0.676,0.991)	0.68465	(0.505,0.516,0.520,0.531)	0.68465
4	(0.351,0.359,0.363,0.372)	0.36127	(0.356,0.365,0.369,0.378)	0.36722	(0.360,0.369,0.373,0.382)	0.371	(0.367,0.376,0.380,0.389)	0.37804	(0.508,0.663,0.690,0.851)	0.37804
5	(0.299,0.308,0.311,0.320)	0.30946	(0.299,0.308,0.311,0.319)	0.30911	(0.298,0.307,0.310,0.319)	0.30876	(0.298,0.307,0.310,0.319)	0.30841	(0.576,0.673,0.731,0.837)	0.30841
6	(0.747,0.982,1.056,1.266)	1.01269	(0.685,0.917,0.993,1.200)	0.94876	(0.626,0.854,0.932,1.139)	0.88778	(0.473,0.684,0.796,1.066)	0.75476	(0.528,0.725,0.812,0.998)	0.75476
7	(0.268,0.276,0.279,0.288)	0.27785	(0.267,0.276,0.279,0.287)	0.27727	(0.267,0.275,0.278,0.287)	0.27668	(0.266,0.275,0.278,0.286)	0.27609	(0.601,0.795,0.883,1.064)	0.27609
8	(0.574,0.750,0.847,0.993)	0.79099	(0.600,0.726,0.788,0.912)	0.75639	(0.588,0.733,0.803,0.944)	0.767	(0.571,0.749,0.837,1.010)	0.79172	(0.832,0.868,0.872,0.909)	0.79172
9	(0.502,0.511,0.515,0.525)	0.51317	(0.501,0.511,0.514,0.524)	0.51249	(0.501,0.510,0.513,0.523)	0.5118	(0.500,0.509,0.513,0.523)	0.51112	(0.641,0.732,0.786,0.886)	0.51112
10	(0.624,0.634,0.638,0.648)	0.63597	(0.625,0.635,0.639,0.649)	0.63719	(0.626,0.636,0.641,0.651)	0.63842	(0.658,0.668,0.672,0.683)	0.66999	(0.647,0.656,0.661,0.671)	0.66999
11	(0.829,1.059,1.116,1.311)	1.07886	(0.796,1.023,1.079,1.271)	1.04200	(0.679,0.920,0.980,1.183)	0.94054	(0.538,0.811,0.908,1.284)	0.88542	(0.444,0.670,0.750,1.071)	0.88542
12	(0.537,0.619,0.652,0.744)	0.63803	(0.524,0.605,0.639,0.730)	0.62439	(0.511,0.592,0.625,0.716)	0.61087	(0.634,0.719,0.766,0.835)	0.73881	(0.365,0.411,0.433,0.515)	0.73881

Table 14
Ranking order of suppliers for three scenarios.

Supplier	Scenario 1 (w1<w2)					Scenario 2 (w1>w2)					Scenario 3 (w1=w2)				
	α=0	α=0.25	α=0.5	α=0.75	α=1	α=0	α=0.25	α=0.5	α=0.75	α=1	α=0	α=0.25	α=0.5	α=0.75	α=1
1	1	1	2	2	2	8	3	3	2	8	3	3	2	2	2
2	6	4	4	6	6	6	4	10	10	7	7	7	8	8	8
3	9	9	9	9	9	12	5	1	1	5	9	9	7	6	6
4	12	12	12	10	10	5	1	9	6	12	10	10	10	10	10
5	10	10	10	11	11	4	12	4	3	3	11	11	11	11	11
6	3	2	1	1	1	3	2	6	8	2	2	2	3	4	4
7	11	11	11	12	12	7	7	8	9	4	12	12	12	12	12
8	5	5	5	4	4	11	11	11	5	9	4	4	4	3	3
9	7	7	7	7	7	9	9	12	11	1	8	8	9	9	9
10	2	6	6	5	5	10	8	2	4	10	6	5	5	7	7
11	4	3	3	3	3	2	6	5	7	11	1	1	1	1	1
12	8	8	8	8	8	1	10	7	12	6	5	6	6	5	5

three scenarios for different α-levels in which one maximizes the average of the efficiency ratios of the other *n−1* suppliers by finding a multiplier bundle and assuming the constraint that the ratio for the k^{th} supplier remains at its predetermined optimal level. To properly complete the final phase of the framework, we defuzzify the results using the ranking method proposed in Definition 5 of Appendix I as shown in the "Np" columns of Tables 11–13

The ranking order of the suppliers can be obtained for the three different scenarios for all the α levels as given in Table 14.

Phase 4: According to the framework, we classify suppliers in terms of their rankings into three categories using color code analogies as follows:

- Green (rank $\leq$ 4): Preferred suppliers
- Yellow (5 $\leq$ rank $\leq$ 8): Approved suppliers
- Red (9 $\leq$ rank $\leq$ 12): Phase-out suppliers

The result of this classification scheme is shown in Table 14 using the visualization of the color codes to provide better insight to managers and decision-makers for evaluating the suppliers.

7. Conclusions and future research directions

A review of the literature shows that there are many gaps in the theory and application of supplier selection with sustainable sourcing. For example, there are essentially no supplier assessment decision support systems that integrate sustainability criteria with conventional criteria such as price, quality, flexibility, etc. This paper addresses this gap by proposing a four-phase framework for evaluating the performance of a set of potential suppliers by considering various sustainability, operational and organizational criteria in one unified model.

The framework is robust and effective because it develops a broad based approach within which to evaluate suppliers, and at the same time utilizes advanced DEA modeling techniques that enable the decision maker to accurately compare the performance of each supplier. The first phase is based on the traditional Kraljic portfolio segmentation model (Kraljic, 1983). The second phase enhances the segmentation by providing both quantitative and qualitative criteria for each group of suppliers in terms of their operational, organizational and sustainability aspects. The third phase discriminates among the suppliers using advanced frontier analysis, enabled to handle both normal inputs and desirable inputs as well as desirable outputs and undesirable outputs. The model is innovative as it represents a novel general version of cross-efficiency that enables the decision maker to identify his/her aggressive and benevolent level in distinct situations.

Attempts to model sustainability criteria have often been hampered because they are difficult to define and measure due to their inherent vagueness and impreciseness. Using crisp values for the imprecise and subjective information may lead to an over-simplification of the sustainable evaluation problem. Another innovative aspect of our model is that it can evaluate the efficiencies of the suppliers when the input and output data are fuzzy and can handle criteria that are measured either quantitatively or using linguistic variables.

Phase 4 groups suppliers into 3 categories (*preferred, approved* and *phase-out*) based on the performance measures which is a useful classification of suppliers providing insight and information at the sourcing and procurement stages.

Beyond a mere numerical example, our case study of Semicon shows how crucial a formal model can be in the implementation of sustainable sourcing when the measurements are vague and imprecise. The case shows that integrating sustainability considerations with more traditional criteria is a powerful means to increase the competiveness and effectiveness of an industry like semiconductor manufacturing that has a significant social, environmental and economic impact around the world.

There are many ways that this research can be extended. For example, it might be useful to develop a decision support software package that can be used by the decision-makers or managers to aid in the implementation of the model. The program could include a group decision support component whereby the managers interact in a feedback loop to develop the criteria and assign the values to the input and output data. Another extension of the model would be to consider a multi-stage model with trend analysis. This can be particularly practical for applications of sustainability where it is more important for the decision maker to plan the future than to monitor the past.

Another future research direction would be to develop similar models for other types of decisions in which sustainability can play an important role such as long-term strategic decisions such as diversification strategies or new product development. Appropriate case analyses could also provide practical insight into how sustainability considerations could be integrated into the decision making process for these types of applications.

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Appendix I. Fuzzy sets theory

This appendix is composed of some basic definitions of fuzzy sets, fuzzy numbers, and linguistic variables (Zadeh, 1965):

Definition 1. A fuzzy set $\tilde{A}$ in a universe of discourse X is characterized by a membership function $\mu_{\tilde{A}}(x) \rightarrow [0,1]$ which indicates the grade of membership of x in $\tilde{A}$.

Definition 2. The α-cut of a fuzzy set $\tilde{A}$ is a crisp subset of X and is formulated as $\tilde{A}_\alpha = \{X | \mu_{\tilde{A}}(x) \geq \alpha\}$ where $\mu_{\tilde{A}}(x)$ is the membership function of $\tilde{A}$ and α varies within [0,1].

Definition 3. A fuzzy set $\tilde{A}$ is called a *fuzzy number* iff it satisfies the two following properties:

a) Normality: A fuzzy set $\tilde{A}$ is called *normal* iff $\mathrm{Sup}_x \mu_{\tilde{A}}(x)=1$.

b) Convexity: A fuzzy set $\tilde{A}$ is called *convex* if $\mu_{\tilde{A}}\,(\lambda x + (1-\lambda)y) \geq \min\{\mu_{\tilde{A}}(x),\, \mu_{\tilde{A}}(y)\}, \forall\, x, y \in \Re, \forall \lambda \in [0,1]$.

Definition 4. A trapezoidal fuzzy number can be denoted as a quadruplet $\tilde{A} = (a^l, a^{m1}, a^{m2}, a^u)$ where its membership function $\mu_{\tilde{A}}(x)$ is given by:

$$\mu_A{}^{\sim}(x) = \begin{cases} \dfrac{x-a^l}{a^{m1}-a^l}, & a^l \leq x \leq a^{m1}, \\ 1, & a^{m1} \leq x \leq a^{m2}, \\ \dfrac{a^u - x}{a^u - a^{m2}}, & a^{m2} \leq x \leq a^u, \\ 0, & otherwise. \end{cases}$$

The trapezoidal fuzzy number $\tilde{A} = (a^l, a^{m1}, a^{m2}, a^u)$ is transformed into a real number A if $a^l{=}a^{m1}{=}a^{m2}{=}a^u$. On the contrary, a real number a can be transformed into a trapezoidal fuzzy number as (a, a, a, a). Notice that if $a^m = a^{m1}{=}a^{m2}$, then, $\tilde{A} = (a^l, a^m, a^u)$ is called *a triangular fuzzy number*. Without loss of generality, we utilize trapezoidal fuzzy numbers for simplicity and ease of interpretation. The use of other types of fuzzy numbers can be in question since they may increase computational complexity without adding any significant benefit (Wang and Elhag, 2006).

Definition 5. Assuming $\tilde{A} = (a^l, a^{m1}, a^{m2}, a^u)$ is a trapezoidal fuzzy number, the nearest point of $\tilde{A}$ can be calculated as follows (Asady and Zendehnam, 2007):

$$\tilde{A} = \frac{a^{m1}+a^{m2}}{2} + \frac{a^u - a^{m1} - a^{m2} + a^l}{4}.$$

Appendix II. Definition of indicators

Definition of indicators in the operational aspect:

- **OP1.** Quality
  - **OP1.1.** *Business improvement program:* Systematic programs of a firm to analyze and improve existing processes to achieve the goals such as increasing profits and performance, reducing costs and accelerating schedules. These programs include a methodology or strategy to increase the likelihood of successful results such as six sigma, lean manufacturing and just-in-time.
  - **OP1.2.** *Quality management system:* A set of coordinated business processes of a firm to meet quality policy and quality objectives with the aim to continually improve the effectiveness and efficiency of its performance such as ISO 9000, ISO 9001 and ISO 19011.
  - **OP1.3.** *% of customer rejections:* The rejected rate by customers due to different reasons such as unsatisfactory quality.
  - **OP1.4.** *% of products not rejected after inspection:* Percentage of products not rejected after the measurements, tests, and gauges are applied to certain characteristics. The comparison with specified standards is accomplished to examine if the product or activity is in line with the targets.
  - **OP1.5.** *General quality*: The general quality of a product or service is obtained from the market over the long-term.
- **OP2.** Cost
  - **OP2.1.** *Total cost of products:* The total economic cost of production consists of variables costs (such as labor and raw materials) and fixed costs (such as the cost of buildings and machinery).
  - **OP2.2.** *Manufacturing cost:* Manufacturing cost includes costs of all the resources consumed in the process of making a product which is classified into three categories: direct materials cost, direct labor cost and manufacturing overhead.
  - **OP2.3.** *Logistic cost:* Logistic cost includes cost of goods flowing between source and consumers.
  - **OP2.4.** *Ordering cost:* Ordering cost includes all costs associated with preparing a purchase order.
  - **OP2.5.** *Shipment cost:* Shipment cost includes the cost of transporting commodities and merchandise goods and cargo by different modes; sea, land or air.
  - **OP2.6.** *Quantity discount:* Quantity discount includes an incentive offer to a buyer that results in a decreased cost per unit of goods or materials when purchased in greater numbers.
- **OP3.** Financial situation
  - **OP3.1.** *Financial records disclosure:* This indicator is a document that shows all relevant information pertaining to a company that may influence an investment decision.
  - **OP3.2.** *Liquidity ratio:* It is a financial metric that is used to determine a company's ability to pay off its short-term debt obligations. The liquidity ratio is the result of dividing the total cash by short-term borrowings.
  - **OP3.3.** *Asset (debt) ratio*: It is a financial ratio that shows the percentage of a company's assets that are in debt. It is the ratio of total debt to total assets.
- **OP4.** Flexibility
  - **OP4.1.** *Product volume changes*: It is the capability of changing the number of products that are made and sold.
  - **OP4.2.** *Delivery lead time*: This shows the time between the initiation of production of an order and the state of delivery.
  - **OP4.3.** *Set-up time*: It is the time required to prepare a machine, process, or system to function or accept a job.

Definition of indicators in the organizational aspect:

- **OR1.** Relationship
  - **OR1.1.** *Long-term relationship*: It is a relationship that is based upon joint opportunities, mutual trust, respect and open &

honest communication between supplier and buyer. The focus is on reducing supply chain costs and improving the quality of goods and services.

- **OR2.** Technology
  - **OR2.1.** *Launch of new products*: A product launch is a marketing strategy consisting of a planned and scheduled sequence of products with the goal to increase sales as much as possible in a short time span.
  - **OR2.2.** *Use of new technologies*: Use of new technologies that are currently being developed or will be developed over the next five to ten years such as information technology, wireless data communication, man-machine communication, on-demand printing, bio-technologies, and advanced robotics.
- **OR3.** Culture
  - **OR3.1.** *Feeling of trust*: It is the belief in the reliability, truth, ability, or strength of the firm.
  - **OR3.2.** *Strategic fit*: Future growth strategy is in line with the firm's existing strengths and market opportunities.

Definition of indictors in sustainability:

- **SOC.1.** Social
  - **SOC.1.1.** *Discrimination exposure risks*: All conditions of employment must be based on an individual's ability to do the job, not based on personal characteristics or beliefs. There should not be discrimination based on race, color, national origin, gender, sexual orientation, religion, disability, and other similar factors.
  - **SOC.1.2.** *Child labor practice risks*: No person shall be employed at an age younger than the legal minimum age for working in any specific jurisdiction. At no time shall suppliers or their subcontractors employ workers less than 18 years of age.
  - **SOC.1.3.** *Corruption exposure*: Nature, scope, and effectiveness of any program and practices that assess and manage the impacts of operations on communities, including entering, operating, and exiting. Percentage and total number of business units analyzed for risks related to corruption. Percentage of employees trained in an organization's anti-corruption policies and procedures. Monetary value of significant fines and total number of non-monetary sanctions for non-compliance with laws and regulations.
- **ENV.2.** Environment
  - **ENV.2.1.** *Pollution impact*: Average volume of air emission pollutant, waste water, solid wastes and harmful materials releases per day during the measurement period.
  - **ENV.2.2.** *Energy consumption*: This indicates resource consumption in terms of raw material, energy, and water during the measurement period.
  - **ENV.2.3.** *Eco-design requirements for energy using products*: It includes design of products for reduced consumption of material/energy, design of products for reuse, recycle, recovery of material, design of products to avoid or reduce use of hazardous materials.
  - **ENV.2.4.** *Environmental regulatory compliance (ISO 14001)*: It entails environmental certifications such as ISO 14000, environmental policies, planning of environmental objectives, checking and control of environmental activities.
- **ECN.3.** Economic
  - **ECN.3.1.** *Economic performance*: An organization's economic performance as a basis for sustainability addresses the direct economic impacts of the organization's activities such as employee compensation, donations and other community investments, and the economic value added by these activities.
  - **ECN.3.2.** *Local labor premium*: It shows a range of ratios of standard full-time wage offered to an employee in the lowest employment category (except intern or apprentice wages) by gender compared to compensation per hour or other unit of time for employment allowed under law at significant locations of operation. This indicator helps to demonstrate how an organization contributes to the economic well-being of employees in significant locations of operation.
  - **ECN.3.3.** *Indirect economic impacts*: Indirect economic impacts include the additional impacts generated as money circulates through the economy. In other words, indirect economic impacts are the results -sometimes non-monetary– of financial transactions and the flow of money between an organization and its stakeholders.

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