# Evaluation and selection of suppliers considering green perspectives

## Comparative analysis on application of FMLMCDM and fuzzy-TOPSIS

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### Abstract

**Purpose** – The purpose of this paper is to adapt integrated hierarchical evaluation platform (associated with "green" performance indices) toward evaluation and selection of alternative suppliers under green supply chain (GSC) philosophy.

**Design/methodology/approach** – In this context, incompleteness, vagueness, imprecision, as well as inconsistency associated with subjective evaluation information aligned with ill-defined suppliers' assessment indices has been tackled through logical exploration of fuzzy set theory. A fuzzy-based multi-level multi-criteria decision-making (FMLMCDM) approach as proposed by Chu and Varma (2012), has been case empirically studied in the context of green suppliers selection.

**Findings** – Result obtained thereof, has been compared to that of fuzzy-TOPSIS to validate application potential of the aforementioned FMLMCDM approach.

**Originality/value** – The proposed method has been found fruitful from managerial implication viewpoint.

**Keywords** Decision support systems, Supplier evaluation

**Paper type** Research paper

## 1. Introduction

Green supply chain management (GSCM) is basically a systematic and integrated management philosophy for the companies to maintain their sustainability and competitiveness in the recent global market. In GSCM, supplier selection is an important issue for improving a firm's environmental performance. This is because a good supplier helps supply materials that comply with the regulations and further assists in green design, affecting the performance of the entire supply chain (Tsui and Wen, 2012).

Interestingly, there is a gap in research on how an organization can effectively manage supplier development programs with special emphasis on green perspectives. The use of formal models to aid green supplier development management is virtually non-existent (Bai and Sarkis, 2010a). Decision support tools and methodologies can help organizations; especially supply chain managers to make more effective decisions (Bai and Sarkis, 2010b) in relation to green supplier selection problem.

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## 2. State of art

Traditionally, when evaluating supplier performance, companies used to consider factors such as price, quality, flexibility, etc. However, with increased environmental pressures, many companies have begun to consider environmental issues into traditional supply chain construct and the measurement of their suppliers' environmental performance (Humphreys *et al.*, 2003). A performance evaluation system for green suppliers is thus necessary to determine the suitability of suppliers to cooperate with the firm. While the works on the evaluation and/or selection of suppliers are abundant, those that concern environmental issues are rather limited (Lee *et al.*, 2009).

Noci (1997) designed a conceptual approach that identified measures for assessing a supplier's environmental performance and suggested effective techniques for developing the supplier selection procedure according to an environmental viewpoint. Humphreys *et al.* (2003) outlined the development of a knowledge-based system which integrated environmental factors into the supplier selection process. The system employed both case-based reasoning and decision support components including multi-attribute analysis. Tsoulfas and Pappis (2008) proposed a decision model based on environmental performance indicators, which supported decision making in supply chains in presence of environmental considerations. Lee (2008) applied structural equation modeling (SEM) to examine the relationships found in supplier involvement in course of operational life-cycle stages, environmentally friendly practices and environmental performances. Jabbour and Jabbour (2009) examined the extent of exploration of environmental requirements in the supplier selection process in Brazilian companies. This paper analyzed whether there was a relation between the level of environmental management maturity and the inclusion of environmental criteria in the companies' suppliers selection task. Lee *et al.* (2009) proposed a model for evaluating green suppliers. The Delphi method was applied first to differentiate the criteria for evaluating traditional suppliers and green suppliers. A hierarchy was then constructed to evaluate the importance of the selected criteria and the performance of green suppliers. To consider vagueness associated with experts' opinions, the fuzzy extended analytic hierarchy process (AHP) was exploited. Awasthi *et al.* (2010) presented a fuzzy multi-criteria approach for evaluating environmental performance of suppliers. This approach consisted of three steps. The Step 1 involved identification of criteria for assessing environmental performance of suppliers. In Step 2, the experts rated the selected criteria and the various alternatives (suppliers) against each of the criteria. Linguistic assessments were used to rate the criteria and the alternatives. These linguistic ratings were then combined through fuzzy Technique for Order Performance by Similarity to ideal solution (TOPSIS) to generate an overall performance score for each alternative. The alternative with the highest score was chosen as the one with highest environmental performance.

Bai and Sarkis (2010a) explored rough set theory to investigate the relationships between organizational attributes, supplier development program involvement attributes, and performance outcomes. The performance outcomes focussed on environmental and business dimensions. Kuo *et al.* (2010) developed a green supplier selection model which integrated artificial neural network and two multi-attribute decision analysis methods: data envelopment analysis (DEA) and analytic network process (ANP). In another reporting, Bai and Sarkis (2010b) utilized grey system and rough set theory toward integrating sustainability into supplier selection process. Yeh and Chuang (2011) developed an optimum mathematical planning model for green partner selection, which involved four objectives such as cost, time, product quality and green appraisal score. Kuo *et al.* (2011) attempted toward evaluation of green suppliers by applying the fuzzy analytic hierarchy process (FAHP) and the Vlsekriterijumska Optimizacija I Kompromisno Resenje (VIKOR) in a printed circuit board company as a case study. The work evaluated and assessed the performances of three types of green suppliers (the suppliers of processing machine tools, the suppliers of raw materials and the suppliers of maintenance spare parts). The weight of performance indicators was derived by FAHP method, which was fed as inputs to the VIKOR method for evaluating the performance of different types of green suppliers.

Buyukozkan and Cifci (2012) examined GSCM and GSCM capability dimensions and thereby proposed an evaluation framework for green suppliers. The identified components were integrated into a hybrid fuzzy multiple criteria decision-making model combined the fuzzy Decision-Making Trial and Evaluation Laboratory Model (DEMATEL), the analytical network process (ANP), and TOPSIS in a fuzzy context. Tsui and Wen (2012) developed the green supplier selection procedure for the optoelectronics industry. This study proposed an integrated method which combined AHP, Preference Ranking Organization Method for Enrichment Evaluations I and II methods to solve the green supplier selection problem for the TFT-LCD case industry. Peng (2012) proposed a green supplier evaluation model by exploring AHP and grey relational analysis. Amindoust *et al.* (2012) proposed a ranking model based on fuzzy inference system (FIS) toward facilitating sustainable supplier selection. In order to handle the subjectivity of decision makers' (DMs) assessments, fuzzy logic was applied and an effective ranking method on the basis of FIS was proposed for green supplier selection problem. Agarwal and Vijayvargy (2012) presented a methodology to evaluate suppliers using portfolio analysis based on the ANP and environmental factors. This paper discerned various characteristics of the suppliers and also produced recommendations on supplier management for an exemplary case scenario. It also provided insight into the role of intangible factors in decisions related to supply chain. The methodology generated decision rules relating various attributes to the performance outcomes.

Shen *et al.* (2013) proposed a fuzzy multi-criteria approach for green suppliers' evaluation. The authors applied fuzzy set theory (FST) to translate subjective human perceptions into a solid crisp value. These linguistic preferences were combined through fuzzy-TOPSIS to generate an overall performance score for each supplier. Hsu *et al.* (2013) utilized the DEMATEL approach to recognize the influential criteria of carbon management in GSC for improving overall performance of suppliers in terms of carbon management. Kannan *et al.* (2013) presented an integrated approach of fuzzy multi-attribute utility theory and multi-objective programming, for rating and selecting the best green suppliers according to economic and environmental criteria and then allocating the optimum order quantities among them. Lee *et al.* (2013) revealed the existence of a positive and significant linkage between green suppliers with both environmental performance and competitive advantage. The authors conducted a mail survey; empirical data of 119 ISO 14001 manufacturing firms in Malaysia was gathered for this study. SEM technique was applied in this research paper. Environmental performance was shown to positively and significantly affecting competitive advantage; while environmental performance was seemed to play a partial mediating role between greening the supplier and competitiveness. Such significant finding was especially essential for the manufacturing sector registered with ISO 14001 who intended to enhance their environmental performance and carve a niche competitive edge in the business arena. With the consideration of environmental protection, Zhang *et al.* (2013) introduced the importance of "green criteria" in partner selection problem (PSP). Two green criteria, i.e., carbon emission and lead content in manufacturing production, were first brought into PSP. An improved algorithm, named Pareto genetic algorithm for PSP (Pareto-PSGA), was designed for addressing the specific PSP.

Dehghani *et al.* (2013) proposed an approach for supplier selection and allocation taking into accounts the environmental implications. The most important purchase items were identified using ABC analysis. Then, in order to evaluate the performance of suppliers accurately, performance evaluation criteria were identified and screened. Next, using ANP, suppliers were ranked. Finally, orders allocation was done to qualified suppliers through implementing a linear multi-objective programming model. In order to show the applicability of proposed approach, purchasing process of Asia Pishro Diesel Company was studied as a case study. Akman and Pişkin (2013) proposed a model for evaluating green performance of suppliers through a hybrid multi-criteria decision-making model in order to evaluate green performance of the suppliers. The ANP was applied to handle the relationships and dependence of selection criteria and sub-criteria and to determine weights of the criteria. TOPSIS was then used to sequence the suppliers for ideal solution of the suppliers' green performance evaluation problem. Deshmukh and Sunnapwar (2013) carried out factor analysis to help DMs understand the important environmental dimensions. This study also focussed on developing a decision support tool which could help companies to integrate environmental criteria into their green supplier selection process. Shen *et al.* (2013) examined GSCM and proposed a fuzzy multi-criteria approach for green suppliers' evaluation. FST was applied to translate the subjective human perceptions into a solid crisp value. These linguistic preferences were combined through fuzzy-TOPSIS to generate an overall performance score for each supplier. Dou *et al.* (2014) introduced a grey ANP-based model to identify green supplier development programs that would effectively improve suppliers' performance. Yadav and Sharma (2015) applied the DEA approach embedded into AHP methodology for supplier selection process.

Supplier selection is one of the fundamental issues associated in supply chain management as it contributes significantly to overall supply chain performance extent. The right choice of performance metrics and measures is critical to the success and competitiveness of the firms in the era of globalization (Bhagwat and Sharma, 2007). A large and growing body of literature to supplier evaluation and selection exists. In recent years, an increasing environmental awareness has favored the emergence of the new GSC paradigm (Genovese *et al.*, 2013). In GSCM, an organization's environmental performance is mostly affected by its suppliers' environmental performance, and selecting green suppliers is a key strategic consideration in order to be more competitive in today's global market (Kannan *et al.*, 2013). In GSCM decision making, approaches for evaluating green supplier performance must use both qualitative and quantitative environmental data (Govindan *et al.*, 2013). However, such decision making is problematic due to the need of considering tangible and intangible factors both, which cause vagueness, ambiguity and complexity (Yucel and Guneri, 2011). At the same time, the vagueness of the information in this type of problem makes decision making more complicated (Amid *et al.*, 2006; Yang, 2010). Consequently, many researchers realized the application potential of FST as offering an efficient mean of handling this uncertainty effectively and of converting human judgments into meaningful results (Yang, 2010; Yucel and Guneri, 2011; Zadeh, 1965; Amid *et al.*, 2006).

This paper adopts the fuzzy multi-level multi-criteria decision-making (FMLMCDM) approach as proposed by Chu and Varma (2012) in evaluating green suppliers; here, criteria have been considered only qualitative (subjective) in nature. A hierarchical structure has been mathematically explored to depict the multiple levels multiple criteria and computation formulas have been clearly reported. Ratings of suppliers vs qualitative criteria and the importance weights of all the criteria have been assessed through linguistic values represented by fuzzy numbers. However, when there is more than one level in the criteria hierarchy, the multiplication of more than three fuzzy numbers will be encountered. As pointed out by Chu and Velásquez (2009) and Chu and Varma (2012), currently there no such solution is readily available to produce the membership function for the multiplication of more than three fuzzy numbers. The best way to resolve the above limitations may be to defuzzify all the fuzzy numbers before applying them to the suggested model. Thus, a proper defuzzification method is indeed necessary. Chu and Varma (2012) suggested the method of center of area (COA) (Section 3, Equations (2)-(4)) to rank fuzzy numbers due to its simplicity of implementation. The concept of COA defuzzification could be found in Tong (1978) as early as 1978. Motivated by the work by Chu and Varma (2012), herein, formulae for COA in defuzzifying triangular fuzzy numbers (TFNs) have been adapted for the purpose of defuzzifying fuzzy numbers (Figures 1-3, Equations (2)-(4)). Ratings of

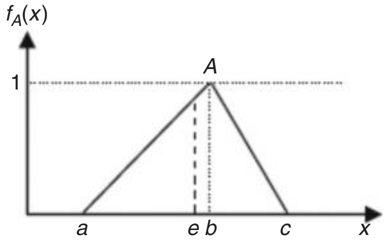


**Figure 1.** Triangular fuzzy number $A$ and its defuzzification value $e$

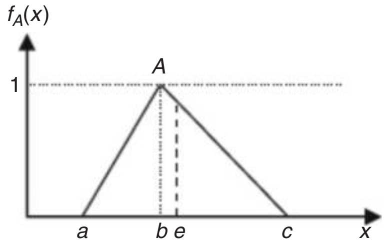


**Figure 2.** Triangular fuzzy number $A$ and its defuzzification value $e$

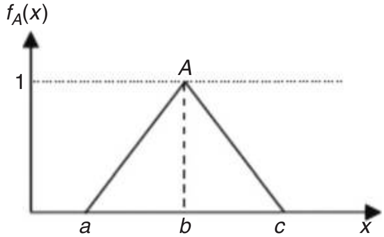


**Figure 3.** Triangular fuzzy number $A$ and its defuzzification value $e$

suppliers vs qualitative criteria and the importance weights of all the criteria have been assessed in linguistic values represented by TFNs. These fuzzy numbers have been defuzzified by the ranking approach of COA before they have been explored to the model. The final evaluation value of each supplier could be obtained by additive weighted ratings based on back propagation from the last to the first level in the hierarchical structure. Decision could then be made based on the evaluation values, the larger the value the better the performance. The ranking order of candidate green suppliers has been compared to that of fuzzy-TOPSIS.

## 3. FST

As computational part of the current work explores a fuzzy-based MLMCDM approach in comparison with fuzzy-TOPSIS; clear understanding on basics of fuzzy numbers set theory, fuzzy mathematics in combination with MLMCDM approach and elements of TOPSIS is indeed required. Hence, the following sections deal with theories of fuzzy sets, definition of fuzzy numbers, linguistic values, defuzzification formula, FMLMCDM model and fuzzy-TOPSIS.

### *3.1 Fuzzy sets*

A fuzzy set $A$ can be denoted by $A = \{(x, f_A(x)) | x \in U\}$, where $U$ is the universe of discourse, $x$ is an element in $U$, $A$ is a fuzzy set in $U$, $f_A(x)$ is the membership function of $A$ at $x$ (Kaufmann and Gupta, 1991). The larger $f_A(x)$, the stronger the grade of membership for $x$ in $A$.

### *3.2 Fuzzy numbers*

A real fuzzy number $A$ is described as any fuzzy subset of the real line $R$ with membership function $f_A$ which possesses the following properties (Dubois and Prade, 1978):

(1) $f_A$ is a continuous mapping from $R$ to [0, 1];

(2) $f_A(x) = 0, \forall x \in (-\infty, a|$;

(3) $f_A$ is strictly increasing on $[a, b]$;

(4) $f_A(x) = 1, x \in [b, c]$;

(5) $f_A$ is strictly deceasing on $[c, d]$; and

(6) $f_A = 0, \forall x \in |d, \infty)$.

Here $a$, $b$, $c$, $d$ are real numbers. We may let $a = -\infty$, or $a = b$, or $b = c$, or $c = d$, or $d = +\infty$.

Unless elsewhere specified, it is assumed that $A$ is convex, normal and bounded, i.e. $-\infty < a, d < \infty$. For convenience, fuzzy number $A$ can be denoted by $A = (a, b, c, d)$. The opposite of $A$ can be given by $-A = (-d, -c, -b, -a;1)x$ (Kaufmann and Gupta, 1991). Fuzzy number $A$ is a TFN, denoted by $(a, b, c)$, if, its membership function $f_A$ is given by van Laarhoven and Pedrycz (1983):

$$f_A(x) = \begin{cases} (x-a)/(b-a), & a \leqslant x \leqslant b, \\ (x-c)/(b-c), & b \leqslant x \leqslant c, \\ 0, & \text{Otherwise.} \end{cases} \tag{1}$$

### *3.3 Linguistic values*

A linguistic variable is a variable whose values are expressed in linguistic terms. Linguistic variable is a very helpful concept for dealing with situations which are too complex or not well-defined to be reasonably described by traditional quantitative expressions (Zadeh, 1975/1976). It is assumed that DMs have fully understood the meanings of these linguistic values and their corresponding fuzzy numbers before they assign these values to criteria.

## 4. Defuzzifying TFNs with COA

The following formulas are developed to defuzzify TFNs based on dividing the area under the membership function in half. The defuzzification formulas for fuzzy number $A$ in Equation (1) by using COA, i.e. $I_L(A)=I_R(A)$, are presented in the following three situations:

(1) If $\overline{ab} > \overline{bc}$ as shown in Figure 1.

Thus, according to Figure 1, $e$ is derived from "$I_L(A)=I_R(A)$" as:

$$e = a + \frac{1}{2}\left[2a^2 - 2ab - 2ac + 2bc\right]^{\frac{1}{2}} \tag{2}$$

(2) If $\overline{ab} < \overline{bc}$ as shown in Figure 2.

Thus, according to Figure 2, $e$ is derived from "$I_L(A)=I_R(A)$" as:

$$e = c - \frac{1}{2}\left[2c^2 + 2ab - 2ac - 2bc\right]^{\frac{1}{2}} \tag{3}$$

(3) If $\overline{ab} = \overline{bc}$ as shown in Figure 3.

According to Figure 3, the defuzzification value $e$ equals to $b$. Thus, $e$ is derived from "$I_L(A)=I_R(A)$" as:

$$e = \frac{1}{2}(a+c) \tag{4}$$

## 5. FMLMCDM approach: model development

### *5.1 Notations*

Some important mathematical notations used in the proposed model are defined as follows:

$D_v$ denotes decision maker $v$, $v=1, \ldots, q$

$A_i$ denotes fuzzy numbers used to evaluate the importance of the importance of the criteria, $i=1, \ldots, n$

$B_i$ denotes fuzzy numbers used to evaluate the suitability of alternatives vs qualitative criteria, $i=1, \ldots, n$

$e(A_i)$ denotes the defuzzified value of $A_i$ through COA

$e(B_i)$ denotes the defuzzified value of $B_i$ through COA

$f_{x_1x_2, \ldots, x_i, \ldots, x_n}$ denotes the $n$ level (general) hierarchy structure to depict the relationship among criteria

$m_{x_1x_2, \ldots, x_{(i-1)}}$ denotes number of sub-criteria for criterion $f_{x_1x_2, \ldots, x_i}$

$w_{x_1x_2, \ldots, x_iv}$ denotes the weight given by the $v$th decision maker to the $x_1x_2, \ldots, x_i^{th}$ criterion, $1 \leqslant v \leqslant q$

$W$ denotes vector

$M$ denotes matrix

$r_{x_1 x_2, \ldots, x_i tv}$ denotes the suitability given by the $v$th decision maker to the $x_1 x_2, \ldots, x_i^{th}$ criterion for alternative $t$

$R_{m_{x_1 x_2, \ldots, x_{(i-1)}} \times p}$ denotes $m_{x_1 x_2, \ldots, x_{(i-1)}} \times p$ matrix of the $m_{x_1 x_2, \ldots, x_{(i-1)}}$ suitability values of sub-criteria of the criterion $f_{x_1 x_2, \ldots, x_{(i-1)}}$ from $p$ alternatives

*5.2 The MLMCDM model*

In this section, the proposed COA defuzzification method is applied to establish a MLMCDM (multiple levels multiple criteria decision making) model under fuzzy environment. Suppose the importance weights of different criteria and the ratings of various alternatives under qualitative criteria in the model are assessed in linguistic terms (Zadeh, 1975/1976) represented by TFNs. Further suppose a set of linguistic terms represented by positive TFNs $A_i, i=1, \ldots, n$, are applied by DMs $D_v, v=1, \ldots, q$, to evaluate the importance of the criteria. Also a set of linguistic terms represented by positive TFNs $B_i$, $i=1, \ldots, n$, are applied by DMs to evaluate the suitability of alternatives vs qualitative criteria. By applying formulas (2)-(4), we obtain the values of COA of these fuzzy numbers as $e(A_i)$ and $e(B_i)$, respectively. The proposed model is developed by the following procedure.

*5.2.1 Establish a multiple-levels hierarchy structure for criteria*. A general hierarchical structure to depict criteria is presented as follows:

$$F_{x_i} = \left\{ f_{x_1 x_2, \ldots, x_i, \ldots, x_n} \right\} \tag{5}$$

For example, $f_{x_1}$ represents the first-level criteria of evaluated alternatives, $f_{x_1 x_2}$ represents second-level criteria of $f_{x_1}$, and the number of the second-level criteria is $m_{x_1}$. Herein, the criteria in the hierarchical structure are assumed to be independent.

*5.2.2 Decide the weights*. When DMs assign weights to criteria, they must understand the meanings of the linguistic weights and their corresponding fuzzy numbers; in other words, we assume that DMs' understanding of the concept of "importance" is in full compliance with the way that weights are used in the model.

The average weights associated with $n$-level hierarchical structure are developed the following equation:

$$w_{x_1 x_2, \ldots, x_i} = \frac{1}{q} \left\{ w_{x_1 x_2, \ldots, x_i 1} + w_{x_1 x_2, \ldots, x_i 2} + \ldots + w_{x_1 x_2, \ldots, x_i v} + \ldots + w_{x_1 x_2, \ldots, x_i q} \right\} \tag{6}$$

Here $w_{x_1 x_2, \ldots, x_i v}$ is a defuzzified TFN from $e(A_i)$. Also $w_{x_1 x_2, \ldots, x_i}$ represents the weight of criterion $f_{x_1 x_2, \ldots, x_i}$.

*5.2.3 Average alternative suitability vs qualitative criteria*. The average suitability of alternative $t$, $t=1, \ldots, p$, vs each subjective criterion associated with $n$-level hierarchy structure is presented as follows:

$$r_{x_1 x_2, \ldots, x_i t} = \frac{1}{q} \left\{ r_{x_1 x_2, \ldots, x_i t1} + r_{x_1 x_2, \ldots, x_i t2} + \ldots + r_{x_1 x_2, \ldots, x_i tv} + \ldots + r_{x_1 x_2, \ldots, x_i tq} \right\} \tag{7}$$

Here $r_{x_1 x_2, \ldots, x_i tv}$ is a defuzzified TFN from $e(B_i)$ and $r_{x_1 x_2, \ldots, x_i t}$ represents the average suitability of alternative $t$ vs criterion $f_{x_1 x_2, \ldots, x_i}$.

*5.2.4 Normalization of alternative suitability vs qualitative criteria*. Values (or suitability) of alternatives vs different quantitative criteria need to be normalized because they have different units. If only benefit (or cost) qualitative criteria are used, normalization can be omitted. In this model, suitability of alternatives vs quantitative criteria can be classified into benefit (B) and cost (C) ones. The normalization of the suitability can be accomplished by applying the following two formulas:

$$r_{x_1x_2,\ldots,x_it} = \frac{S_{x_1x_2,\ldots,x_it}}{max_t\{S_{x_1x_2,\ldots,x_it}\}}, \tag{8}$$

$$r_{x_1x_2,\ldots,x_it} = \frac{min_t\{S_{x_1x_2,\ldots,x_it}\}}{S_{x_1x_2,\ldots,x_it}}. \tag{9}$$

Here $r_{x_1x_2,\ldots,x_it}$ denotes the normalized value of $S_{x_1x_2,\ldots,x_it}$. Also $S_{x_1x_2,\ldots,x_it}$ denotes the suitability value of alternative $t$ vs criterion $f_{x_1x_2,\ldots,x_i}$.

*5.2.5 Synthetic evaluation*. The additive weighted evaluation matrices in the structure can be obtained by using multiplication and addition to aggregate the evaluation matrices and their corresponding weights matrices as follows:

$$\begin{aligned} M_{x_1x_2,\ldots,x_{(i-1)}} &= W_{x_1x_2,\ldots,x_{(i-1)}} \times R_{m_{x_1x_2,\ldots,x_{(i-1)}}\times p} \\ &= \left[\sum_{x_i=1}^{m_{x_1x_2,\ldots,x_{(i-1)}}} w_{x_1x_2,\ldots,x_i}\cdot r_{x_1x_2,\ldots,x_i1} \sum_{x_i=1}^{m_{x_1x_2,\ldots,x_{(i-1)}}} w_{x_1x_2,\ldots,x_i}\cdot r_{x_1x_2,\ldots,x_i2}\cdots \right. \\ &\quad \left. \sum_{x_i=1}^{m_{x_1x_2,\ldots,x_{(i-1)}}} w_{x_1x_2,\ldots,x_i}\cdot r_{x_1x_2,\ldots,x_it}\cdots \sum_{x_i=1}^{m_{x_1x_2,\ldots,x_{(i-1)}}} w_{x_1x_2,\ldots,x_i}\cdot r_{x_1x_2,\ldots,x_ip}\right] \\ &= \left[r_{x_1x_2,\ldots,x_{(i-1)}1} r_{x_1x_2,\ldots,x_{(i-1)}2}\ldots r_{x_1x_2,\ldots,x_{(i-1)}t}\ldots r_{x_1x_2,\ldots,x_{(i-1)}p}\right] \end{aligned} \tag{10}$$

Here $M_{x_1x_2,\ldots,x_{(i-1)}}$ is a $1\times p$ vector with the additive weighted evaluations of the $p$ alternatives over the criteria set $f_{x_1x_2,\ldots,x_i}$, $W_{x_1x_2,\ldots,x_{(i-1)}}$ is the vector of the corresponding criteria weights and $R_{m_{x_1x_2,\ldots,x_{(i-1)}}\times p}$ is a matrix with the suitability of the alternatives on the criteria. $w_{x_1x_2,\ldots,x_{(i-1)}}$ is derived by Equation (6), $t$ represents alternative $t$. $r_{x_1x_2,\ldots,x_it}$ is defined from Equation (7) when $f_{x_1x_2,\ldots,x_i}$ is a qualitative criterion with no sub-criteria, from Equations (8) and (9) when $f_{x_1x_2,\ldots,x_i}$ is a quantitative criterion with no sub-criteria, or from $\sum_{x_{(i+1)}=1}^{m_{x_1x_2,\ldots,x_i}} w_{x_1x_2,\ldots,x_{(i+1)}}\cdot r_{x_1x_2,\ldots,x_{(i+1)}t}$ when $f_{x_1x_2,\ldots,x_i}$ is not further analyzed into lower-level sub-criteria. $\sum_{x_i=1}^{m_{x_1x_2,\ldots,x_{(i-1)}}} w_{x_1x_2,\ldots,x_i}\cdot r_{x_1x_2,\ldots,x_it}$ denotes the additive weighted evaluation value, $r_{x_1x_2,\ldots,x_{(i-1)}t}$, of sub-criterion $f_{x_1x_2,\ldots,x_{(i-1)}}$ of $f_{x_1x_2,\ldots,x_{(i-2)}}$ from alternative $t$, and is the corresponding element of *th*e $x_{(i-1)}$th row and the $t$th column in $R_{m_{x_1x_2,\ldots,x_{(i-2)}}\times p}$. The aggregation at every level of the hierarchy is done similarly to Equation (10).

The final additive weighted evaluation matrix can then be derived by Equation (10) based on the rule of back propagation as follows:

$$M = W \times R_{m\times p} = \left[\sum_{x_1=1}^{m} w_{x_1}\cdot r_{x_1 1} \sum_{x_1=1}^{m} w_{x_1}\cdot r_{x_1 2}\ldots \sum_{x_1=1}^{m} w_{x_1}\cdot r_{x_1 t}\ldots \sum_{x_1=1}^{m} w_{x_1}\cdot r_{x_1 p}\right]$$

$$= \left[r_1 r_2 \ldots r_t \ldots r_p\right] \tag{11}$$

Here $M$ represents the set of final additive weighted evaluation of all the $m$ major criteria from $p$ alternatives, and is the $1\times p$ evaluation matrix. Here $R_{m\times p}$ represents a $m\times p$ matrix. Also $w_{x_1}$ and $r_{x_1 t}$ are the corresponding elements in $W$ and $R_{m\times p}$, respectively. $w_{x_1}$ is derived by Equation (6). Now, $r_{x_1 t}$ is derived from Equation (7) when $f_{x_1}$ is a qualitative criterion with no sub-criteria, from Equations (8) and (9) when $f_{x_1}$ is a quantitative criterion with no sub-criteria, or from $\sum_{x_2=1}^{m_{x_1}} w_{x_1 x_2}\cdot r_{x_1 x_2 t}$ when $f_{x_1}$ is not further analyzed into lower-level sub-criteria. Also $\sum_{x_1=1}^{m} w_{x_1}\cdot r_{x_1 t}$ denotes the final additive weighted evaluation value, $r_t$, of the major criterion $f_{x_1}$ from alternative $t$. The better performance the alternative, the higher the evaluation value; therefore the alternative that has the highest evaluation value should be chosen (Table I).

## 6. Fuzzy-TOPSIS

The procedural steps of fuzzy-TOPSIS using TFNs have been presented below (Ding, 2011; Liao and Kao, 2011; Haldar *et al.*, 2014).

*Step 1*: a fuzzy multi-criteria group decision-making problem can be concisely expressed in matrix format as $\tilde{\mathbf{X}} = \left[\tilde{x}_{ij}\right]_{m\times n}$ with the weight vector $\tilde{\mathbf{W}} = [\tilde{w}_1, \tilde{w}_2, \ldots, \tilde{w}_n]$.

The importance weight of each criterion can be obtained by assigning either directly or indirectly using pairwise comparisons. DMs use the linguistic variables shown in Table III to evaluate the importance of the criteria and the ratings of alternatives with respect to various criteria. Assume that a decision group has $K$ persons, and the importance of the criteria and the ratings of alternatives with respect to each criterion can be calculated as:

$$\tilde{x}_{ij} = \frac{1}{K}\left[\tilde{x}_{ij}^{1}(+)\tilde{x}_{ij}^{2}(+)\ldots(+)\tilde{x}_{ij}^{K}\right] \tag{12}$$

$$\tilde{w}_{j} = \frac{1}{K}\left[\tilde{w}_{j}^{1}(+)\tilde{w}_{j}^{2}(+)\ldots(+)\tilde{w}_{j}^{K}\right] \tag{13}$$

Here $\tilde{x}_{ij}^{K}$ and $\tilde{w}_{j}^{K}$ are, respectively, the aggregated ratings of alternatives and the aggregated ratings of the importance weight of the $k$th decision maker, and (+) indicates the fuzzy arithmetic summation function.

*Step 2*: the normalized decision matrix is formed using Equations (14)-(17). To avoid the complicated normalization formula used in classical TOPSIS, in some papers a linear scale transformation is used to transform the various criteria scales into a comparable scale. Thereby, it is possible to obtain the normalized fuzzy decision matrix

| Goal | 1st-level criteria | 2nd-level criteria | 3rd-level criteria | 4th-level criteria |
|---|---|---|---|---|
| Green supplier evaluation and selection | $f_1$ | $f_{11}$ | $f_{111}$ | $f_{1111}$ |
| | | | | $f_{1112}$ |
| | | | | $f_{1113}$ |
| | | | $f_{112}$ | $f_{1121}$ |
| | | | | $f_{1122}$ |
| | | | | $f_{1123}$ |
| | | | | $f_{1124}$ |
| | | $f_{12}$ | $f_{121}$ | $f_{1211}$ |
| | | | | $f_{1212}$ |
| | | | | $f_{1213}$ |
| | | | | $f_{1214}$ |
| | | | $f_{122}$ | $f_{1221}$ |
| | | | | $f_{1222}$ |
| | | $f_{13}$ | $f_{131}$ | $f_{1311}$ |
| | | | | $f_{1312}$ |
| | | | $f_{132}$ | $f_{1321}$ |
| | $f_2$ | $f_{21}$ | $f_{211}$ | $f_{2111}$ |
| | | | | $f_{2112}$ |
| | | | $f_{212}$ | $f_{2121}$ |
| | | | $f_{213}$ | $f_{2131}$ |
| | | | $f_{214}$ | $f_{2141}$ |
| | | | | $f_{2142}$ |
| | | | $f_{215}$ | $f_{2151}$ |
| | | | | $f_{2152}$ |
| | | | $f_{216}$ | $f_{2161}$ |
| | | | | $f_{2162}$ |
| | | $f_{22}$ | $f_{221}$ | $f_{2211}$ |
| | | | $f_{222}$ | $f_{2221}$ |

**Table I.** The forth-level general hierarchical structure of criteria

denoted by $\tilde{\mathbf{R}}$:

$$\tilde{R} = \left[\tilde{r}_{ij}\right]_{m\times n}$$

Here $B$ and $C$ are the set of benefit criteria and cost criteria, respectively, and:

$$\tilde{r}_{ij} = \left(\frac{a_{ij}}{c_j^*}, \frac{b_{ij}}{c_j^*}, \frac{c_{ij}}{c_j^*}\right), \; j \in B, \tag{14}$$

$$\tilde{r}_{ij} = \left(\frac{a_j^-}{c_{ij}}, \frac{a_j^-}{b_{ij}}, \frac{a_j^-}{a_{ij}}\right), \; j \in C, \tag{15}$$

$$c_j^* = \max_i \; c_{ij}, \; If \; j \in B, \tag{16}$$

$$a_j^- = \min_i \; a_{ij}, \; If \; j \in C. \tag{17}$$

*Step 3*: now the weighted normalized decision matrix is formed using Equations (18)-(19):

$$\tilde{\mathbf{V}} = [\tilde{v}_{ij}]_{m\times n},\ i = 1, 2,\ ...,\ n, \tag{18}$$

$$\tilde{v}_{ij} = \tilde{r}_{ij} \otimes \tilde{w}_{ij} \tag{19}$$

*Step 4*: sorting of the positive ideal solution $A^+$ and the negative ideal solution $A^-$ are determined using Equations (20)-(21):

$$A^+ = (\tilde{v}_1^+, \tilde{v}_2^+,\ ...,\ \tilde{v}_n^+), \tag{20}$$

$$A^- = (\tilde{v}_1^-, \tilde{v}_2^-,\ ...,\ \tilde{v}_n^-). \tag{21}$$

*Step 5*: calculation of the separation measure.

Calculate the distance of each alternative from the positive ideal solution and the negative ideal solution (Equations (23)-(24)). This has been computed according to Dalalah *et al.* (2011), the distance between two TFNs $\tilde{A}_1 = (a_1, b_1, c_1)$ and $\tilde{A}_2 = (a_2, b_2, c_2)$ is calculated using Equation (22), as:

$$d\left(\tilde{A}_1, \tilde{A}_2\right) = \sqrt{\frac{\left[(a_1-a_2)^2 + (b_1-b_2)^2 + (c_1-c_2)^2\right]}{3}} \tag{22}$$

$$d_i^+ = \sum_{j=1}^{k} d\left(\tilde{v}_{ij}, v_j^+\right),\ i = 1, 2,\ ...,\ m \tag{23}$$

$$d_i^- = \sum_{j=1}^{k} d\left(\tilde{v}_{ij}, v_j^-\right),\ i = 1, 2, ...,\ m. \tag{24}$$

*Step 6*: the closeness coefficient ($CC_i$) for each of the supplier alternatives is determined using Equation (25):

$$CC_i = \frac{d_i^-}{d_i^- + d_i^+},\ i = 1, 2,\ ...,\ m. \tag{25}$$

## 7. Case empirical research

In the present reporting, a double-layer hierarchical green supplier evaluation platform has been adapted as depicted in Table II. It has been aimed to evaluate (select) and benchmark suppliers' performance in view of three candidate green suppliers such as $A_1$, $A_2$, $A_3$. The appraisement platform, i.e. multi-level evaluation platforms have been chosen from the knowledge of past literature (Kuo *et al.*, 2010; Yeh and Chuang, 2011) and case empirically studied.

Hereby, the double-layer evaluation index system (Table II) assumed consists of several subjective (qualitative) green supplier evaluation indices as well as sub-indices (at Levels 1 and 2, respectively) which encompasses several beneficial

| 1st-level indices; $C_i$ | 2nd-level indices; $C_{ij}$ | Definitions |
|---|---|---|
| Management competencies, $C_1$ | Senior management support, $C_{11}$ | Goals and objectives of green practices to be supported by the management for implementation |
| | Environment partners, $C_{12}$ | It is the relationship between supplier firm and its collaborative partners associated in green context |
| | Training, $C_{13}$ | It articulates the learning of best practices by employees for handling the specific task |
| | Information exchange, $C_{14}$ | The act of passing information from one firm to another, especially electronically, or a system |
| Green image, $C_2$ | Customer's purchasing retention, $C_{21}$ | To get past customers to purchase again |
| | Green market share, $C_{22}$ | It defines being hike or decline in the share value taking into account green reputation of the firm |
| | Stakeholder's relationship, $C_{23}$ | Stakeholder is the individual/group/organization that responds successfully toward delivery of project |
| Design for environment, $C_3$ | Recycle, $C_{31}$ | It is a reuse of resources in an efficient way for reducing the cost of production and environmental pollution |
| | Reuse, $C_{32}$ | Reuse of an item or goods implies effective recovery of recycled material, energy and toxic emission from both initial material manufacture and manufacturing processes |
| | Remanufacture, $C_{33}$ | A worn out, defective, or discarded product are brought to disassemble stage |
| | Disassembly, $C_{34}$ | The disassembly is a process where individual product is being split up into its associated minor parts from repairment perspectives with negligible environmental impact |
| | Minimal disposal, $C_{35}$ | It is final placement or riddance of wastes, excess, scrap, etc., under proper process and authority with no intention to retrieve |
| Environmental management systems, $C_4$ | Having environmental protection policies of suppliers, $C_{41}$ | It refers to the adherence of green laws, regulations and other policies/mechanisms toward environmental protection |
| | Having environmental protection plans of suppliers, $C_{42}$ | Planning to obey government green rules, legislation, etc., by the supplier firm |
| | Implement and operation, $C_{43}$ | It articulates effective implementation and exploration of operational resources (technology, assesses and man-machine interaction) of supplier firm in green supply chain confine |
| | Passing ISO 14000 verification of suppliers, $C_{44}$ | ISO 14000 is a series of environmental management standards developed in support of organizations green performance. The ISO 14000 standards provide a guideline or framework for organizations that need to systematize and improve their environmental management efforts Passing through the ISO 14000 verification assess the capability of the supplier firm to maintain considerable green performance |

(*continued*)

**Table II.** Green supplier evaluation index system

| 1st-level indices; $C_i$ | 2nd-level indices; $C_{ij}$ | Definitions |
|---|---|---|
| Environmental competencies, $C_5$ | Clean technology availability, $C_{51}$ | It is defined as an elimination of unwanted energy sources and materials from point of origin to point of delivery (end users). Clean technology aligns recycling, renewable energy, information technology, green transportation, green chemistry, energy efficiency technologies, water technologies and green buildings, etc. |
| | Use of environment friendly materials, $C_{52}$ | It expresses the usage of those materials which are environment friendly |
| | Pollution reduction capability, $C_{53}$ | Capability to reduce waste creation and emission of pollutants released to land, air, and water without transferring pollutants from one medium to another |
| | Returns handling capability,$C_{54}$ | Capability of a firm to handle revert (complained/returned) goods/products in green supply chain architecture confine |

**Table II.**

attributes/criteria. Management competencies ($C_1$), "green image" ($C_2$), design for environment ($C_3$), environmental management systems ($C_4$) and environmental competencies ($C_5$) has been considered at the first level of the criteria hierarchy; all are beneficial in nature. Each first-level index is followed a number of subjective sub-indices at second level. The definitions (explanations) of various performance evaluation indices (that exist in double-layer hierarchy criteria) as have also been depicted in Table II.

To facilitate evaluating importance grade (priority importance) of individual evaluation indices as well as appropriateness ratings (performance extent) of subjective evaluation indices at different levels; a committee of five DMs (expert group) such as ($DM_1$, $DM_2$, …, $DM_5$) has been assumed constructed.

In this paper, priority weights against individual evaluation indices and performance extent (appropriateness ratings) against subjective evaluation indices have been obtained through linguistic information as provided by the expert group. Linguistic human judgment has further been transformed into appropriate TFN set. Here, the set of linguistic variables for rating as well as weight assignment against individual performance indices has been expressed by fuzzy numbers (1-5 point scale) as pointed out in Table III. The procedural steps of the entire evaluation as well as appraisement module to support green supplier selection followed by results of case illustration have been summarized as follows.

**Table III.** Set of linguistic variables and corresponding fuzzy representation for assessing rating and priority weight against individual evaluation indices

| Linguistic term (appropriateness rating) | Corresponding fuzzy numbers | Linguistic term (priority weights) | Corresponding fuzzy numbers |
|---|---|---|---|
| Unsatisfactory (U) | (0,0,0.25) | Unimportant (UI) | (0,0.1,0.3) |
| Poor (P) | (0,0.25,0.5) | Slightly important (SI) | (0,0.2,0.5) |
| Medium (M) | (0.25,0.5,0.75) | Fairly important (FI) | (0.3,0.45,0.7) |
| Satisfactory (S) | (0.5,0.75,1) | Important (I) | (0.5,0.7,0.8) |
| Excellent (E) | (0.75,1,1) | Very important (VI) | (0.7,0.9,1) |

*7.1 Case illustration: exploration of FMLMCDM approach*

*7.1.1 Step 1: gathering information from the expert group in relation to performance rating and importance weights of different evaluation indices using linguistic terms*. In order to evaluate priority importance (weight) against individual first- and second-level indices, as well as appropriateness rating against individual second-level indices; a committee of fives DMs, $DM_1$, $DM_2$, $DM_3$, $DM_4$, $DM_5$ has been formed to express their subjective preferences (evaluation score) in linguistic terms which have been further transformed into appropriate TFNs set (1-5 point scale) (Table III). The following linguistic terms: unsatisfactory (U), poor (P), medium (M), satisfactory (S) and excellent (E) have been explored for assessing suitability of performance (rating) against individual second-level indices. Similarly, the linguistic terminology: unimportant (UI), slightly important (SI), fairly important (FI), important (I) and very important (VI) has been used for assigning priority weight of different evaluation indices.

The expert panel assessed the priority importance (weight) against individual second level as well as first-level performance indices and provided expert opinion in linguistic terms as depicted in Tables IV and V, respectively. Also, the appropriateness rating (in linguistic terms) against individual second-level evaluation indices as assigned by the expert panel have been depicted in Tables VI-VIII, for alternative green suppliers $A_1$, $A_2$ and $A_3$, respectively.

*7.1.2 Step 2: approximation of the linguistic evaluation information by TFN set*. Linguistic decision-making information have been transformed into appropriate fuzzy numbers as per Table III. By exploring the concept of TFN in FST, fuzzy average rules (Equations (6)-(7)), aggregated fuzzy priority weight against individual second as well as first-level evaluation indices have been computed (Tables IV-V). Similarly, the aggregated fuzzy appropriateness rating against individual second-level evaluation indices (for preferred candidate alternatives $A_1$, $A_2$ and $A_3$) has been computed as

| | Priority weight (in linguistic term) | | | | | |
|---|---|---|---|---|---|---|
| $C_{ij}$ | $DM_1$ | $DM_2$ | $DM_3$ | $DM_4$ | $DM_5$ | Aggregated fuzzy weight (AFW) |
| $C_{11}$ | I | VI | VI | VI | VI | (0.66,0.86,0.96) |
| $C_{12}$ | VI | I | I | FI | FI | (0.46,0.64,0.80) |
| $C_{13}$ | VI | FI | I | I | I | (0.50,0.69,0.82) |
| $C_{14}$ | VI | FI | VI | I | FI | (0.50,0.68,0.84) |
| $C_{21}$ | I | VI | VI | VI | VI | (0.66,0.86,0.96) |
| $C_{22}$ | I | VI | VI | FI | VI | (0.58,0.77,0.90) |
| $C_{23}$ | VI | VI | FI | FI | VI | (0.54,0.72,0.88) |
| $C_{31}$ | VI | VI | VI | FI | SI | (0.48,0.67,0.84) |
| $C_{32}$ | VI | VI | VI | FI | SI | (0.48,0.67,0.84) |
| $C_{33}$ | VI | VI | VI | I | FI | (0.58,0.77,0.90) |
| $C_{34}$ | VI | I | SI | I | VI | (0.48,0.68,0.82) |
| $C_{35}$ | VI | FI | VI | I | VI | (0.58,0.77,0.90) |
| $C_{41}$ | I | UI | FI | I | FI | (0.32,0.48,0.66) |
| $C_{42}$ | I | UI | FI | I | FI | (0.32,0.48,0.66) |
| $C_{43}$ | I | FI | FI | FI | FI | (0.34,0.50,0.72) |
| $C_{44}$ | I | FI | FI | FI | SI | (0.28,0.45,0.68) |
| $C_{51}$ | I | VI | FI | SI | SI | (0.30,0.49,0.70) |
| $C_{52}$ | I | VI | FI | SI | VI | (0.44,0.63,0.80) |
| $C_{53}$ | I | VI | I | SI | VI | (0.48,0.68,0.82) |
| $C_{54}$ | I | VI | VI | I | VI | (0.62,0.82,0.92) |

**Table IV.** Priority weight (in linguistic term) as provided by DMs and corresponding aggregated fuzzy weight against individual second-level indices depicted in Tables VI-VIII. Finally, aforesaid aggregated fuzzy scores (rating as well as weight) have been transformed in crisp score (defuzzification); results have been finished in Tables IX-XI. By following (Equation (10)), i.e. back propagating fuzzy rule, the appropriateness rating (crisp rating) against individual first-level indices has been computed for preferred candidate alternatives $A_1$, $A_2$ and $A_3$ and revealed in Table XII.

*7.1.3 Step 3: construction of normalized as well as weighted normalized decision-making matrix*. After constructing Table XII (the decision-making matrix), it is essential to normalize criteria values. Equations (8)-(9) have been explored and, finally, normalized rating (Table XIII) has been multiplied with corresponding weights (crisp) against individual first-level indices (Table X) to evaluate the weighted normalized decision-making matrix as depicted in Table XIV.

*7.1.4 Step 4: evaluation and selection of preferred alternative*. After constructing the weighted normalized matrix, the ranking orders of preferred candidate alternatives has been determined by employing Equation (11). The ranking order appears to be $A_3 > A_2 > A_1$ (Table XV).

**Table V.** Priority weight (in linguistic term) as provides by DMs and corresponding aggregated fuzzy weight against individual first-level indices

| | Priority weight (in linguistic term) | | | | | |
|---|---|---|---|---|---|---|
| $C_i$ | $DM_1$ | $DM_2$ | $DM_3$ | $DM_4$ | $DM_5$ | Aggregated fuzzy weight (AFW) |
| $C_1$ | FI | I | I | FI | FI | (0.38,0.55,0.74) |
| $C_2$ | FI | FI | FI | FI | FI | (0.30,0.45,0.70) |
| $C_3$ | FI | VI | VI | SI | FI | (0.54,0.70,0.68) |
| $C_4$ | FI | I | I | I | FI | (0.42,0.60,0.76) |
| $C_5$ | I | I | I | SI | FI | (0.36,0.55,0.72) |

**Table VI.** Appropriateness rating (in linguistic term) as provided by DMs and corresponding aggregated fuzzy rating against individual second-level indices for alternative $A_1$

| | Appropriateness rating (in linguistic term) | | | | | |
|---|---|---|---|---|---|---|
| $C_{ij}$ | $DM_1$ | $DM_2$ | $DM_3$ | $DM_4$ | $DM_5$ | Aggregated fuzzy rating (AFR) |
| $C_{11}$ | M | E | E | E | P | (0.50,0.75,0.85) |
| $C_{12}$ | P | M | U | M | M | (0.15,0.35,0.60) |
| $C_{13}$ | S | M | M | M | P | (0.25,0.50,0.75) |
| $C_{14}$ | S | M | E | M | P | (0.35,0.60,0.80) |
| $C_{21}$ | U | E | M | M | M | (0.30,0.50,0.70) |
| $C_{22}$ | M | E | E | M | U | (0.40,0.60,0.75) |
| $C_{23}$ | M | E | E | U | U | (0.35,0.50,0.65) |
| $C_{31}$ | M | M | E | U | U | (0.25,0.40,0.60) |
| $C_{32}$ | M | M | E | U | M | (0.30,0.50,0.70) |
| $C_{33}$ | M | M | U | M | M | (0.20,0.40,0.65) |
| $C_{34}$ | M | U | P | M | P | (0.10,0.30,0.55) |
| $C_{35}$ | U | M | M | M | P | (0.15,0.35,0.60) |
| $C_{41}$ | U | M | M | M | P | (0.15,0.35,0.60) |
| $C_{42}$ | M | M | M | M | P | (0.20,0.45,0.70) |
| $C_{43}$ | M | M | M | M | M | (0.25,0.50,0.75) |
| $C_{44}$ | M | E | M | U | U | (0.25,0.40,0.60) |
| $C_{51}$ | M | E | P | M | M | (0.30,0.55,0.75) |
| $C_{52}$ | U | E | P | M | M | (0.25,0.45,0.65) |
| $C_{53}$ | M | E | M | U | M | (0.30,0.50,0.70) |
| $C_{54}$ | U | U | P | U | U | (0.00,0.05,0.30) |

| $C_{ij}$ | Appropriateness rating (in linguistic term) DM$_1$ | DM$_2$ | DM$_3$ | DM$_4$ | DM$_5$ | Aggregated fuzzy rating (AFR) |
|---|---|---|---|---|---|---|
| $C_{11}$ | U | E | E | E | E | (0.60,0.80,0.85) |
| $C_{12}$ | E | U | U | M | E | (0.35,0.50,0.65) |
| $C_{13}$ | E | U | M | M | E | (0.40,0.60,0.75) |
| $C_{14}$ | E | M | U | E | E | (0.50,0.70,0.80) |
| $C_{21}$ | M | E | U | E | M | (0.40,0.60,0.75) |
| $C_{22}$ | E | E | E | E | E | (0.75,1.00,1.00) |
| $C_{23}$ | E | E | M | U | E | (0.50,0.70,0.80) |
| $C_{31}$ | E | M | E | U | U | (0.35,0.50,0.65) |
| $C_{32}$ | M | M | E | U | U | (0.25,0.40,0.60) |
| $C_{33}$ | E | U | E | M | M | (0.40,0.60,0.75) |
| $C_{34}$ | M | U | U | E | P | (0.20,0.35,0.55) |
| $C_{35}$ | U | M | M | E | P | (0.25,0.45,0.65) |
| $C_{41}$ | U | U | U | M | P | (0.05,0.15,0.40) |
| $C_{42}$ | M | E | U | U | P | (0.20,0.35,0.55) |
| $C_{43}$ | M | E | M | U | S | (0.35,0.55,0.75) |
| $C_{44}$ | M | U | M | U | S | (0.20,0.35,0.60) |
| $C_{51}$ | M | E | U | M | S | (0.35,0.55,0.75) |
| $C_{52}$ | E | E | U | M | S | (0.45,0.65,0.80) |
| $C_{53}$ | E | E | U | U | U | (0.30,0.40,0.55) |
| $C_{54}$ | E | U | U | M | U | (0.20,0.30,0.50) |

**Table VII.** Appropriateness rating (in linguistic term) as provided by DMs and corresponding aggregated fuzzy rating against individual second-level indices for alternative $A_2$

| $C_{ij}$ | Appropriateness rating (in linguistic term) DM$_1$ | DM$_2$ | DM$_3$ | DM$_4$ | DM$_5$ | Aggregated fuzzy rating (AFR) |
|---|---|---|---|---|---|---|
| $C_{11}$ | S | E | E | E | P | (0.55,0.80,0.90) |
| $C_{12}$ | S | M | U | M | M | (0.25,0.45,0.70) |
| $C_{13}$ | U | M | M | M | M | (0.20,0.40,0.65) |
| $C_{14}$ | S | E | E | E | P | (0.55,0.80,0.90) |
| $C_{21}$ | U | E | M | E | M | (0.40,0.60,0.75) |
| $C_{22}$ | U | E | M | E | E | (0.50,0.70,0.80) |
| $C_{23}$ | M | M | P | M | E | (0.30,0.55,0.75) |
| $C_{31}$ | M | M | S | M | E | (0.40,0.65,0.85) |
| $C_{32}$ | M | P | S | P | M | (0.20,0.45,0.70) |
| $C_{33}$ | E | M | U | S | M | (0.35,0.55,0.75) |
| $C_{34}$ | M | U | P | M | P | (0.10,0.30,0.55) |
| $C_{35}$ | U | M | M | M | P | (0.15,0.35,0.60) |
| $C_{41}$ | U | M | U | S | P | (0.15,0.30,0.55) |
| $C_{42}$ | M | M | M | S | P | (0.25,0.50,0.75) |
| $C_{43}$ | M | M | M | S | S | (0.35,0.60,0.85) |
| $C_{44}$ | M | S | M | U | S | (0.30,0.50,0.75) |
| $C_{51}$ | S | S | E | M | S | (0.50,0.75,0.95) |
| $C_{52}$ | U | E | E | M | S | (0.45,0.65,0.80) |
| $C_{53}$ | S | E | M | U | U | (0.30,0.45,0.65) |
| $C_{54}$ | U | U | M | M | U | (0.10,0.20,0.45) |

**Table VIII.** Appropriateness rating (in linguistic term) as provided by DMs and corresponding aggregated fuzzy rating against individual second-level indices for alternative $A_3$

*7.2 Case illustration: exploration of fuzzy-TOPSIS*

In this phase, fuzzy-TOPSIS has been applied on the same supplier selection problem. The difference between FMLMCDM approach and fuzzy-TOPSIS is that fuzzy-TOPSIS explores a single level (a set of criteria) of evaluation criteria. Thus, data of a multi-level

**Table IX.**
Priority weight (crisp representation) against individual second-level indices

| $C_{ij}$ | Priority weight (crisp representation) |
|---|---|
| $C_{11}$ | 0.83 |
| $C_{12}$ | 0.63 |
| $C_{13}$ | 0.67 |
| $C_{14}$ | 0.67 |
| $C_{21}$ | 0.83 |
| $C_{22}$ | 0.75 |
| $C_{23}$ | 0.71 |
| $C_{31}$ | 0.66 |
| $C_{32}$ | 0.66 |
| $C_{33}$ | 0.75 |
| $C_{34}$ | 0.66 |
| $C_{35}$ | 0.75 |
| $C_{41}$ | 0.49 |
| $C_{42}$ | 0.49 |
| $C_{43}$ | 0.52 |
| $C_{44}$ | 0.47 |
| $C_{51}$ | 0.50 |
| $C_{52}$ | 0.62 |
| $C_{53}$ | 0.66 |
| $C_{54}$ | 0.79 |

**Table X.**
Priority weight (crisp representation) against individual first-level indices

| $C_i$ | Priority weight (crisp representation) |
|---|---|
| $C_1$ | 0.56 |
| $C_2$ | 0.48 |
| $C_3$ | 0.65 |
| $C_4$ | 0.59 |
| $C_5$ | 0.54 |

evaluation hierarchy must be transformed into a single level before applying fuzzy-TOPSIS. This is done by following back propagation method and by exploring fuzzy weightage average rule (Samantra *et al.*, 2013). FMLMCDM explores defuzzified values (of fuzzy numbers) at every step of computation. On the contrary, fuzzy-TOPSIS utilizes fuzzy operational rules. It determines a fuzzy positive ideal and a fuzzy anti-ideal solution. Then based on separation distance of each alternative with respect to fuzzy positive ideal and fuzzy negative ideal solution, a closeness coefficient is determined. Alternatives are then ranked in accordance with their closeness coefficient values. The computational steps of fuzzy-TOPSIS have been described below.

Computed fuzzy multi-criteria group decision-making (FMCGDM) matrix has been furnished in Table XVI. This represents a set of criteria (at first level) $C_1$, $C_2$, $C_3$, $C_4$, $C_5$ and the alternatives $A_1$, $A_2$, $A_3$. This matrix has been obtained by utilizing aggregated fuzzy ratings of individual second-level criterions (and corresponding aggregated fuzzy weights) as shown in Tables IV, VI, VII and VIII for the preferred candidate alternatives. The fuzzy ratings of various first-level criterions have been normalized fist. The normalized decision-making matrix has been multiplied with corresponding priority weight of various first-level criterions

| $C_{ij}$ | Computed rating (crisp representation) $A_1$ | $A_2$ | $A_3$ |
|---|---|---|---|
| $C_{11}$ | 0.71 | 0.76 | 0.76 |
| $C_{12}$ | 0.36 | 0.50 | 0.46 |
| $C_{13}$ | 0.50 | 0.59 | 0.41 |
| $C_{14}$ | 0.59 | 0.67 | 0.76 |
| $C_{21}$ | 0.50 | 0.59 | 0.59 |
| $C_{22}$ | 0.59 | 0.93 | 0.67 |
| $C_{23}$ | 0.50 | 0.67 | 0.54 |
| $C_{31}$ | 0.41 | 0.50 | 0.64 |
| $C_{32}$ | 0.50 | 0.41 | 0.45 |
| $C_{33}$ | 0.41 | 0.59 | 0.55 |
| $C_{34}$ | 0.31 | 0.36 | 0.31 |
| $C_{35}$ | 0.36 | 0.45 | 0.36 |
| $C_{41}$ | 0.36 | 0.19 | 0.33 |
| $C_{42}$ | 0.45 | 0.36 | 0.50 |
| $C_{43}$ | 0.50 | 0.55 | 0.60 |
| $C_{44}$ | 0.41 | 0.38 | 0.51 |
| $C_{51}$ | 0.54 | 0.55 | 0.74 |
| $C_{52}$ | 0.45 | 0.64 | 0.64 |
| $C_{53}$ | 0.50 | 0.41 | 0.46 |
| $C_{54}$ | 0.11 | 0.33 | 0.24 |

**Table XI.** Appropriateness rating (crisp representation) against individual second-level indices for alternative suppliers as $A_1$, $A_2$ and $A_3$

| $C_i$ | Computed rating (crisp representation) $A_1$ | $A_2$ | $A_3$ |
|---|---|---|---|
| $C_1$ | 1.55 | 1.80 | 1.72 |
| $C_2$ | 1.22 | 1.67 | 1.38 |
| $C_3$ | 1.40 | 1.63 | 1.62 |
| $C_4$ | 0.84 | 0.73 | 0.95 |
| $C_5$ | 0.96 | 1.20 | 1.26 |

**Table XII.** Appropriateness rating (crisp representation) against individual first-level indices for alternative suppliers as $A_1$, $A_2$ and $A_3$

| $C_i$ | Normalized decision-making matrix $A_1$ | $A_2$ | $A_3$ |
|---|---|---|---|
| $C_1$ | 0.86 | 1.00 | 0.95 |
| $C_2$ | 0.73 | 1.00 | 0.83 |
| $C_3$ | 0.86 | 1.00 | 0.99 |
| $C_4$ | 0.89 | 0.77 | 1.00 |
| $C_5$ | 0.76 | 0.96 | 1.00 |

**Table XIII.** Computed normalized decision-making matrix

| $C_i$ | Weighted normalized appropriateness rating $A_1$ | $A_2$ | $A_3$ |
|---|---|---|---|
| $C_1$ | 0.48 | 0.55 | 0.53 |
| $C_2$ | 0.35 | 0.48 | 0.39 |
| $C_3$ | 0.55 | 0.65 | 0.64 |
| $C_4$ | 0.53 | 0.46 | 0.59 |
| $C_5$ | 0.42 | 0.52 | 0.55 |

**Table XIV.** The weighted normalized decision-making matrix shown in Table V. Table XVII represents the weighted normalized decision matrix. Fuzzy positive ideal solution ($A^+$) and fuzzy negative ideal solution ($A^-$) has been obtained and presented in Table XVII. Distance (separation measures) of each alternative with respect to ideal as well as negative ideal solution have been obtained and shown in Table XVIII. Based on $d_i^+$ as well as $d_i^-$, the closeness coefficient $CC_i$ ($i=1, 2, 3$) of alternatives $A_1$, $A_2$ and $A_3$ have been determined and shown in Table XVIII. The ranking order of candidate suppliers appear $A_3 > A_2 > A_1$, which appears same as obtained in FMLMCDM approach.

**Table XV.** Evaluation of ranking score and corresponding ranking order of candidate alternatives as $A_1$, $A_2$ and $A_3$

| Alternatives ($A_i$) | Final evaluation score | Ranking order |
|---|---|---|
| $A_1$ | 2.33 | 3 |
| $A_2$ | 2.65 | 2 |
| $A_3$ | 2.71 | 1 |

**Table XVI.** Computed fuzzy multi-criteria group decision-making (FMCGDM) matrix

| | Computed fuzzy rating of individual first-level indices | | | | |
|---|---|---|---|---|---|
| Alternative ($A_i$) | $C_1$ | $C_2$ | $C_3$ | $C_4$ | $C_5$ |
| $A_1$ | (0.20,0.57,1.22) | (0.23,0.53,1.08) | (0.12,0.39,1.03) | (0.10,0.43,1.43) | (0.11,0.36,1.03) |
| $A_2$ | (0.29,0.66,1.24) | (0.35,0.76,1.31) | (0.18,0.46,1.06) | (0.09,0.35,1.25) | (0.18,0.46,1.13) |
| $A_3$ | (0.25,0.63,1.28) | (0.26,0.62,1.18) | (0.15,0.46,1.14) | (0.12,0.48,1.57) | (0.17,0.48,1.22) |

**Table XVII.** Weighted normalized decision matrix and fuzzy positive and negative ideal solutions

| Alternative ($A_i$) | $C_1$ | $C_2$ | $C_3$ | $C_4$ | $C_5$ |
|---|---|---|---|---|---|
| $A_1$ | (0.06,0.24,0.70) | (0.05,0.18,0.58) | (0.06,0.24,0.61) | (0.03,0.16,0.69) | (0.03,0.16,0.61) |
| $A_2$ | (0.09,0.28,0.72) | (0.08,0.26,0.70) | (0.08,0.28,0.63) | (0.03,0.13,0.60) | (0.05,0.21,0.66) |
| $A_3$ | (0.07,0.27,0.74) | (0.06,0.21,0.63) | (0.07,0.28,0.68) | (0.03,0.18,0.76) | (0.05,0.21,0.72) |
| Fuzzy positive ideal solution ($A^+$) | (0.09,0.28,0.74) | (0.08,0.26,0.70) | (0.08,0.28,0.68) | (0.03,0.18,0.76) | (0.05,0.21,0.72) |
| Fuzzy negative ideal solution ($A^-$) | (0.06,0.24,0.70) | (0.05,0.18,0.58) | (0.06,0.24,0.61) | (0.03,0.13,0.60) | (0.03,0.16,0.61) |

**Table XVIII.** Distance (separation measures) $d_i^+$ as well as $d_i^-$ and closeness coefficient $CC_i$ of alternatives $A_1$, $A_2$ and $A_3$

| Alternative ($A_i$) | $d_i^+$ | $d_i^-$ | $CC_i$ | Ranking order |
|---|---|---|---|---|
| $A_1$ | 0.285 | 0.055 | 0.16 | 3 |
| $A_2$ | 0.169 | 0.192 | 0.53 | 2 |
| $A_3$ | 0.072 | 0.277 | 0.79 | 1 |

## 8. Managerial implication

Today's business environment has forced the industries to focus on effective supply chain management in order to gain competitive advantage. With the growing worldwide awareness of environmental protection and the corresponding increase in legislation and regulations, green supplier selection has become an important issue for the companies to gain environmental sustainability. A firm's environmental performance is not only related to the firm's inner environmental efforts, but also it is greatly affected by the suppliers' environmental performance as well as "green image." During recent years, how to determine an appropriate supplier in the GSC has become a key strategic consideration. Apart from objective criteria there exist a number of subjective criteria to be taken under consideration while selecting a potential supplier in GSCM. Subjectivity of evaluation information often invites vagueness and ambiguity in the decision making and hence, exploration of FST may be proved fruitful. However, the choice of an efficient decision support module is of utmost important. To this end present work exhibits application potential of FMLMCDM approach in comparison with fuzzy-TOPSIS. Similar ranking order has been obtained from both FMLMCDM as well as fuzzy-TOPSIS which indicates that both the methods are competent. However, working principles of FMLMCDM differs to that of fuzzy-TOPSIS (Table XIX). Industry management may explore these fuzzy-based decision support modules in suitable circumstances to promote effective supplier selection considering green perspectives.

## 9. Conclusion

Present study highlights application feasibility of fuzzy-based MLMCDM module (in comparison with fuzzy-TOPSIS) toward appraisement and selection of green

| Sl. no. | FMLMCDM | Fuzzy-TOPSIS |
|---|---|---|
| 1. | Works on multi-level multi-criteria model. Each main criterion is divided into sub-criteria; each sub-criterion is divided into sub-sub-criteria and so on | Explores a set of criterions at single level |
| 2. | Can consider both subjective as well as objective data | Proposed approach can consider only subjective (fuzzy) data |
| 3. | Fuzzy appropriateness rating as well as fuzzy priority weight needs to be defuzzified first. Then by layer-wise (higher level to lower level of the criteria hierarchy), a unique supplier selection score is computed | Based on "Fuzzy Weighted Average" rule appropriateness ratings as well as priority weights of sub-criteria (at higher level) are utilized to compute appropriateness rating of a criterion (at higher/preceding level) |
| 4. | The unique supplier selection score is used to rank the alternative suppliers | It computes an ideal solution and anti-ideal solution set. Then separation distances of each alternative with respect to ideal and anti-ideal solution are computed. Finally, a closeness coefficient is computed to rank the alternative suppliers |
| 5. | Fuzzy operational rules are not utilized here. Because, initially all fuzzy data are converted into representative crisp values (defuzzified values). At every stage exploration of defuzzified values may increase chance of error | Fuzzy operational rules are utilized here. Defuzzification of a fuzzy number is not required at all |

**Table XIX.** Difference between two MCDM approaches adapted in this paper: FMLMCDM and fuzzy-TOPSIS suppliers in GSCM. The aforesaid module is capable of working under multi-level integrated criteria hierarchy of green supplier performance appraisement index system. It can further be extended to consider subjective as well as objective performance criterions both. Exploration of FST efficiently overcomes ambiguity as well as vagueness associated with subjective (linguistic) human judgment. Effectiveness of the said fuzzy embedded MLMCDM has been empirically tested in comparison with fuzzy-TOPSIS and illustrated in detail for better understanding of the procedural steps as well as computational part of data analysis.

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