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# Sustainable Supplier Selection in Intuitionistic Fuzzy Environment: A Decision Making Perspective

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# Sustainable Supplier Selection in Intuitionistic Fuzzy Environment: A Decision Making Perspective

**Abstract**

**Purpose -** Supplier selection considering economic, environmental and social sustainability issues has been attempted in this case empirical study.

**Design/methodology/approach –** Subjective human judgment bears some kind of vagueness and ambiguity; fuzzy set theory has immense potential to overcome this. Owing to the advantage of intuitionistic fuzzy numbers set over classical fuzzy numbers set; three decision-making approaches have been applied here in intuitionistic fuzzy setting (viz. intuitionistic-TOPSIS, intuitionistic-MOORA and intuitionistic-GRA) to facilitate supplier selection in sustainable supply chain.

**Findings –** The stated objective of this research "to verify application potential of different decision support systems (in intuitionistic fuzzy setting) in the context of sustainable supplier selection" has been carried out successfully. A case empirical research has been conducted by applying three different decision making approaches: Intuitionistic Fuzzy-TOPSIS (IF-TOPSIS), Intuitionistic Fuzzy-MOORA (IF-MOORA) and Intuitionistic Fuzzy-GRA (IF-GRA) to an empirical data set of sustainable supplier selection problem. The ranking orders thus obtained through exploration of aforesaid three approaches have been explored and compared.

**Originality/value –** As compared to generalized fuzzy numbers, intuitionistic fuzzy numbers exhibit a membership degree, a non-membership degree and the extent of hesitation; a better way to capture inconsistency, incompleteness and imprecision of human judgment. Application potential of aforesaid three decision support approaches has been demonstrated in this reporting for a case sustainable supplier selection.

***Keywords:*** Supplier selection; Sustainability; Intuitionistic-TOPSIS; Intuitionistic-MOORA; Intuitionistic-GRA

## 1. Background

The concept of sustainable supply chain management (SSCM) is to integrate economic and social thinking along with environmental awareness into the traditional supply chain management. The sustainability in supply chain comes into existence right from the product design and development to the material selection, manufacturing, packaging, transportation, warehousing, distribution, consumption, return, and disposal (Linton et al. 2007; Walker et al., 2008; Chu et al., 2009; Büyüközkan and Çifçi, 2011).

Supplier selection is an important assignment in industrial context to attain the preferred level of quality and quantity at the reasonable cost of desired raw/finished material with on-time delivery. Suppliers are the dealers who provide raw materials, components and after sales service that an organization cannot self-give (Kuo et al., 2011). Earlier, in traditional supply chain management, quality, cost, and delivery were considered as common and frequently used criteria for potential supplier selection; whereas, in sustainable supply chain management, economic, social, and environmental sustainability criteria need to be considered simultaneously because they allow an organization to achieve long term economic viability and position sustainability within the broader rubric of supply chain management in sustainability perspective (Carter and Rogers, 2008).

In traditional supply chain construct, social sustainability factors have not been considered yet (i.e. before 2009); however, many authors have included environmental aspects on the traditional supply chain to make it 'green' and to reduce the anti-environmental effects up to a certain limit (Handfield et al., 2002; Humphreys et al., 2003; Lee et al., 2009). Afterwards, the existence of green supply chain and green supplier selection have still been a need of an obligation to incorporate social sustainability factors into the entire process of green supply chain management.

In order to achieve a sustainable supply chain, all of the chain members from suppliers to top managers must have affinity with sustainability (Amindoust et al., 2012). Sustainable development and sustainability are frequently interpreted as a synthesis of economic, environmental and social development well known as a triple-bottom-line approach (Gauthier, 2005). Sustainability has been a major concern for organizations as awareness about environmental degradation, natural resource depletion and climate change has increased considerably. In addition, voices raised by social organizations on various social and environmental issues in developing countries have forced organizations to focus on sustainable manufacturing practices (Mani, 2014). Hence, the study of sustainable supply chain management has gained immense momentum during past two decades. Although the studies focus on three pillars of sustainability viz. economic (profit), environment (planet) and social (people); the social aspect has not been explored much due to the "humanness" and the difficulty in getting tangible outcomes from it (Elkington, 1998; Carter and Easton, 2011; Ashby et al.2012; Mani et al. 2014). Recently, industries have come to know that the evaluation of suppliers must be performed on the basis of sustainable perspectives and hence, a triple bottom line (economic, social, and environmental performance) approach into supplier assessment and selection decisions has been introduced to implants a new set of trade-offs (Dai and Jennifer, 2012). Because of the fast and agile developments in the technology, purchase department has become the fully responsible authority to play this crucial role of selection of potential supplier in all respect. Relevant research in the context of sustainable supply chain could be retrieved from (Bai and Sarkis, 2010; Verdecho et al., 2010; Büyüközkan and Çifçi, 2011; Goebel et al., 2012; Amindoust et al., 2012; Azadnia et al., 2012; Dai and Blackhurst, 2012; Gimenez and Tachizawa, 2012; Molamohamadi et al., 2013; Ghadimi and Heavey, 2014; Chaharsooghi and Ashrafi, 2014; Orji and Wei, 2014;

Mani et al., 2014; Jauhar et al., 2014; Sarkis and Dhavale, 2015; Azadnia et al., 2015; Orji and Wei, 2015).

In supply chain management, supplier selection has long been viewed as a Multi-Criteria Decision Making (MCDM) Problem. In traditional supplier selection, the criteria like cost, quality, delivery requirement and service etc. are generally considered. Today's market demand has enforced supply chain managers towards emphasizing sustainability concepts to be embedded into the supply chain management. Organizations are therefore looking towards 'greening' the supply chain by considering green design, green manufacturing, green packaging & distribution, green delivery etc. Adaptation to Green Supply Chain (GSC) seems to satisfy one of the components to ensure a firm's sustainability. A sustainable supply chain must adhere to the green principles along with business (economic) as well as social criteria. In view of sustainability issues, potential suppliers must be selected by considering economic sustainability, environmental (green) sustainability as well as social sustainability criteria.

In general, supplier selection is a complex decision making task involving objective (quantitative) and subjective (qualitative) evaluation criteria. Quantitative criteria can easily be dealt with traditional decision making tools and techniques. However, decision making information in regards of ill-defined subjective criteria is basically vague. Application of fuzzy set theory has proved its efficacy in dealing with imprecise and vague information in ambiguous decision environment (Zadeh, 1965; Herrera et al., 2005; Guo, 2013; Zimmermann, 1987; Szmidt and Kacprzyk, 1998; 2002; Xu and Yager, 2006; Dengfeng, 1999). Motivated by this, traditional decision making approaches have been extended to operate under fuzzy environment to solve a variety of supplier selection problem. Plenty of literature is readily available highlighting application of classical/conventional fuzzy set theory embedded with different decision making techniques (Bevilacqua et al., 2006; Lin, 2012; Amid et al., 2006; Wang et al., 2009; Chen et al., 2006; Aksoy et al., 2014; Dalalah et al., 2011; Sanayei, et al., 2010; Kannan et al., 2013; Igoulalene et al., 2015; Díaz-Madroñero et al., 2010; Li et al., 2012; Büyüközkan and Çifçi, 2012; Sahu et al., 2014; Sahu et al., 2016). Apart from classical fuzzy set theory, Intuitionistic Fuzzy Sets (IFSs) are being attempted to solve industrial decision making problems due to its advantage over conventional fuzzy sets.

Intuitionistic Fuzzy Set (IFS) introduced by (Atanassov, 1986; 1999; 1989; 1994; 2000) which is a generalization of the concept of Zadeh's fuzzy set and is more suitable to deal with these cases in comparison with fuzzy sets (Guo, 2013). An IFS is characterized by a membership function, a non-membership function, and a hesitation margin (hesitation degree), thus IFS can depict the fuzzy character of data more detail and comprehensively than fuzzy set which is only characterized by a membership function (Zhang and Xu, 2012). The hesitation margin is very useful to express the lack of knowledge and the hesitancy concerning both membership and non-membership of an element to a set (Guo, 2013). Expression of hesitation is particularly helpful for the decision makers. Intuitionistic fuzzy set has proved to be highly useful to deal with uncertainty and vagueness, and it is a very suitable tool to be used to describe the imprecise or uncertain decision information (Guo, 2013). A number of literatures discussed the topic of IFVs theory which was widely used in many decision making fields (Xu and Yager, 2008; Ye, 2013; Liang et al., 2013; Yu, 2013; Guo, 2013; Husain et al., 2012; Boran et al., 2009; De et al., 2000).

The concept of an intuitionistic fuzzy set can be understood as an alternative approach to define a fuzzy set in cases where available information is not sufficient for defining an imprecise concept by means of a conventional/classical fuzzy set. In a generic sense, the theory of intuitionistic fuzzy sets is the generalization of fuzzy sets. Therefore, it is expected that intuitionistic fuzzy sets could effectively be used to simulate human decision making processes and any activities related to human judgment by human expertise and knowledge (Dengfeng, 2003), which are inevitably imprecise or not totally reliable (Husain et al., 2012).

Therefore, it is of great importance to transform hybrid multi-criteria decision matrix into intuitionistic fuzzy decision matrix which is more flexible to handle vagueness or uncertainty and can avoid the loss and distortion of the original decision information (Guo, 2013).

The objective of this research is to verify application potential of different decision support systems (in intuitionistic fuzzy setting) in the context of sustainable supplier selection. A case empirical research has been conducted by applying three different decision making approaches: Intuitionistic Fuzzy-TOPSIS (IF-TOPSIS), Intuitionistic Fuzzy-MOORA (IF-MOORA) and Intuitionistic Fuzzy-GRA (IF-GRA) to an empirical dataset of sustainable supplier selection problem. The ranking orders thus obtained through exploration of aforesaid three approaches have been compared.



## 2. Preliminaries of Intuitionistic Fuzzy Set Theory

IFSs introduced by Atanassov (1986) are extension of the classical FS proposed by (Zadeh, 1965), which is a suitable way to deal with vagueness. Some basic concepts about IFSs have been introduced below.

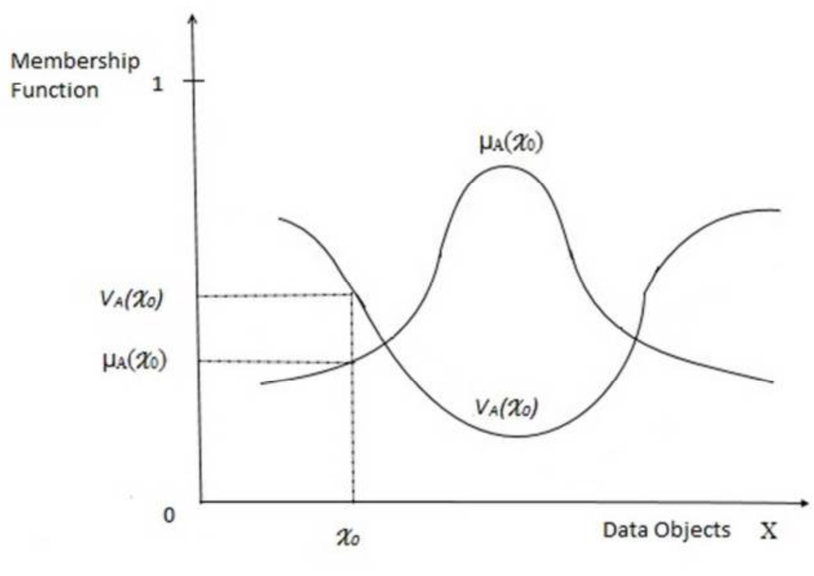


Fig. 1: Membership functions of intuitionistic fuzzy set IFS (Lu and Ng, 2005)
An Intuitionistic Fuzzy Number $[\mu_A(x_0), \nu_A(x_0)]$

IFS $A$ in a finite set $X$ can be written as (Fig. 1):

$$A = \{\langle x, \mu_A(x), \nu_A(x) \rangle | x \in X\},$$

where $\mu_A(x): X \to [0,1]$ and $\nu_A(x): X \to [0,1]$ are membership function and non-membership function, respectively, such that: $0 \le \mu_A(x) + \nu_A(x) \le 1$.

The third parameter of the IFS $A$ is: $\pi_A(x) = 1 - \mu_A(x) - \nu_A(x)$, which is known as the intuitionistic fuzzy index or hesitation degree of whether $x$ belongs to $A$.

It is obviously seen that, for every $x \in X$, $0 \le \pi_A(x) \le 1$.

If the $\pi_A(x)$ is little, then the knowledge about $x$ is more certain; if $\pi_A(x)$ great, then the knowledge about $x$ is more uncertain. Obviously, when $\mu_A(x) = 1 - \nu_A(x)$, for all elements of the universe, the traditional FS concept is recovered (Shu et al., 2006).

Let $A = (\mu_A, \nu_A)$, $B = (\mu_B, \nu_B)$ be two intuitionistic fuzzy numbers, $\lambda > 0$, then (Guo, 2013)

$$A \oplus B = (\mu_A + \mu_B - \mu_A\mu_B, \nu_A\nu_B) \quad (1)$$

$$\lambda A = \left(1 - (1 - \mu_A)^\lambda, \nu_A^\lambda\right) \quad (2)$$

$$A^\lambda = \left(\mu_A^\lambda, 1 - (1 - \nu_A)^\lambda\right) \quad (3)$$

Let $A$ and $B$ are IFSs of the set $X$, then multiplication operator (Atanassov, 1986):

$$A \otimes B = \{\langle x, \mu_A(x).\mu_B(x), \nu_A(x) + \nu_B(x) - \nu_A(x).\nu_B(x) \rangle | x \in X\} \quad (4)$$

Let $A = (\mu_A, \nu_A, \pi_A)$ be an intuitionistic fuzzy number, the defuzzified value of $A$ is obtained as:

$$defuzz(A) = 1 - \frac{1 - \mu_A}{1 - \pi_A} \quad (5)$$

# 4. Methodology

## 4.1 Intuitionistic Fuzzy-TOPSIS

TOPSIS (Technique for Order Preference by Similarity to Ideal Solution) has been presented in (Chen and Hwang, 1992), with reference to (Hwang and Yoon, 1981). The basic principle is that the chosen alternative should have the shortest distance from the positive-ideal solution and the farthest distance from the negative-ideal solution.

TOPSIS has been successfully applied to the areas of human resources management (Chen and Tzeng, 2004), transportation (Janic, 2003), product design (Kwong and Tam, 2002), manufacturing (Milani et al., 2005), water management (Srdjevic et al., 2004), quality control (Yang and Chou, 2005), and location analysis (Yoon and Hwang, 1985). However, decision making problems involving subjective data cannot be analyzed by traditional TOPSIS technique. Therefore, the basic formulations of TOPSIS has been extended to work under fuzzy environment; since fuzzy set theory has the capability in dealing with vague and ambiguous decision information in an efficient way. The fuzzy based TOPSIS approach (TOPSIS in combination with classical fuzzy set theory) and subsequent application could be retrieved in (Chen, 2000; Jahanshahloo et al., 2006; Roghanian et al., 2010).

The information acquired from the literature depicts that, an intuitionistic fuzzy set, which is characterized by a membership function (degree of acceptance), a non-membership function (degree of rejection) and the degree of indeterminacy or the degree of hesitancy, is a more general and suitable way to deal with imprecise information, when compared to a fuzzy set. Therefore, apart from extending traditional TOPSIS by classical fuzzy set theory; application of intuitionistic fuzzy set theory could be more fruitful in this context. Therefore, the following section attempts to apply intuitionistic fuzzy-TOPSIS towards a decision making problem of sustainable supplier selection.

The intuitionistic fuzzy-TOPSIS method, as proposed by (Boran et al., 2009; 2011) has been described below.

**Step 1:** Let $A = \{A_1, A_2, ..., A_m\}$ be a set of alternatives, $W = \{w_1, w_2, ..., w_n\}$ be a set of weights, and $C = \{C_1, C_2, ..., C_n\}$ be a set of criteria. Constitute a group of Decision Makers and determine the importance of each one. Where $\{DM_1, DM_2, ..., DM_K\}$ is the set of decision makers (DMs). The importance of each DM is rated through a linguistic term expressed by intuitionistic fuzzy numbers.

Let $D_k = (\mu_k, \nu_k, \pi_k)$ be an IFN for the rating of the $k^{th}$ decision-maker. Then, the weight of the $k^{th}$ decision maker can be obtained as:

$$\lambda_k = \frac{\left(\mu_k + \pi_k\left(\frac{\mu_k}{\mu_k + \nu_k}\right)\right)}{\sum_{k=1}^{K}\left(\mu_k + \pi_k\left(\frac{\mu_k}{\mu_k + \nu_k}\right)\right)} \tag{6}$$

and $\sum_{k=1}^{K} \lambda_k = 1.$ (7)

**Step 2:** Determine weight of criteria.

Normally, all criteria may not be assumed to be equal importance, and DMs might give different opinions about the same criteria. Hence, all opinions need to be considered and combined into one. Linguistic terms are used to rate the importance of criteria by every DM.

Let $W$ represents a set of grades of importance. To obtain $W$, all the individual decision-maker opinions for the importance of each criterion need to be fused.

Let $w_j^{(k)} = \left(\mu_j^{(k)}, \nu_j^{(k)}, \pi_j^{(k)}\right)$ be an IFN assigned to criterion $C_j$ by the $k^{th}$ decision-maker. Then, the weights of the criteria are calculated by using IFWA (Xu, 2007d).

$$w_j = IFWA_\lambda\left(w_j^{(1)}, w_j^{(2)}, ..., w_j^{(K)}\right)$$

$$= \lambda_1 w_j^{(1)} \oplus \lambda_2 w_j^{(2)} \oplus ... \oplus \lambda_K w_j^{(K)}$$

$$= \left[ 1 - \prod_{k=1}^{K} \left(1 - \mu_j^{(k)}\right)^{\lambda_k}, \prod_{k=1}^{K} \left(\nu_j^{(k)}\right)^{\lambda_k}, \prod_{k=1}^{K} \left(1 - \mu_j^{(k)}\right)^{\lambda_k} - \prod_{k=1}^{K} \left(\nu_j^{(k)}\right)^{\lambda_k} \right] \quad (8)$$

$$W = \left[w_1, w_2, ..., w_j, ..., w_n\right]$$

Here $w_j = \left(\mu_j, \nu_j, \pi_j\right)\left(j = 1,2,...,n\right)$.

**Step 3:** Construct an aggregated intuitionistic fuzzy decision matrix based on the decision-makers' opinions.

Let $R^{(k)} = \left(r_{ij}^{(k)}\right)_{m \times n}$ be an intuitionistic fuzzy decision matrix of decision makers. $\lambda = \left(\lambda_1, \lambda_2, ..., \lambda_K\right)^T$ is a weight set of decision-maker, and $\lambda_k \in [0,1]$. In the group decision making process, all the individual decisions need to be fused into group opinion to construct an aggregated intuitionistic fuzzy decision matrix. To do that, IFWA operator is used.

$$R = \left(r_{ij}\right)_{m \times n},$$

where $r_{ij} = IFWA_\lambda\left(r_{ij}^{(1)}, r_{ij}^{(2)}, ..., r_{ij}^{(K)}\right)$

$$= \lambda_1 r_{ij}^{(1)} \oplus \lambda_2 r_{ij}^{(2)} \oplus ... \oplus \lambda_K r_{ij}^{(K)}$$

$$= \left[ 1 - \prod_{k=1}^{K} \left(1 - \mu_{ij}^{(k)}\right)^{\lambda_k}, \prod_{k=1}^{K} \left(\nu_{ij}^{(k)}\right)^{\lambda_k}, \prod_{k=1}^{K} \left(1 - \mu_{ij}^{(k)}\right)^{\lambda_k} - \prod_{k=1}^{K} \left(\nu_{ij}^{(k)}\right)^{\lambda_k} \right] \quad (9)$$

The aggregated intuitionistic fuzzy decision matrix is defined as follows:

$$R = \begin{bmatrix} \left(\mu_{11}, \nu_{11}, \pi_{11}\right) & \left(\mu_{12}, \nu_{12}, \pi_{12}\right) & \cdots & \left(\mu_{1n}, \nu_{1n}, \pi_{1n}\right) \\ \left(\mu_{21}, \nu_{21}, \pi_{21}\right) & \left(\mu_{22}, \nu_{22}, \pi_{22}\right) & \cdots & \left(\mu_{2n}, \nu_{2n}, \pi_{2n}\right) \\ \vdots & \vdots & \ddots & \vdots \\ \left(\mu_{m1}, \nu_{m1}, \pi_{m1}\right) & \left(\mu_{m2}, \nu_{m2}, \pi_{m2}\right) & \cdots & \left(\mu_{mn}, \nu_{mn}, \pi_{mn}\right) \end{bmatrix}$$

$$= \begin{bmatrix} r_{11} & r_{12} & \cdots & r_{1n} \\ r_{21} & r_{22} & \cdots & r_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ r_{m1} & r_{m2} & \cdots & r_{mn} \end{bmatrix}$$

Here, $r_{ij} = (\mu_{ij}, \nu_{ij}, \pi_{ij})(i = 1,2,...,m; j = 1,2,...,n)$ is an element of an aggregated intuitionistic fuzzy decision matrix.

**Step 4:** Construct an aggregated weighted intuitionistic fuzzy decision matrix.

After the weight of criteria and the ratings of alternatives are determined, the aggregated weighted intuitionistic fuzzy decision matrix is constructed.

$R$ and $W$ are two IFSs of the set $X$. According to the following definition (Atanassov, 1986):

$$R' = R \otimes W = (\mu'_{ij}, \nu'_{ij}) = \{\langle x, \mu_{ij}\mu_j, \nu_{ij} + \nu_j - \nu_{ij}.\nu_j \rangle\} \text{ and} \quad (10)$$

$$\pi'_{ij} = 1 - \nu_{ij} - \nu_j - \mu_{ij}\mu_j + \nu_{ij}\nu_j. \quad (11)$$

Then, the aggregated weighted intuitionistic fuzzy decision matrix can be defined as follows:

$$R' = \begin{bmatrix} (\mu'_{11}, \nu'_{11}, \pi'_{11}) & (\mu'_{12}, \nu'_{12}, \pi'_{12}) & \cdots & (\mu'_{1n}, \nu'_{1n}, \pi'_{1n}) \\ (\mu'_{21}, \nu'_{21}, \pi'_{21}) & (\mu'_{22}, \nu'_{22}, \pi'_{22}) & \cdots & (\mu'_{2n}, \nu'_{2n}, \pi'_{2n}) \\ \vdots & \vdots & \ddots & \vdots \\ (\mu'_{m1}, \nu'_{m1}, \pi'_{m1}) & (\mu'_{m2}, \nu'_{m2}, \pi'_{m2}) & \cdots & (\mu'_{mn}, \nu'_{mn}, \pi'_{mn}) \end{bmatrix}$$

$$= \begin{bmatrix} r'_{11} & r'_{12} & \cdots & r'_{1n} \\ r'_{21} & r'_{22} & \cdots & r'_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ r'_{m1} & r'_{m2} & \cdots & r'_{mn} \end{bmatrix}$$

Here, $r'_{ij} = (\mu'_{ij}, \nu'_{ij}, \pi'_{ij})(i = 1,2,...,m; j = 1,2,...,n)$ is an element of the aggregated weighted intuitionistic fuzzy decision matrix.

**Step 5:** Obtain the intuitionistic fuzzy positive ideal solution and the intuitionistic fuzzy negative ideal solution.

Let $J_B$ and $J_C$ be benefit criteria and cost criteria, respectively. $A^*$ is the intuitionistic fuzzy positive ideal solution, and $A^-$ is the intuitionistic fuzzy negative ideal solution. Then, $A^*$ and $A^-$ are obtained as:

$$A^* = (r_1'^*, r_2'^*, ..., r_n'^*), \quad (12)$$

$$r_j'^* = \left(\mu_j'^*, \nu_j'^*, \pi_j'^*\right), \; j = 1,2,\ldots,n \text{ and} \tag{13}$$

$$A^- = \left(r_1'^-, r_2'^-, \ldots, r_n'^-\right), \tag{14}$$

$$r_j'^- = \left(\mu_j'^-, \nu_j'^-, \pi_j'^-\right), \; j = 1,2,\ldots,n \text{ and} \tag{15}$$

where

$$\mu_j'^* = \left\{\left(\max_i \{\mu_{ij}'\} \middle| j \in J_B\right), \left(\min_i \{\mu_{ij}'\} \middle| j \in J_C\right)\right\}, \tag{16}$$

$$\nu_j'^* = \left\{\left(\min_i \{\nu_{ij}'\} \middle| j \in J_B\right), \left(\max_i \{\nu_{ij}'\} \middle| j \in J_C\right)\right\}, \tag{17}$$

$$\pi_j'^* = \left\{\left(1 - \max_i \{\mu_{ij}'\} - \min_i \{\nu_{ij}'\} \middle| j \in J_B\right), \left(1 - \min_i \{\mu_{ij}'\} - \max_i \{\nu_{ij}'\} \middle| j \in J_C\right)\right\}, \tag{18}$$

$$\mu_j'^- = \left\{\left(\min_i \{\mu_{ij}'\} \middle| j \in J_B\right), \left(\max_i \{\mu_{ij}'\} \middle| j \in J_C\right)\right\}, \tag{19}$$

$$\nu_j'^- = \left\{\left(\max_i \{\nu_{ij}'\} \middle| j \in J_B\right), \left(\min_i \{\nu_{ij}'\} \middle| j \in J_C\right)\right\}, \tag{20}$$

$$\pi_j'^- = \left\{\left(1 - \min_i \{\mu_{ij}'\} - \max_i \{\nu_{ij}'\} \middle| j \in J_B\right), \left(1 - \max_i \{\mu_{ij}'\} - \min_i \{\nu_{ij}'\} \middle| j \in J_C\right)\right\}. \tag{21}$$

**Step 6:** Calculate the separation measures.

To measure the separation between alternatives on IFS, the distance measures proposed by (Atanassov, 1999) and (Szmidt and Kacprzyk, 2000), including the generalizations of Hamming distance, Euclidean distance, and their normalized distance measures, can be used. After selecting the distance measure, the separation measures, $S_i^*$ and $S_i^-$, of each alternative from intuitionistic fuzzy positive-ideal and negative-ideal solutions are calculated. In this article the Hamming distance concept has been explored.

$$S_i^* = \frac{1}{2}\sum_{j=1}^{n}\left[\left|\mu_{ij}' - \mu_j'^*\right| + \left|\nu_{ij}' - \nu_j'^*\right| + \left|\pi_{ij}' - \pi_j'^*\right|\right] \tag{22}$$

$$S_i^- = \frac{1}{2}\sum_{j=1}^{n}\left[\left|\mu'_{ij} - \mu'^-_j\right| + \left|\nu'_{ij} - \nu'^-_j\right| + \left|\pi'_{ij} - \pi'^-_j\right|\right] \tag{23}$$

**Step 7:** Calculate the relative closeness coefficient to the intuitionistic ideal solution.

The relative closeness coefficient of each alternative $A_i$ with respect to the intuitionistic fuzzy positive-ideal solution $A^*$ is defined as follows:

$$CC_i^* = \frac{S_i^-}{S_i^* + S_i^-}, \text{where } 0 \le CC_i^* \le 1. \tag{24}$$

**Step 8:** Rank the alternatives:

After the relative closeness is determined, alternatives are ranked according to descending order of $CC_i^*$ values.

## 4.2 Intuitionistic Fuzzy-MOORA

The Multi-Objective Optimization by Ratio Analysis (MOORA) was introduced by (Brauers and Zavadskas, 2006). Initially, MOORA comprised two different approaches: (i) Ratio System and, (ii) The Reference Point Approach. Subsequently, these authors further developed the method (Brauers and Zavadskas, 2010) thus presenting the MULTIMOORA (MOORA plus the Full Multiplicative Form). Traditional MOORA was established to solve decision making problems considering crisp data. Applications of crisp-MOORA could be found in (Karande and Chakraborty, 2012; Kildiene, 2013; Görener et al., 2013; Chakraborty, 2011; Gadakh et al., 2013; Brauers et al., 2008; Brauers and Zavadskas, 2009). In order to take care of subjectivity of the decision information; later traditional MOORA was extended with generalized fuzzy number and generalized interval-valued fuzzy numbers set theory. The methodological descriptions of fuzzy-MULTIMOORA could be reviewed from (Baležentis and Zeng, 2013; Stanujkic, 2013; Baležentis et al., 2012; Liu et al., 2014). In the following section, owing to the advantages of intuitionistic fuzzy sets over classical fuzzy sets; MOORA coupled with intuitionistic fuzzy set theory has been delineated to solve a particular decision making problem within scope of the current research. The intuitionistic fuzzy-MOORA applied herein consists of two parts: (i) The Ratio System Approach, adapted from the work by (Pérez-Domínguez, et al., 2015), and, (ii) The Reference Point Approach that has been newly proposed in this paper.

**Ratio System Approach**

(Step 1 to Step 4) remain the same as described in Section 4.1.

**Step 5:** Compute the sum of costs and benefits. In this step, the benefit $(J_B)$ and cost $(J_C)$ criteria are identified. In this sense, the benefit criteria are those where maximum values are desired. On the other hand, cost criteria are where minimum values are preferred.

Thus, Eq. (25) represents the sum of benefit criteria

$$J_B|A_i = \sum_{j=1}^{g}(\mu'_{ij}, v'_{ij}, \pi'_{ij}) \quad (25)$$

Here, $J_B|A_i$ are the sum of the benefit criteria for alternative $A_i\,(i=1,2,...,m)(j=1,2,...,g)$.

Then the following Eq. (26) defines the sum of the cost criteria.

$$J_C|A_i = \sum_{j=g+1}^{n}(\mu'_{ij}, v'_{ij}, \pi'_{ij}) \quad (26)$$

Here, $J_C|A_i$ represents the sum of the cost criteria for alternative $A_i\,(i=1,2,...,m)(j=g+1,g+2,...,n)$

**Step 6:** Defuzzification of the sum of benefits and costs. In this step, $J_B|A_i$ and $J_C|A_i$ are defuzzified using Eq. (5) as proposed by (Zhang and Xu, 2012).

**Step 7:** Compute the contribution of each alternative $N|A_i$. Calculate the contribution of each alternative $N|A_i$ with Eq. (27).

$$N|A_i = defuzz(J_B|A_i) - defuzz(J_C|A_i) \quad (27)$$

The $N|A_i$ value can be positive or negative depending on the sum of beneficial criteria and cost criteria in the decision matrix. An ordinal ranking of $N|A_i$ shows the final contribution of each alternative. Thus, the best alternative has the highest $N|A_i$ value, whilst the worst alternative has the lowest $N|A_i$ value.

**Step 8:** Rank the alternatives. Alternatives are sorted according to descending order of $N|A_i$.

**Reference Point Approach**

(Step 1 to Step 4) remain the same as described in Section 4.1.

**Step 5:** The Maximal Objective Reference Point (vector) $r$ is found according to the Eq. (28). The $j^{th}$ coordinate of the reference point resembles the maximum or minimum of the $j^{th}$ criterion $r_j$.

$$r_j = \left(\mu_j^r, \nu_j^r, \pi_j^r\right), \; (j = 1,2,\ldots,n) \tag{28}$$

$$\mu_j^r = \left\{\left(\max_i \{\mu'_{ij}\} \middle| j \in J_B\right), \left(\min_i \{\mu'_{ij}\} \middle| j \in J_C\right)\right\}, \tag{29}$$

$$\nu_j^r = \left\{\left(\min_i \{\nu'_{ij}\} \middle| j \in J_B\right), \left(\max_i \{\nu'_{ij}\} \middle| j \in J_C\right)\right\}, \tag{30}$$

$$\pi_j^r = \left\{\left(1 - \max_i \{\mu'_{ij}\} - \min_i \{\nu'_{ij}\} \middle| j \in J_B\right), \left(1 - \min_i \{\mu'_{ij}\} - \max_i \{\nu'_{ij}\} \middle| j \in J_C\right)\right\}, \tag{31}$$

**Step 6:** Then every element of weighted normalized responses matrix is recalculated and final rank is given according to deviation from the reference point and the Min-Max Metric of Tchebycheff (Eq. 32):

$$\min_i \left(\max_j d\left(r_j, r'_{ij}\right)\right) \tag{32}$$

Here $d\left(r_j, r'_{ij}\right) = \frac{1}{2}\left[\left|\mu_j^r - \mu'_{ij}\right| + \left|\nu_j^r - \nu'_{ij}\right| + \left|\pi_j^r - \pi'_{ij}\right|\right]$ is the Hamming distance between $r_j$ and $r'_{ij}$.

### 4.3 Intuitionistic Fuzzy-GRA

Grey relational analysis method was originally developed by (Deng, 1989) and was widely used in many multiple attribute decision making problems. The method is suitable for solving problems with complicated interrelationships between multiple factors and variables (Wei, 2010; 2011; Kuo and Liang, 2011; Guo, 2013). It is very helpful to solve the uncertainty problems under the discrete data and incomplete information (Deng, 1988; 1989; 2002; Liu et al., 1999; Liu and Lin, 1998; Dang et al., 2004; Zhang et al., 2005; Wei, 2006). Traditional GRA can be applied in decision making situations that consider real data. To cope up with imprecision and incompleteness arising from human judgment in regards of vague (ill-defined) evaluation criteria; traditional GRA has been extended to work under fuzzy environment.

Apart from GRA extended with classical fuzzy set theory, intuitionistic fuzzy-GRA has also been reported in literature. Hou (2010) investigated the problem of intuitionistic fuzzy-GRA with completely known (crisp) attribute weight information. Guo (2013) also explored intuitionistic fuzzy-GRA in which attribute weights were computed by entropy method. In this reporting, intuitionistic fuzzy-GRA has also been attempted; attributes weights have been acquired through multiple-judge in terms of linguistic variables. Linguistic weights have been translated into appropriate intuitionistic fuzzy numbers. By applying IFWA operator, decision-makers' pulled opinion has been combined to obtain aggregated intuitionistic fuzzy weight against each of the evaluation criteria. These have been defuzzified again and explored in course of computing overall grey relational grade; based on which suppliers ranking has been done.

The following section describes methodological basis of intuitionistic fuzzy-GRA to be applied in a supplier selection problem considering sustainability attributes.

(Step 1 to Step 3) remain the same as described in Section 4.1.

**Step 4:** Determine crisp weight of individual evaluation criteria.

Referring to (Eq. 8), aggregated intuitionistic fuzzy weight of individual criterion is to be defuzzified by using (Eq. 5) to obtain corresponding crisp scores. These need to be normalized again so that sum of individual criteria weights equals to 1. Normalized crisp weights of the criteria are utilized in computing grey relation grade for each of the candidate alternatives.

**Step 5:** Determine the referential sequence based on intuitionistic fuzzy numbers.

$$r^{+} = \left(\left(\mu_1^{+}, \nu_1^{+}\right), \left(\mu_2^{+}, \nu_2^{+}\right), \ldots, \left(\mu_n^{+}, \nu_n^{+}\right)\right) \tag{33}$$

$$r_j^{+} = \left(\mu_j^{+}, \nu_j^{+}\right) = \left(\max_i \mu_{ij}, \min_i \nu_{ij}\right)\ j = 1,2,\ldots,n;\ j \in J_B$$

Otherwise,

$$r_j^{+} = \left(\mu_j^{+}, \nu_j^{+}\right) = \left(\min_i \mu_{ij}, \max_i \nu_{ij}\right)\ j = 1,2,\ldots,n;\ j \in J_C$$

**Step 6:** Calculate the grey relational coefficient of each alternative from referential sequence using the following equation:

$$\xi_{ij}^{+} = \frac{\min\limits_{1\le i\le m}\min\limits_{1\le j\le n} d\left(r_{ij}, r_j^{+}\right) + \rho \max\limits_{1\le i\le m}\max\limits_{1\le j\le n} d\left(r_{ij}, r_j^{+}\right)}{d\left(r_{ij}, r_j^{+}\right) + \rho \max\limits_{1\le i\le m}\max\limits_{1\le j\le n} d\left(r_{ij}, r_j^{+}\right)}, i = 1,2,\ldots,m;\ j = 1,2,\ldots,n. \tag{34}$$

Here the identification coefficient $\rho = 0.5$. The symbol $\rho$ represents the equation's 'contrast control', sometimes also be referred to as the 'environmental coefficient' or the 'distinguishing coefficient'. This coefficient is a free parameter. Its value, over a broad appropriate range of values, does not affect the ordering of the grey relational grade values, but a good value of the contrast control is needed for clear identification of key system factors (Pramanik and Mukhopadhyaya, 2011). For the end points 0 and 1, i.e. for $\rho = 1$, the comparison environment is unaltered and for $\rho = 0$, the comparison environment disappears.

In cases, where data variation is large, $\rho$ usually ranges from 0.1 to 0.5 for reducing the extremely large $\max_{1\le i\le m}\max_{1\le j\le n} d\left(r_{ij}, r_j^+\right)$. In general $\rho$ is set as 0.5.

**Step 7:** Calculate the grey relational grade of each alternative from the reference sequence using the following equation.

$$\xi_i^+ = \sum_{j=1}^{n} w_{jC}^N.\xi_{ij}^+, i = 1,2,...,m. \tag{35}$$

Also, $\sum_{j=1}^{n} w_{jC}^N = 1$. Here $w_j^N$ is the normalized crisp weight of $j^{th}$ criterion.

**Step 8:** Rank the alternatives $A_i\left(i = 1,2,...,m\right)$ and select the best one in accordance with $\xi_i^+\left(i = 1,2,...,m\right)$. If any alternative has the highest $\xi_i^+$ value, then, it is the most important alternative.

## 5. Case Empirical Illustration

A case empirical illustration has been provided herein to exhibit application potential of TOPSIS, MOORA and Grey Relation Analysis (GRA) in intuitionistic fuzzy setting. A supplier selection problem considering sustainability criteria has been solved in intuitionistic fuzzy environment. Based on extensive literature review on supplier selection, a criteria list has been constructed (Table 1.1) in view of three sustainability dimensions: Economic, Social and Environmental. The following criteria: Price ($C_1$), On time delivery ($C_2$), Service and relationship ($C_3$), Flexibility ($C_4$), Quality ($C_5$), Financial capability ($C_6$), Production facilities ($C_7$), Organization ($C_8$) have been considered under economic; Rights of Stakeholders ($C_9$), Work safety ($C_{10}$), Information disclosure ($C_{11}$), Respect for policy ($C_{12}$) have been considered under social; Recycling ($C_{13}$), Waste electrical equipments ($C_{14}$), Ozone depleting chemicals ($C_{15}$), Green R&D ($C_{16}$), Green design ($C_{17}$), Environmental management system ($C_{18}$), Environmental competencies ($C_{19}$), Innovation ($C_{20}$), Resource consumption ($C_{21}$), Green product ($C_{22}$), Pollution control ($C_{23}$) have been considered under environmental dimension of sustainability. The definitions of aforesaid sustainability criteria have been provided in Table 1.2.

In this work, aforesaid evaluation criteria have been assessed in terms of subjective judgment of a group of Decision-Makers (DMs). DMs have been instructed to express their opinion in regards of priority weight of the criteria and appropriateness (rating) of alternatives with respect to different criteria. In this decision making, the importance of the DMs has been expressed by means of decision-maker's weight. Since decision group consists of a number of DMs from different background. DMs may be from the members of top managerial body of the company; they may be academician, management consultant etc. They possess experience in a varied degree in different areas. Hence, it is customary to assign appropriate weight against individual DMs. DMs' personal opinions in combination of DMs' weights need to be clubbed in computing the aggregated decision making data. The following linguistic terms set: Beginner (B), Practitioner (Pr), Proficient (Pt), Expert (E) and Master (M) has been selected to assign weight (importance) of the decision-makers. In order to express priority weight of individual sustainability criteria, the following linguistic terms set: Very Unimportant (VU), Unimportant (U), Medium (M), Important (I), and Very Important (VI) has been explored. Appropriateness ratings of criteria have been evaluated by means of the linguistic terms set: Extremely Bad (EB), Very Bad (VB), Bad (B), Medium Bad (MB), Fair (F), Medium Good (MG), Good (G), Very Good (VG) and Excellent (E). Aforesaid linguistic variables and corresponding intuitionistic fuzzy numbers representations have been depicted in Tables 2-3.

The empirical case study on sustainable supplier selection comprises of five supplier alternatives ($A_1$, $A_2$, $A_3$, $A_4$, and $A_5$), each to be evaluated in view of twenty three criteria ($C_1$ to $C_{23}$) selected adhering to three sustainability dimensions viz. economic, social and environmental. It has been assumed that four decision-makers (DM1, DM2, DM3 and DM4) have taken part in the context of decision making. The importance (weight) of decision-makers has been shown in Table 4 with corresponding intuitionistic fuzzy as well as crisp representation to be utilized in course of data analysis. DMs have been instructed to assign priority weight against individual sustainability criteria by using the linguistic terms set as given in Table 2. Apart from assigning subjective criteria weight, DMs have also been requested to rate the alternative suppliers ($A_1$, $A_2$, $A_3$, $A_4$, and $A_5$, respectively) with respect to given sustainability criteria in accordance with the linguistic terminologies as provided in Table 3. Priority weights of criteria as well as appropriateness ratings of alternative suppliers with respect to the criteria, expressed in linguistic terms, have further been transformed into appropriate intuitionistic fuzzy numbers as per Tables 2-3, respectively. Intuitionistic fuzzy decision making data have been analyzed further through three decision making approaches in intuitionistic fuzzy setting viz. intuitionistic-TOSIS, intuitionistic-MOORA and intuitionistic-GRA to select the best supplier from sustainability viewpoint from amongst a set of candidate suppliers. The stepwise computations and results obtained thereof have been described in detail below.

### 5.1 Results of IF-TOPSIS

In course of IF-TOPSIS, aggregated criteria weights $w_j$ have been computed by using (Eq. 8) and depicted in Table 5. In this computation decision-makers' weight $\lambda_k$ has been utilized. The weights of the decision-makers have been computed using (Eq. 6) as tabulated in Table 4. The crisp weight set for the decision-making group has been computed as $\lambda_1 = 0.3483$, $\lambda_2 = 0.3055$, $\lambda_3 = 0.2037$, and $\lambda_4 = 0.1426$.

Intuitionistic fuzzy decision matrix has been constructed next (Table 6). Aggregated intuitionistic fuzzy ratings of alternative suppliers with respect to evaluation criteria have been obtained by exploring (Eq. 9). Aggregated intuitionistic fuzzy rating of criterion has been multiplied with aggregated intuitionistic fuzzy weigh of criteria (Eq.10), and thus intuitionistic weighted fuzzy decision matrix has been obtained. Then the intuitionistic fuzzy positive ideal solution $A^*$ and the intuitionistic fuzzy negative ideal solution $A^-$ have been obtained using (Eqs. 12-21). Next, Hamming distances for supplier alternatives with respect to the positive ideal solution as well as negative ideal solution have been obtained for each of the candidate supplier alternatives with respect to individual evaluation criteria. Separation measures $S_i^+$ and $S_i^-$ for each alternatives with respect to positive ideal as well as negative ideal solution, respectively, have been computed using (Eqs. 22-23) for alternative suppliers and furnished in Table 7. Finally, the relative closeness coefficient $CC_i$ to the intuitionistic fuzzy positive ideal solution has been determined using (Eq. 24) for individual suppliers and shown in Table 7. Based on the relative closeness coefficient $CC_i$ suppliers have been ranked. The ranking order of candidate supplier alternatives thus obtained in exploring IF-TOPSIS appears as $A_5>A_4>A_2>A_1>A_3$.

### 5.2 Results of IF-MOORA

Intuitionistic fuzzy MOORA applied herein consists of two parts: (i) *Ratio System Approach* and (ii) *Reference Point Approach*. In Ratio System Approach, utilizing data from intuitionistic fuzzy weighted decision matrix, the sum of all benefit criteria $J_B|A_i$ has been computed by using (Eq. 1 and Eq. 25) for each of the alternative suppliers and tabulated in Table 8. Here, all sustainability criteria have been assumed beneficial in nature; and accordingly, linguistic variables and corresponding intuitionistic fuzzy representations for assessing appropriateness of criteria have been selected as per Table 3. The value of $J_B|A_i$ being an intuitionistic fuzzy number has to be defuzzified (Eq. 5) to obtain $N|A_i$ and thus to determine suppliers ranking order. The values of $N|A_i$ i.e. $defuzz(J_B|A_i)$ for individual supplier alternatives have been given in Table 8. The ranking order of candidate suppliers thus obtained as: $A_5>A_4>A_2>A_1>A_3$.

In Reference Point Approach of intuitionistic fuzzy-MOORA, the intuitionistic fuzzy reference point $r_j$ has been determined by using (Eqs. 28-31) and furnished in Table 9. (It is to be noted that the intuitionistic fuzzy reference point $r_j$ is nothing but the intuitionistic fuzzy ideal solution $A^*$ considered in IF-TOPSIS). Next, Hamming distance of each alternative with respect to the reference point $d(r_j, r'_{ij})$ have been computed. The ranking order of supplier alternatives thus obtained based on $\min_i(\max_j d(r_j, r'_{ij}))$ appears as: $A_5>A_4>A_2>A_1>A_3$ (Table 9) same as in case of Ratio System Approach.

### 5.3 Results of IF-GRA

In course of intuitionistic-GRA, aggregated intuitionistic fuzzy criteria weights $w_j$ (referring to Table 11) have been defuzzified using (Eq. 5) to obtained crisp-weight $w_{jC}$. These have further been normalized to obtain normalized weight $w_{jC}^N$ so as to satisfy the condition $\sum_{j=1}^{n} w_{jC}^N = 1$, prerequisite of GRA. Computed crisp-weight $w_{jC}$ and corresponding normalized weight $w_{jC}^N$ of criteria have been given in Table 5. In intuitionistic fuzzy-GRA, the data in relation to the aggregated intuitionistic fuzzy ratings $(r_{ij})$ of supplier alternatives with respect to criteria (i.e. intuitionistic fuzzy decision matrix as given in Table 6) have been utilized to obtain referential sequence $r_j^+$ obtained by using Eq. 33. Table 10 exhibits computation results of $d(r_{ij}, r_j^+)$ for individual supplier alternatives and corresponding values of $\max_{1\le j\le n} d(r_{ij}, r_j^+)$ and $\min_{1\le j\le n} d(r_{ij}, r_j^+)$ to be explored next in computing grey relation coefficient $\xi_{ij}^+$

of individual supplier alternatives. The grey relational coefficient $\xi_{ij}^{+}$ of each alternative from referential sequence has been computed using (Eq. 34). Table 11 shows the grey relational grade $\xi_{i}^{+}$ of each alternative from the reference sequence obtained using (Eq. 35); based on which suppliers have been ranked. The preference order of candidate supplier alternatives thus obtained in intuitionistic fuzzy-GRA has been obtained as: $A_5>A_4>A_2>A_1>A_3$. It has been observed that ranking order of candidate suppliers appears the same for IF-TOPSIS, IF-MOORA as well as IF-GRA.



**6. Managerial Implication**

In today's competitive global marketplace, organizations are focusing on sustainability issues onto the supply chain management. In many countries, due to implementation of strict government regulations and increased citizen consciousness, manufacturing units are enforced to look after sustainability issues in every segment of supply chain activities. Literature supports that sustainability in supply chain management is a combined effort in integrating social and economic factors along with the environmental issues. In supply chain management, appropriate supplier selection is a vital decision making task greatly affecting overall performance of the organization. As the emphasis on sustainability issues got increased drastically in last two decades, this sort of selection has become more complex; organizations are expecting potential partner/ supplier who can boost up sustainability onto their collective work. Plenty of decision making tools and techniques have been attempted in past literature assisting purchase managers in regards of sustainable supplier selection; application of fuzzy based decision support tools have proved its effectiveness specially in vague and ambiguous decision environment. In classical fuzzy set theory, fuzzy numbers are represented by a membership function; whereas, in intuitionistic fuzzy set theory, an intuitionistic fuzzy number is characterized by a true-membership function, a falsemembership function and a hesitation region, to better cope up the imperfection of subjective human judgment as compared to fuzzy numbers in classical fuzzy set. In order to validate application potential of decision making tools in intuitionistic fuzzy environment onto a supplier selection case study incorporating sustainability dimensions; the work attempts intuitionistic-TOPSIS, intuitionistic-MOORA and intuitionistic-GRA, respectively. Similar ranking order of candidate suppliers as obtained in aforesaid three decision making approaches proves consistency of these methods. Purchasing managers are advised to adopt methodological pathways delineated herein for effective supplier selection in sustainability perspectives. The intuitionistic fuzzy based decision making approaches reported here may be fruitfully applied in a variety of decision making problems in industrial contest. Purchasing managers may be encouraged to conduct such a group decision making by considering subjective evaluation criteria in intuitionistic fuzzy domain to overcome real world decision making problems. The decision-making group i.e. the experts need to be judiciously chosen to take part in such decision making. Weights of the decision-makers need to be assigned properly prior to analyze decision-makers' judgments.



**7. Conclusion**

The contributions of aforesaid research have been summarized below.

1. Adaptation to a list of criteria from sustainability perspective to facilitate supplier selection. Sustainability encompasses of economic, social as well as environmental sustainably. The selection criteria on the basis of three sustainability dimensions have been accumulated through literature review and these have been utilized for effective decision making.

2. Owning to the advantages of intuitionistic fuzzy set over generalized fuzzy set, application potential of intuitionistic-TOPSIS, intuitionistic-MOORA and intuitionistic-GRA have been

attempted to a sustainable supplier selection problem. The similar ranking order of candidate suppliers thus obtained supports consistency of aforesaid three decision support tools in intuitionistic fuzzy setting. A variety of decision support tools based on the concept of intuitionistic fuzzy numbers set theory could be well articulated from existing literature; however, application of these decision support tools in the context of sustainable supplier selection has rarely been addressed.

3. The specialty of the decision support tools attempted in the present work is that these tools consider importance (weight) of the decision-makers. In most of the decision making approaches, weights the decision-makers are assumed equal; means their opinions are equally important.

4. Apart from applying Ratio System part of intuitionistic-MOORA, which is readily available in existing literature, the current research extends intuitionistic-MOORA by introducing Reference Point Approach. The formulations of Reference Point Approach in intuitionistic fuzzy setting have been developed herein. It has been observed that both Ratio System Approach and Reference Point Approach provide similar ranking order of candidate suppliers.

5. In formulations of intuitionistic-GRA as retrieved from existing literature, criteria weights are expressed in terms of crisp (real) numbers. However, it is well understood that it is difficult to assign priority weights against subjective criteria in terms of exact values. This unrealistic assumption can be avoided if criteria weights are given in a subjective way rather than objective. Hence, in this study, criteria weights have been assigned by the decision-makers in terms of linguistic variables. Linguistic criteria weights have been transformed into appropriate intuitionistic fuzzy numbers. By utilizing IFWA operator, individual decision-maker's judgments have been combined to compute the aggregated intuitionistic criteria weight. Aggregated intuitionistic criteria weights have been directly utilized in intuitionistic-

TOPSIS and intuitionistic-MOORA along with aggregated intuitionistic fuzzy rating of criteria. But, in case of intuitionistic-GRA it is prerequisite that the sum of criteria weights must be equal to unity. To satisfy this condition, aggregated intuitionistic criteria weights have been defuzzified first. Defuzzified (crisp) criteria weights have further been normalized to compute normalized criteria weight. Normalized criteria weights have been utilized to compute grey relational grade of individual supplier alternatives.

The limitations of aforesaid research have been pointed out below.

1. The work has introduced a conceptual illustrative example i.e. an empirical case study, rather than a real world application. Validity and accuracy of these decision making modules need to be investigated.

2. Another concern is the operational feasibility of these methodologies. The availability of the decision making information and the fuzzified data needed for the application of these methodologies seems to be one of the possible barriers to this operational feasibility. Over time, supply chain managers should be encouraged to gather this type of data by conducing discussions and survey pursued by the selected decision-making group, not only for application of these methodologies, but also for undertaking important managerial decisions for their organization.

3. The study applies intuitionistic-MOORA to solve a sustainable supplier selection problem. Apart from applying Ratio System part of MOORA, this paper develops the formulation of Reference Point Approach of MOORA in intuitionistic fuzzy environment. However, traditional MOORA has further been extended and renamed as MULTIMOORA since it includes Full Multiplicative Form in addition to Ratio System part and Reference Point approach. Therefore, methodological steps (formulations) for applying Full Multiplicative Form in intuitionistic fuzzy setting could be attempted in future. However, it has been observed that in Full Multiplicative Form of MULTIMOORA, division operator between two

intuitionistic fuzzy numbers needs to be exploited. Because, in case of Full Multiplicative Form, the ranking index is determined in terms of the ratio between sums of all benefit criteria and sum of all adverse criteria. The division operator and how it works for two intuitionistic fuzzy numbers has not been reported yet in the available literature resource. Therefore, difficulty still exists in formulating Full Multiplicative Form of MULTIMOORA in intuitionistic fuzzy setting.

4. This study explores three decision support modules viz. TOPSIS, MOORA and GRA extended with intuitionistic fuzzy numbers set. These approaches may be attempted to operate under interval-valued intuitionistic fuzzy environment. Apart from using intuitionistic fuzzy set theory, vague numbers set theory can also be utilized to aid the said decision making.

5. The ranking order of alternative suppliers as obtained through IF-TOPSIS, IF-MOORA and IF-GRA has been compared to that of fuzzy-TOPSIS i.e. TOPSIS extended with classical/conventional fuzzy set (trapezoidal fuzzy numbers). It has been observed that similar ranking order has been obtained both in conventional fuzzy setting and intuitionistic fuzzy setting. This may be due to the fact that we have considered same linguistic scale (for determining decision-makers' weights, criteria weights, and ratings of alternatives with respect to criteria); the only difference is that in intuitionistic fuzzy decision making approaches, linguistic decision making data have been translated into intuitionistic fuzzy numbers; whereas, in classical fuzzy-TOPSIS, linguistic data have been transformed into appropriate generalized trapezoidal fuzzy numbers. In both the cases, fuzzy representation corresponding to the selected linguistic variables has been decided as an increasing order of membership grade. Hence, it is realized that the superiority of exploring intuitionistic fuzzy numbers set over conventional fuzzy numbers set is theoretically established so far; but it may be difficult to prove mathematically. Existing literature also remains silent in this aspect.

Future study may take care of aforesaid aspects. Moreover, the proposed approach may be compared with existing decision making modules already available in literature.

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Table 1.1: Sustainability attributes relevant to supplier selection

| Sustainability dimensions | Sustainability criteria | Citations |
|---|---|---|
| Economic | Price, $C_1$ | Kuo et al., 2010; Keskin et al., 2010; Yeh and Chuang, 2010; Zhu et al., 2010; Orji and Wei, 2014; Bai and Sarkis, 2010; Büyüközkan and Çifçi, 2011; Amindoust et al., 2012; Azadnia et al., 2012; Dai and Blackhurst, 2012; Ghadimi and Heavey, 2014 |
| | On time delivery, $C_2$ | Kuo et al., 2010; Tseng and Chiu, 2010; Yeh and Chuang, 2010; Zhu et al., 2010; Orji and Wei, 2014; Bai and Sarkis, 2010; Amindoust et al., 2012; Azadnia et al., 2012; Dai and Blackhurst, 2012; Ghadimi and Heavey, 2014 |
| | Service and relationship, $C_3$ | Kuo et al., 2010; Tseng and Chiu, 2010; Weber and Current, 1993; Chang et al., 2011; Zhu et al., 2010; Orji and Wei, 2014; Bai and Sarkis, 2010; Amindoust et al., 2012 |
| | Flexibility, $C_4$ | Tseng and Chiu, 2010; Zhu et al., 2010; Orji and Wei, 2014; Bai and Sarkis, 2010; Büyüközkan and Çifçi, 2011; Amindoust et al., 2012 |
| | Quality, $C_5$ | Kuo et al., 2010; Tseng and Chiu, 2010; Chang et al., 2011; Lee et al., 2009; Zhu et al., 2010; Orji and Wei, 2014; Büyüközkan and Çifçi, 2011; Amindoust et al., 2012; Azadnia et al., 2012; Ghadimi and Heavey, 2014 |
| | Financial capability, $C_6$ | Keskin et al., 2010; Orji and Wei, 2014; Büyüközkan and Çifçi, 2011; Amindoust et al., 2012 |
| | Production facilities, $C_7$ | Keskin et al., 2010; Orji and Wei, 2014; Büyüközkan and Çifçi, 2011; Amindoust et al., 2012 |
| | Organization, $C_8$ | Tseng and Chiu, 2010; Zhu et al., 2010; Orji and Wei, 2014; Amindoust et al., 2012 |
| Social | Rights of Stakeholders, $C_9$ | Kuo et al., 2010; Orji and Wei, 2014; Bai and Sarkis, 2010; Amindoust et al., 2012; Azadnia et al., 2012 |
| | Work safety, $C_{10}$ | Keskin et al., 2010; Orji and Wei, 2014; Bai and Sarkis, 2010; Amindoust et al., 2012; Azadnia et al., 2012; Dai and Blackhurst, 2012; Ghadimi and Heavey, 2014 |

| | | |
|---|---|---|
| | Information disclosure, $C_{11}$ | Kuo et al., 2010; Orji and Wei, 2014; Amindoust et al., 2012 |
| | Respect for policy, $C_{12}$ | Kuo et al., 2010; Orji and Wei, 2014; Amindoust et al., 2012 |
| Environmental | Recycling, $C_{13}$ | Yeh and Chuang, 2011; Orji and Wei, 2014; Amindoust et al., 2012 |
| | Waste electrical equipments, $C_{14}$ | Kuo et al., 2010; Orji and Wei, 2014; Amindoust et al., 2012 |
| | Ozone depleting chemicals, $C_{15}$ | Kuo et al., 2010; Orji and Wei, 2014; Amindoust et al., 2012 |
| | Green R&D, $C_{16}$ | Tseng and Chiu, 2010; Awasthi et al., 2010; Orji and Wei, 2014; Amindoust et al., 2012 |
| | Green design, $C_{17}$ | Tseng and Chiu, 2010; Yeh and Chuang, 2010; Awasthi et al., 2010; Humphreys et al., 2003; Orji and Wei, 2014; Amindoust et al., 2012 |
| | Environmental management system, $C_{18}$ | Kuo et al., 2010; Tseng and Chiu, 2010; Yeh and Chuang, 2010; Awasthi et al., 2010; Humphreys et al., 2003; Hsu et al., 2013; Lee et al., 2009; Zhu et al., 2010; Bai and Sarkis, 2009; Orji and Wei, 2014; Bai and Sarkis, 2010; Amindoust et al., 2012; Azadnia et al., 2012 |
| | Environmental competencies, $C_{19}$ | Humphreys et al., 2003; Hsu et al., 2013; Lee et al., 2009; Orji and Wei, 2014; Amindoust et al., 2012; Kim, 2000 |
| | Innovation, $C_{20}$ | Tseng and Chiu, 2010; Orji and Wei, 2014; Amindoust et al., 2012 |
| | Resource consumption, $C_{21}$ | Zhu et al., 2010; Bai and Sarkis, 2009; Orji and Wei, 2014; Bai and Sarkis, 2010; Amindoust et al., 2012 |
| | Green product, $C_{22}$ | Tseng and Chiu, 2010; Lee et al., 2009; Zhu et al., 2010; Orji and Wei, 2014; Amindoust et al., 2012 |
| | Pollution control, $C_{23}$ | Tseng and Chiu, 2010; Yeh and Chuang, 2010; Awasthi et al., 2010; Zhu et al., 2010; Bai and Sarkis, 2009; Orji and Wei, 2014; Bai and Sarkis, 2010; Amindoust et al., 2012; Azadnia et al., 2012 |

Table 1.2: Criteria definitions

| Sustainability criteria | Definitions |
|---|---|
| Price, $C_1$ | This is a criterion whose minimum value is preferred (lesser-is-better). Total cost involves cost of purchasing, installation and training (Awasthi et al., 2010). |
| On time delivery, $C_2$ | It is a performance indicator in relation to delivery of goods. It is related to the lead time between placement and arrival of an order (Kuo et al., 2010). |
| Service and relationship, $C_3$ | This is about the service offered by the suppliers to keep the delivered products in function and to provide necessary support or maintenance, if required. A relationship is an important criterion in suppliers' selection to be developed based on long term trust based businesses. It can be understood as long term relationship, level of trust and understanding (Punniyamoorthy et al., 2011; Choi and Hartley, 1996; Pearson and Ellram, 1995; Kannan and Tan, 2006). |
| Flexibility, $C_4$ | Flexibility of supplier is a complex and multi-dimensional capability that requires a firm's wide effort to increase market responsiveness and to reduce waste and environmental impact (Dreyer and Gronhaug, 2004). Supply chain flexibility can be rationalised by considering two key antecedents of flexibility, sourcing and vendor flexibility (Gosling and Naim, 2010). |
| Quality, $C_5$ | The ability to meet quality specifications consistently (Yazdani, 2014). This criteria includes issues like whether or not the frequent quality assessment of the parts is being done by the supplier and do they have a strong commitment for preventing quality failures or not (Çifçi and Büyüközkan, 2011). |
| Financial capability, $C_6$ | Financial assessment can be viewed as a screening process or preliminary condition that the supplier must pass before a detailed evaluation begins (Bello, 2003). The objective of this criterion is to figure out whether or not the suppler has the monetary ability to build up and deal with the agreement, including any change requirements. |
| Production facilities, $C_7$ | It is a maximum conceivable output of an economy in a given time period with the proper utilization of available resources. Availability of high level of production facilities and capacities lead to high chance of supplier selection (Punniyamoorthy et al., 2011). This factor includes process flexibility, volume flexibility, training, and promotion of JIT concept, handling and packaging capability, machine capacity and capability, facilities for measurement, calibration and testing (Billesbach, et al.1991; Choi and Hartley, 1996; Kannan and Tan, 2006; Silva et al., 2002). |
| Organization, $C_8$ | This includes three sets of sub-factors: culture, technology, and relationships (Zhu et al., 2010). Based on the past literature and expert opinions, the sub-criteria considered under this factor are physical size of the organization, geographical location, reputation and position in the industry, ethical |

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|---|---|
| | standards, educational qualification of human resources, etc. (Dickson, 1966; Pearson and Ellram, 1995; Tan, 2002). High level of organizational commitment and proper management leads to high chance of supplier selection. |
| Rights of Stakeholders, $C_9$ | This defines the interest and control of shareholders, consumers and communities over whole organizational process (Kuo et al., 2010). Stakeholders are people or organizations with a personal attention in the result of their particular projects. Stakeholders have legitimate choice making rights. Most partners have obligations to organizations that incorporate educating developers, financing projects, creating scheduling parameters and setting milestone dates. |
| Work safety, $C_{10}$ | It articulates the security features during the whole process of design, manufacturing and selection to avoid physical accidents and loss. Emphasis should be placed on work safety and product quality of the respective suppliers. Quality and work safety highly influences all the other sustainability criteria (Orji and Wei, 2014). |
| Information disclosure, $C_{11}$ | It denotes to a suggestion of pertinent contextual art or information up to defined limit. It is mainly the exposure of non-financial information (Kuo et al., 2010). |
| Respect for policy, $C_{12}$ | Compliance with local regulations and policies (Kuo et al., 2010; Bai and Sarkis, 2009; 2010). |
| Recycling, $C_{13}$ | It is necessary to treat used products (or their accessories) by reprocessing the materials (Yeh and Chaung, 2011). Design of products must be available for reuse, recycle and recovery of material (Kannan et al., 2013; Hsu et al., 2012). |
| Waste electrical equipments, $C_{14}$ | It is one of the three major European Union directives viz. Waste Electrical and Electronic Equipment (WEEE), Restriction of Hazardous Substances (RoHS) and Eco-Design Requirements for Energy Using Products (EUP) that concerns the electronic companies. These three directives show EUs consideration for accomplishing recycling, low toxic substances, and low energy and resources waste (Kuo et al., 2010). |
| Ozone depleting chemicals, $C_{15}$ | It is the control over emission of Ozone depleting chemicals by the manufacturing process. The first global environmental problem identified was depletion of stratospheric ozone. The problem arises from destruction of ozone molecules in the upper atmosphere, primarily by bromine and chlorine from anthropogenic chemicals (Calm and Didion, 1998). Manufacturing process must not contain ozone depleting substances (Kuo et al., 2010). |
| Green R&D, $C_{16}$ | The capability of Research and Development (R&D) of the supplier to meet current and future demand of green products of the firm. It includes checking the supplier's design for environment capability so that the product becomes more environmental friendly (Shaik and Kader, 2011; Awasthi et al., 2010). |

| | |
|---|---|
| Green design, $C_{17}$ | It is the effective implementation of a pro-active 'green' strategy which supports the company in the introduction of new 'green' products by designing components that improve the end-product environmental performance and make product recycling easier (Noci, 1997). |
| Environmental management system, $C_{18}$ | This includes checking a supplier's environmental policies, their implementation and certification of ISO 14001 (Humphreys et al., 2003). It is to be evaluated in terms of the effort of supplier in adherence to the proper environment management (Lee et al., 2009). This improves the quality of products with regard to environmental and value management such as environmental policies, their implementation and respective certifications (Shaik and Kader, 2011). |
| Environmental competencies, $C_{19}$ | This criterion reveals the competencies of suppliers in improving green production and in reducing pollution effects. This may be also assessed in view of the extent of influence and involvement of the management to implement green programs (Shaik and Kader, 2011). |
| Innovation, $C_{20}$ | Supplier's innovation can eventually lead to supply cost reduction and is assumed to impose positive effect on supply quality and delivery time, both of which are combined to determine the supply cost (Kim, 2000). |
| Resource consumption, $C_{21}$ | It is the proper utilization of available resources by reducing adverse environmental impacts of the manufacturing process by optimizing process elements, process courses, and process projects (Cao et al., 2002; He et al., 2007) in an economic way. Green process planning for manufacturing system emphasizes on reducing energy and resource consumption, avoid wastage, reduce noise and harmful environmental effects during manufacturing without sacrificing on productivity, quality, and efficiency (Gogoi and Hazarika, 2014). |
| Green product, $C_{22}$ | It can be evaluated in view of the effort of supplier in producing green products (Lee et al., 2009). It can also be assessed by the effectiveness of a systematic methodology to reduce the environmental impact of products and processes (Yazdani, 2014). |
| Pollution control, $C_{23}$ | This criterion shows the level of control of supplier in producing pollution. This involves checking the pollutant levels against legal requirements (Shaik and Kader, 2011; Lee et al., 2009). It can also be interpreted in terms of the control of waste of all types, including water and energy which are to be reduced or eliminated at the source or by practices such as modifying production, maintenance and facility processes, materials substitution, conservation, recycling and reusing materials (Kuo et al., 2015). |

Table 2: Linguistic terms for assigning importance of decision-makers and priority weight of criteria

| Linguistic term | IFN $(\mu, \nu, \pi)$ |
|---|---|
| Beginner (B)/ Very Unimportant (VU) | (0.1, 0.9, 0) |
| Practitioner (Pr)/ Unimportant (U) | (0.35, 0.6, 0.05) |
| Proficient (Pt)/ Medium (M) | (0.5, 0.45, 0.05) |
| Expert (E)/ Important (I) | (0.75, 0.2, 0.05) |
| Master (M)/ Very Important (VI) | (0.9, 0.1, 0) |

Table 3: Linguistic terms for rating of alternatives

| Linguistic term | IFN $(\mu, \nu, \pi)$ |
|---|---|
| Extremely Bad (EB) | (0.1, 0.9, 0) |
| Very Bad (VB) | (0.1, 0.75, 0.15) |
| Bad (B) | (0.25, 0.6, 0.15) |
| Medium Bad (MB) | (0.4, 0.5, 0.1) |
| Fair (F) | (0.5, 0.4, 0.1) |
| Medium Good (MG) | (0.6, 0.3, 0.1) |
| Good (G) | (0.7, 0.2, 0.1) |
| Very Good (VG) | (0.8, 0.1, 0.1) |
| Excellent (E) | (1,0,0) |

[Source: Luis Pérez-Domínguez, Alejandro Alvarado-Iniesta, Iván Rodríguez-Borbón, Osslan Vergara-Villegas, Intuitionistic fuzzy MOORA for supplier selection, DYNA 82 (191), pp. 34-41].

Table 4: Decision-makers’ importance

| | DM1 | DM2 | DM3 | DM4 |
|---|---|---|---|---|
| Linguistic weight | M | E | Pt | Pr |
| Corresponding IF number | (0.9, 0.1, 0) | (0.75, 0.2, 0.05) | (0.5, 0.45, 0.05) | (0.35, 0.6, 0.05) |
| Weight | 0.3483 | 0.3055 | 0.2037 | 0.1426 |

Table 5: Priority weight of criteria

| Criteria | Aggregated criteria weight, $w_j$ (expressed in IFN) | Crisp weight, $w_{jC}$ (after defuzzification) | Normalized weight, $w_{jC}^N$ |
|---|---|---|---|
| $C_1$ | (0.7926,0.0062,0.0230) | 0.7877 | 0.0449 |
| $C_2$ | (0.6818,0.0095,0.0610) | 0.6611 | 0.0377 |
| $C_3$ | (0.8627,0.0046,0.0061) | 0.8618 | 0.0492 |
| $C_4$ | (0.6818,0.0095,0.0610) | 0.6611 | 0.0377 |
| $C_5$ | (0.7500,0.0072,0.0281) | 0.7428 | 0.0424 |
| $C_6$ | (0.8624,0.0025,0.0169) | 0.8601 | 0.0491 |
| $C_7$ | (0.9000,0.0020,0.0058) | 0.8994 | 0.0513 |
| $C_8$ | (0.7926,0.0062,0.0230) | 0.7877 | 0.0449 |
| $C_9$ | (0.7121,0.0085,0.0322) | 0.7026 | 0.0401 |
| $C_{10}$ | (0.6067,0.0122,0.0750) | 0.5748 | 0.0328 |
| $C_{11}$ | (0.7807,0.0036,0.0274) | 0.7745 | 0.0442 |
| $C_{12}$ | (0.7137,0.0053,0.0582) | 0.6960 | 0.0397 |
| $C_{13}$ | (0.7500,0.0072,0.0281) | 0.7428 | 0.0424 |
| $C_{14}$ | (0.7889,0.0038,0.0429) | 0.7795 | 0.0445 |
| $C_{15}$ | (0.8795,0.0023,0.0071) | 0.8786 | 0.0501 |
| $C_{16}$ | (0.8183,0.0056,0.0085) | 0.8168 | 0.0466 |
| $C_{17}$ | (0.8180,0.0031,0.0226) | 0.8138 | 0.0464 |
| $C_{18}$ | (0.7500,0.0072,0.0281) | 0.7428 | 0.0424 |
| $C_{19}$ | (0.7500,0.0072,0.0281) | 0.7428 | 0.0424 |

| | | | |
|---|---|---|---|
| $C_{20}$ | (0.8627,0.0046,0.0061) | 0.8618 | 0.0492 |
| $C_{21}$ | (0.6487,0.0214,0.0565) | 0.6277 | 0.0358 |
| $C_{22}$ | (0.6590,0.0207,0.0274) | 0.6494 | 0.0370 |
| $C_{23}$ | (0.8677,0.0024,0.0078) | 0.8667 | 0.0494 |

Table 6: Aggregated intuitionistic fuzzy ratings $(r_{ij})$ of supplier alternatives with respect to criteria (Intuitionistic fuzzy decision matrix)

| Criteria | IF ratings for supplier $A_1$ | IF ratings for supplier $A_2$ | IF ratings for supplier $A_3$ | IF ratings for supplier $A_4$ | IF ratings for supplier $A_5$ |
|---|---|---|---|---|---|
| $C_1$ | (0.5000,0.0260,0.0848) | (0.5000,0.0260,0.0848) | (0.3518,0.0490,0.1128) | (1.0000,0.0000,0.0000) | (1.0000,0.0000,0.0000) |
| $C_2$ | (0.5580,0.0222,0.0626) | (0.5677,0.0168,0.0790) | (0.1551,0.0639,0.2109) | (0.6527,0.0088,0.0464) | (1.0000,0.0000,0.0000) |
| $C_3$ | (0.4673,0.0281,0.1049) | (0.5000,0.0260,0.0848) | (0.2500,0.0552,0.1613) | (0.7000,0.0072,0.0405) | (1.0000,0.0000,0.0000) |
| $C_4$ | (0.5000,0.0260,0.0848) | (0.5476,0.0179,0.0824) | (0.4000,0.0394,0.1104) | (0.8000,0.0020,0.0224) | (1.0000,0.0000,0.0000) |
| $C_5$ | (0.6161,0.0102,0.0634) | (0.6000,0.0152,0.0614) | (0.2364,0.0575,0.1908) | (0.7499,0.0029,0.0368) | (1.0000,0.0000,0.0000) |
| $C_6$ | (0.5000,0.0260,0.0848) | (0.6819,0.0078,0.0428) | (0.2500,0.0552,0.1613) | (0.6484,0.0090,0.0584) | (0.8000,0.0020,0.0224) |
| $C_7$ | (0.4471,0.0294,0.1086) | (0.7000,0.0072,0.0405) | (0.1706,0.0624,0.2073) | (0.7828,0.0023,0.0242) | (1.0000,0.0000,0.0000) |
| $C_8$ | (0.6686,0.0117,0.0410) | (0.5677,0.0168,0.0790) | (0.1551,0.0720,0.2028) | (0.7000,0.0072,0.0405) | (1.0000,0.0000,0.0000) |
| $C_9$ | (0.5000,0.0260,0.0848) | (0.6527,0.0088,0.0464) | (0.1862,0.0739,0.1611) | (0.5372,0.0184,0.0842) | (0.7499,0.0029,0.0368) |
| $C_{10}$ | (0.4367,0.0301,0.1105) | (0.5476,0.0179,0.0824) | (0.4000,0.0394,0.1104) | (0.7499,0.0029,0.0368) | (0.7395,0.0056,0.0261) |
| $C_{11}$ | (0.5000,0.0260,0.0848) | (0.5000,0.0260,0.0848) | (0.5000,0.0260,0.0848) | (0.7000,0.0072,0.0405) | (1.0000,0.0000,0.0000) |
| $C_{12}$ | (0.5330,0.0238,0.0797) | (0.6161,0.0102,0.0634) | (0.5476,0.0179,0.0824) | (0.5374,0.0235,0.0652) | (1.0000,0.0000,0.0000) |
| $C_{13}$ | (0.5000,0.0260,0.0848) | (0.5677,0.0168,0.0790) | (0.4673,0.0281,0.1049) | (0.6579,0.0156,0.0388) | (1.0000,0.0000,0.0000) |
| $C_{14}$ | (0.4325,0.0368,0.1049) | (0.5000,0.0260,0.0848) | (0.3912,0.0321,0.1437) | (1.0000,0.0000,0.0000) | (1.0000,0.0000,0.0000) |
| $C_{15}$ | (0.6484,0.0090,0.0584) | (0.6686,0.0117,0.0410) | (0.4367,0.0301,0.1105) | (0.7393,0.0031,0.0383) | (0.7238,0.0062,0.0377) |
| $C_{16}$ | (0.6725,0.0081,0.0439) | (0.6001,0.0193,0.0443) | (0.5000,0.0260,0.0848) | (0.7169,0.0036,0.0414) | (1.0000,0.0000,0.0000) |
| $C_{17}$ | (0.6087,0.0103,0.0764) | (0.5000,0.0260,0.0848) | (0.5374,0.0235,0.0652) | (0.5677,0.0168,0.0790) | (1.0000,0.0000,0.0000) |
| $C_{18}$ | (0.5157,0.0195,0.0879) | (0.6671,0.0083,0.0446) | (0.6000,0.0152,0.0614) | (0.7238,0.0062,0.0377) | (0.6380,0.0094,0.0600) |
| $C_{19}$ | (0.4673,0.0281,0.1049) | (0.7000,0.0072,0.0405) | (0.4532,0.0351,0.1014) | (0.7000,0.0072,0.0405) | (0.7393,0.0031,0.0383) |

| | | | | | |
|---|---|---|---|---|---|
| $C_{20}$ | (0.6774,0.0143,0.0369) | (0.7000,0.0072,0.0405) | (0.4869,0.0325,0.0813) | (0.7499,0.0029,0.0368) | (0.7000,0.0072,0.0405) |
| $C_{21}$ | (0.6000,0.0152,0.0614) | (0.6545,0.0124,0.0538) | (0.5677,0.0168,0.0790) | (0.6000,0.0152,0.0614) | (1.0000,0.0000,0.0000) |
| $C_{22}$ | (0.5537,0.0225,0.0765) | (0.5476,0.0179,0.0824) | (0.2793,0.0383,0.1960) | (0.7169,0.0036,0.0414) | (0.7560,0.0050,0.0337) |
| $C_{23}$ | (0.5000,0.0260,0.0848) | (0.6875,0.0108,0.0389) | (0.4046,0.0240,0.1080) | (1.0000,0.0000,0.0000) | (0.7000,0.0072,0.0405) |

Table 7: Separation measures $S_i^+$ and $S_i^-$ for each alternatives, closeness coefficient $CC_i$ and corresponding ranking order

| Alternatives | $S_i^+$ | $S_i^-$ | $CC_i$ | Ranking order |
|---|---|---|---|---|
| $A_1$ | 6.6365 | 2.9896 | 0.3106 | 4 |
| $A_2$ | 5.5660 | 4.0534 | 0.4214 | 3 |
| $A_3$ | 9.5149 | 0.1095 | 0.0114 | 5 |
| $A_4$ | 3.2576 | 6.3635 | 0.6614 | 2 |
| $A_5$ | 0.3882 | 9.2317 | 0.9596 | 1 |

Table 8: Ranking order as obtained by ***Ratio System Approach*** of MOORA

| Alternatives | $J_B\|A_i$ | $N\|A_i = defuzz(J_B\|A_i)$ | Ranking order |
|---|---|---|---|
| $A_1$ | (1.0000,0.0000,0.0000) | 0.999996717 | 4 |
| $A_2$ | (1.0000,0.0000,0.0000) | 0.999999554 | 3 |
| $A_3$ | (0.9997,0.0000,0.0003) | 0.999722686 | 5 |
| $A_4$ | (1.0000,0.0000,0.0000) | 0.999999999 | 2 |
| $A_5$ | (1.0000,0.0000,0.0000) | 1.000000000 | 1 |

Table 9: Ranking order obtained by ***Reference Point Approach*** of MOORA

| Alternatives | $\max_j d(r_j, r'_{ij})$ | Ranking order based on $\min_i(\max_j d(r_j, r'_{ij}))$ |
|---|---|---|
| $A_1$ | 0.4976 | 4 |
| $A_2$ | 0.4313 | 3 |
| $A_3$ | 0.7464 | 5 |
| $A_4$ | 0.3536 | 2 |
| $A_5$ | 0.2603 | 1 |

Table 10: Computation of $d(r_{ij}, r_j^+)$ for individual supplier alternatives

| Criteria | $d(r_{ij}, r_j^+)$ | | | | | $\max_{1\le j\le n} d(r_{ij}, r_j^+)$ | $\min_{1\le j\le n} d(r_{ij}, r_j^+)$ |
|---|---|---|---|---|---|---|---|
| | $A_1$ | $A_2$ | $A_3$ | $A_4$ | $A_5$ | | |
| $C_1$ | 0.3054 | 0.3054 | 0.4050 | 0.0000 | 0.0000 | 0.4050 | 0.0000 |
| $C_2$ | 0.2634 | 0.2641 | 0.5598 | 0.2012 | 0.0000 | 0.5598 | 0.0000 |
| $C_3$ | 0.3329 | 0.3054 | 0.4833 | 0.1738 | 0.0000 | 0.4833 | 0.0000 |
| $C_4$ | 0.3054 | 0.2763 | 0.3749 | 0.1122 | 0.0000 | 0.3749 | 0.0000 |
| $C_5$ | 0.2287 | 0.2383 | 0.5060 | 0.1449 | 0.0000 | 0.5060 | 0.0000 |
| $C_6$ | 0.2186 | 0.1396 | 0.3199 | 0.1491 | 0.0878 | 0.3199 | 0.0878 |
| $C_7$ | 0.3455 | 0.1738 | 0.5495 | 0.1218 | 0.0000 | 0.5495 | 0.0000 |
| $C_8$ | 0.1920 | 0.2641 | 0.5598 | 0.1738 | 0.0000 | 0.5598 | 0.0000 |
| $C_9$ | 0.2177 | 0.1520 | 0.3604 | 0.1956 | 0.1052 | 0.3604 | 0.1052 |
| $C_{10}$ | 0.2385 | 0.1910 | 0.2615 | 0.1052 | 0.1171 | 0.2615 | 0.1052 |
| $C_{11}$ | 0.3054 | 0.3054 | 0.3054 | 0.1738 | 0.0000 | 0.3054 | 0.0000 |
| $C_{12}$ | 0.2853 | 0.2287 | 0.2763 | 0.2756 | 0.0000 | 0.2853 | 0.0000 |
| $C_{13}$ | 0.3054 | 0.2641 | 0.3329 | 0.1982 | 0.0000 | 0.3329 | 0.0000 |
| $C_{14}$ | 0.3546 | 0.3054 | 0.3923 | 0.0000 | 0.0000 | 0.3926 | 0.0000 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| $C_{15}$ | 0.1480 | 0.1479 | 0.2383 | 0.1096 | 0.1193 | 0.2383 | 0.1096 |
| $C_{16}$ | 0.1898 | 0.2317 | 0.3054 | 0.1641 | 0.0000 | 0.3054 | 0.0000 |
| $C_{17}$ | 0.2390 | 0.3054 | 0.2756 | 0.2641 | 0.0000 | 0.3054 | 0.0000 |
| $C_{18}$ | 0.2018 | 0.1420 | 0.1707 | 0.1162 | 0.1495 | 0.2018 | 0.1162 |
| $C_{19}$ | 0.2249 | 0.1302 | 0.2371 | 0.1302 | 0.1096 | 0.2371 | 0.1096 |
| $C_{20}$ | 0.1429 | 0.1261 | 0.2250 | 0.1052 | 0.1261 | 0.2250 | 0.1052 |
| $C_{21}$ | 0.2383 | 0.2058 | 0.2641 | 0.2383 | 0.0000 | 0.2641 | 0.0000 |
| $C_{22}$ | 0.1911 | 0.1889 | 0.2765 | 0.1191 | 0.1026 | 0.2765 | 0.1026 |
| $C_{23}$ | 0.3054 | 0.1811 | 0.3637 | 0.0000 | 0.1738 | 0.3637 | 0.0000 |

Table 11: Grey relational grade $\xi_i^+$ of each alternative from the reference sequence

| Alternatives | $\xi_i^+ = \sum_{j=1}^{n} w_j^N \xi_{ij}^+$ | Ranking order |
|---|---|---|
| $A_1$ | 0.5340 | 4 |
| $A_2$ | 0.5694 | 3 |
| $A_3$ | 0.4566 | 5 |
| $A_4$ | 0.6900 | 2 |
| $A_5$ | 0.8819 | 1 |