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A fuzzy goal programming approach for selecting sustainable suppliers

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Abstract

Purpose - Due to the ever increasing concern towards sustainability, suppliers nowadays are evaluated on the basis of environmental performances. The data on supplier's performance is not always available in quantitative form and evaluating supplier on the basis of qualitative data is a challenging task. The purpose of this paper is to develop a framework for the selection of suppliers by evaluating them on the basis of both quantitative and qualitative data.

Design/methodology/approach - Literature on sustainability, green supply chain and lean practices related to supplier selection is critically reviewed. Based on this, a two phase fuzzy goal programming approach integrating hyperbolic membership function is proposed to solve the ambiguous supplier selection problem.

Findings - Results obtained through the proposed approach is compared with the traditional models (Jadidi, Zolfaghari, & Cavalieri, 2014; Ozkok & Tiryaki, 2011; Zimmermann, 1978) of supplier selection and was found to be optimal as it achieves higher aspiration level.

Practical implications - The proposed model is adaptive to solve real world problems of supplier selection as all criterion do not possess the same weights, so the managers can change the criterion and their weights according to their requirement.

Originality/value - This paper provides the decision makers a robust framework to evaluate and select sustainable supplier based on both quantitative and qualitative data. The results obtained through the proposed model achieves greater satisfaction level as compared to those achieved by traditional methods.

Keywords - Environmental sustainability, Multi-objective supplier selection, Fuzzy set theory, Goal programming.

Paper Type - Research paper

1. Introduction

In the context of supply chain management, supplier selection problems have received considerable attention due to its conflicting goals and criterion (Choi & Hartley, 1996; De Boer, Labro, & Morlacchi, 2001; Ho, Xu, & Dey, 2010). Supplier selection problem is a major concern for companies where raw material cost accounts for the major part of the product's total cost (Goffin, Szwejczewski, & New, 1997). In some industries, the cost of raw materials and component parts comprises as high as 50 percent to 90 percent of the total product cost (Telgen, 1994). Supplier selection plays a very important role to gain competitiveness by reducing the total product cost.

Supplier selection process basically entails the selection of suppliers based on some tangible and intangible criteria, determination of the product quantities, and placement of the order while adhering to environmental and economic constraints (De Boer, Labro, & Morlacchi, 2001). In today's globally competitive environment, companies pay a greater attention to select right suppliers, who will reduce the product cost, maintain quality and provide good services (Ghodsypour & O'brien, 2001; Ozkok & Tiryaki, 2011).

Due to depleting natural resources and consumers concern towards the eco-friendly products, firms nowadays cannot easily ignore the environmental issues to survive in the global market. The increasing public awareness about the environment and government regulations has motivated many researchers to study the problem of selecting the sustainable suppliers (Azzone & Bertele, 1994; Porter & Linde, 1995; Roome & Hinnells, 1993; Sahu, Datta & Mahapatra, 2014; Taylor, 1993; Walley & Whitehead, 1994; Welford, 1995). In order to achieve a long term success, companies should not only focus on financial aspects of the suppliers but they must also emphasis on lean and environmental practices (Verghese & Lewis, 2007). Seuring & Müller (2008) shows a positive relationship between sustainable supply chain implementation and green supplier selection. The integration of environmental and economic performances to achieve sustainable product development is a major business challenge for the firms. Since the problem of supplier selection involves a tradeoff among the multiple factors (both qualitative and quantitative), most of the studies conducted in this field referred to mathematical model to handle multiple and conflicting decision making criteria. However, the inability of mathematical models to handle ambiguous and imprecise data lead to development of many fuzzy multi criteria decision making models (Chan & Kumar, 2007; Chen, Lin, & Huang, 2006). Where fuzzy goal programming approach proved to be an efficient technique to handle ambiguous information and to access multiple criteria of supplier evaluation (Lin, 2012).

Proposed methodologies in the literature have mainly considered economic and sustainable criterion of supplier selection. Very few studies have emphasized on economic aspect, lean practices and sustainable development together (Amindoust, Ahmed, Saghafinia, & Bahreininejad, 2012). A study by Zayko, Broughman & Hancock (1997) indicates that lean manufacturing can result in a 50 percent reduction of human effort, manufacturing space, tool investment, and product development time, and a 200-500 percent improvement in quality.

To fill the above mentioned gap in the literature, this paper deals with the evaluation of suppliers on the basis of economic, lean, services and environmental criteria. The proposed model in this paper for the supplier selection is divided in two phases. First Phase identifies the weights of criterion and second phase proposes a fuzzy goal programming approach integrating hyperbolic membership funtion to identify a sustainable supplier. The hyperbolic membership function maintains the continuity and differentiability of objective function while transforming the values in membership grade and obtains the result closely as compared to those obtained by linear membership function. The model proposed in this paper can also be generalized to the other frameworks of supplier selection criteria proposed in the literature (Hsu & Hu, 2009; Humphreys & McCloskey, 2006; Kuo, Wang, & Tien, 2010; Noci, 1997).

The rest of the paper is organized as follows- Section 2 shows the pertinent literature review on supplier evaluation. Section 3 describes the basic definitions necessary for this paper. Section 4 proposes a sustainable supplier selection model using a two phase approach. Section 5 evaluates the suppliers for '*Entropy Innovations Private Limited*' (an automobile equipment manufacturing firm) using the proposed model, Section 6 compare the results obtained through proposed model and the traditional models of supplier selection and section 7 concludes the paper.

2. Literature Review

The literature on the supplier selection problem is quite vast. Various review papers (Aissaoui, Haouari, & Hassini, 2007; Choi & Hartley, 1996; De Boer et al., 2001; Ho et al., 2010; Wilson, 1994) have highlighted the issues of supplier selection for multiple problem instances. The study of supplier section process can be traced back to Dickson (1966) considering 23 criteria of supplier selection. Erol, Sencer, & Sari (2011) considered 37 sub-criteria under the three categories environmental sustainability, social sustainability and economic sustainability. Chang, Chen, & Zhuang (2014) incorporated multi-segment (e.g. imperfect-quality discount (IQD) and price-quantity discount (PQD)) and multi-aspiration criteria for the assessment of suppliers. Amin & Zhang (2012) proposed a framework consisting three categories (supplier, parts and process) for defining supplier selection criteria in the field of reverse logistics. Yadav & Sharma, (2016) considered 22 sub-criteria under six categories i.e. quality, cost, delivery, service, flexibility and long term relationship. Singh & Sharma (2014a) and Yadav & Sharma (2015b) highlighted the importance of 'flexibility' and 'long term relationship' for the supplier selection process.

Due to increasing concern towards sustainability, many researchers have considered various green and environmental criteria. Humphreys, McIvor, & Chan (2003) proposed a framework for the environmental criteria such as chemical waste, solid waste, air emission, energy and water waste disposal. Hsu & Hu (2009) incorporated the issues of hazardous substance management for the evaluation of suppliers. Sarkis (1998) grouped together environmental criteria such as design for the environment, life cycle analysis, total quality environmental management and green supply chain. Noci (1997) proposed four categories of criterion: green competencies, current environmental efficiency, supplier's green image and net life cycle cost. Humphreys & McCloskey (2006) categorized the environmental criteria into two broad categories, quantitative and qualitative environmental criteria. Kuo, Wang, & Tien (2010) identified six dimensions of green supplier selection; including cost, quality, delivery, environment, service and corporate social responsibility.

Most of these studies hover around economic and sustainable criterion (Bai & Sarkis, 2010; Büyüközkan & Çifçi, 2011; Jabbour & Jabbour, 2009; Lu, Wu, & Kuo, 2009; Min & Galle, 2001; Noci, 1997; Shaw, Shankar, Yadav, & Thakur, 2012). Very few of the studies considered economic, environmental and lean practices together (Simpson & Power, 2005). Zayko, Broughman & Hancock (1997) indicates that lean manufacturing can result in a 50 percent reduction of human effort, manufacturing space, tool investment, and product development time, and a 200-500 percent improvement in quality. Germain & Dröge (1997) shows the positive correlation between improved inventory, financial, market performance and increased adoption of just-in-time purchasing methods. For the performance evaluation criterion, Ghodsypour & O'Brien, (1998) and Weber et al. (1991) concluded that the number of criteria and their priority completely depend on purchasing specialists, product specification and strategy. In this paper, four categories of supplier selection criteria are considered i.e. economic aspect, lean practices, sustainable development and services by the purchasing specialists on the basis of nature of products. However, the proposed model in this paper can also be generalized to the other frameworks of sustainable supplier selection criterion given in the literature (Hsu & Hu, 2009; Humphreys & McCloskey, 2006; Kuo, Wang, & Tien, 2010; Noci, 1997).

Other techniques used for the evaluation of supplier performance include; mathematical programming (Azadi, Saen & Zoroufchi, 2014; Kumar, Vrat, & Shankar, 2006; Ng, 2008; Tsai & Hung, 2009), Analytical Hierarchy Process (AHP)/fuzzy AHP (Hou & Su, 2007; Rao, 2005; Singh & Sharma, 2014b), Fuzzy set theory (Chan & Kumar, 2007; Chen, Lin, & Huang, 2006; Wu, 2009), and the Analytic Network Process (ANP)/fuzzy ANP (Bayazit, 2006; Lin, 2009; Noci, 1997; Tseng, Chiang, & Lan, 2009).

Majority of the researchers used mathematical programming technique for the supplier evaluation. Ghodsypour & O'Brien (1998) studied a supplier selection problem using analytical hierarchy process and linear programming. Karpak, Kumcu, & Kasuganti (1999) proposed a goal programming model for the minimization of cost and maximization of quality, reliability and delivery. Jadidi, Zolfaghari & Cavalieri (2014) proposed a normalized goal programming model and compared the proposed model with weighted goal programming, weighted max–min models, compromise programming, weighted objectives, TOPSIS (Technique for order of preference by similarity to ideal solution) and min–max goal programming.

The inability of mathematical models to handle ambiguous and imprecise data lead to development of many fuzzy multi criteria decision making models (Chan & Kumar, 2007; Chen et al., 2006; Ghodsypour & O'Brien, 1998; Kahraman, Cebeci, & Ulukan, 2003; Lee, Kang, Hsu, & Hung, 2009; Narasimhan, 1983). The first noteworthy attempt to handle ambiguous information can be traced back to Bellman & Zadeh (1970) for fuzzy programming model. Zimmermann (1978) used this (Bellman & Zadeh, 1970) method to solve fuzzy multi objective linear programming problems. To deal with ambiguous criterion of supplier selection Kahraman et al. (2003) used fuzzy analytic hierarchy process (FAHP) for a Turkey based white good manufacturer. Kumar, Vrat, & Shankar (2004) proposed a fuzzy goal programming approach for vendor selection considering the effect of information uncertainty in the decision making. Pan (2012) developed a fuzzy multi objective linear/nonlinear model considering stochastic demand to deal with imperfect information. Amin & Zhang (2012) proposed a multi objective mixed-integer linear programming model to evaluate the suppliers on the basis of qualitative criterion.

Furthermore, dual methodologies have been adopted in numerous studies for the supplier selection problem (Amid, Ghodsypour, & O'Brien, 2011; Liao & Kao, 2011; Lin, 2012; Shaw, Shankar, Yadav, & Thakur, 2012). Liao & Kao (2011) proposed an integrated fuzzy TOPSIS and multi-choice goal programming approach. Yadav & Sharma (2015a, 2015c) proposed a hybrid methodology by integrating data envelopment analysis (DEA) and analytic hierarchy process (AHP). Amid et al., (2011) developed a weighted max–min fuzzy model to handle effectively the vagueness of input data, an analytic hierarchy process is used to determine the weights of criterion. Shaw et al., (2012) addressed the issue of carbon emission, using fuzzy-analytical hierarchy process and fuzzy multi-objective linear programming. To tackle inherent uncertainty in supplier selection process, Lin (2012) adopted a fuzzy analytic network process to identify top suppliers and integrated it with fuzzy multi-objective linear programming to obtain optimal order allocation.

The fuzzy goal programming approach proved to be an efficient technique to handle ambiguous information and to assess multiple criteria of supplier evaluation. For capturing uncertainty in the model, researchers used linear (Jadidi et al., 2014), triangular (Büyüközkan & Çifçi, 2011; Lee, Kang, Hsu, & Hung, 2009; Lu et al., 2009; Şen, Şen, & Başlıgil, 2010; Shaw et al., 2012), and trapezoidal (Bai & Sarkis, 2010; Labib, 2011) membership functions while transforming objective functions into membership grade. Studies show that very few researchers have used non-linear membership function in the context of supplier selection (Díaz-Madroñero, Peidro, & Vasant, 2010). The summary of related literature is presented in Table 1.

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Table 1: Summary of Literature Review

about here

In this paper, a fuzzy goal programming approach integrating hyperbolic function is proposed to solve the complex supplier selection problem. The hyperbolic membership function maintains the continuity and differentiability of objective function while transforming the values in membership grade and obtains close results compared to those obtained by linear membership functions.

3. Fuzzy Set Theory

Real world problems are vague and uncertain in nature. The information available to decision makers is not always in quantitative form and sometimes they are required to take decisions just on the basis of qualitative data which makes the decision making difficult. Zadeh (1965) introduced the concept of fuzzy set theory to handle the vague and imprecise information, which was first used by Zimmermann (1983) for solving Multi-objective decision making problem. According to Zadeh (1965), $\mu(x): R \rightarrow [0,1]$ is a membership grade of an element x in a set A, where $\mu(x)$ represents the membership function. Variable x is said to have full membership in set A if $\mu(x) = 1$, and the zero membership if $\mu(x) = 0$. Membership value for an objective function is also known as satisfaction level. For higher membership value, objective function is assumed to be fully achieved and for lower membership value, it is assumed to be partially achieved. Zimmermann (1992) highlighted that the real world non quantifiable problems can be represented with the help of linguistic variables. Following example shows the significance of linguistic variable for the decision making process.

Example 1, Suppose that '$Temperature$' is a linguistic variable that can take any value defined in set $A = \{"very\ low", "low", "medium", "low\ high", "medium\ high"\ and\ "high"\}$. We want to forecast it on the basis of previous temperature of last three days that were "Very Low", "Medium" and "Very Low" respectively. So to forecast the temperature first we need to convert it in quantitative form because we cannot apply forecasting techniques on linguistic variables.

Figure 1 shows the mapping of linguistic variable to the corresponding quantitative values and the values of temperature for Day 1 and Day 3 = $(0, 0, 0.1, 0.2)$ and for Day 2 will be $(0.3, 0.45, 0.45, 0.6)$ respectively.

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Fig. 1 Membership grades of linguistic variable

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The trapezoidal and hyperbolic membership function can be defined as follows.

3.1 Trapezoidal membership function: The membership function of a trapezoidal fuzzy number is shown in Figure 2 and is defined as follows (Kaufmann & Gupta, 1991)

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Fig. 2 Trapezoidal membership function

about here

$$\mu_P(x) = \begin{cases} 0 & x<p1 \\ \frac{x-p1}{p2-p1} & p1\le x<p2 \\ 1 & p2\le x<p3 \\ \frac{x-p4}{p3-p4} & p3\le x<p4 \\ 0 & x\ge p4 \end{cases}$$

Where p_1 and p_4 represent the lower bound and the upper bound of the trapezoidal fuzzy number P respectively while p_2 and p_3 represent the strongest grade of the membership. Thus, the trapezoidal fuzzy number of P is represented by (p_1, p_2, p_3, p_4). For a trapezoidal fuzzy number P, if $p_2 = p_3$; then P is called a triangular fuzzy number.

3.2 Hyperbolic membership function: The hyperbolic membership function $\mu_p^h(x)$ of a fuzzy number P is shown in Figure 3 and defined as follows (Leberling, 1981).

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Fig. 3 Hyperbolic membership function

about here

$$\mu_p^h(x) = \begin{cases} 1, & x \leq L \\ \frac{1}{2} + \frac{1}{2}\tanh\left(\left(\frac{U+L}{2} - x\right)\alpha\right), & L < x < U \\ 0, & x \geq U \end{cases}$$

In this function, α is a parameter, where $\alpha = \frac{6}{U-L}$ while U and L represent the upper and lower bound respectively. Hyperbolic membership function satisfies the following properties:

1. It is strictly decreasing function.
2. It is strictly concave for $x \leq \frac{U+L}{2}$
3. It is equal to 0.5 for $x = \frac{U+L}{2}$
4. It is strictly convex for $x \geq \frac{U+L}{2}$
5. For all $x \in R$
    a. $0 < \mu_p^h(x) < 1$
    b. $\mu_p^h(x) = 1$ is the lower asymptotic function of $\mu_p^h(x)$ and $\mu_p^h(x) = 0$ is the upper asymptotic function of $\mu_p^h(x)$

4. Supplier selection model

A supplier selection model considering economic, lean and environmental aspect is proposed in this section. The selection of best supplier from a pool of suppliers for a given product is modeled as a two phase approach. In first phase, the criteria and their corresponding weights are finalized with help of experts i.e. purchasing specialist based on the nature of product. In second phase, a fuzzy goal programming model is developed to select the best supplier. Detailed description of both the phases is provided as follows.

Phase 1: Determination of criterion weights

Supplier selection is a multi-criteria decision making problem which becomes very difficult to solve due to its conflicting objectives and their priorities not being known in advance. In this model, the criteria for supplier selection are finalized with the help of experts considering the nature of products. Respective criterion's rank is obtained in the form of linguistic variable which is later transformed into crisp numbers (weights) with the help of trapezoidal membership function. Following steps describe the determination of weight for each criterion:

Step 1: Selection of a pool of suppliers

In this step, a pool of eligible suppliers (satisfying basic requirements) is taken into consideration from which the best supplier has to be selected. This step involves the engagement of specialists from the purchasing department for the construction of initial pool of suppliers based on their past knowledge and experience about product the requirements.

Step 2: Determination of criteria

In order to determine the evaluation criteria for the suppliers, important criteria are finalized.

Step 3: Ranking of criteria

A team of K experts rank the criterion separately in linguistic form because linguistic responses approximate the real judgment of decision makers. The linguistic response of experts is then transformed into trapezoidal fuzzy numbers (similar to example 1 given earlier).

Step 4: Aggregation of response

Aggregate rank for each criterion is obtained by taking average of K (no. of experts) responses corresponding to that criteria (Chen, 2000). Let the fuzzy trapezoidal number $R_i^k = (p^k, q^k, r^k, s^k)$ is the response of $k^{th} \in (1,2, \dots K)$ expert corresponding to i^{th} criterion then aggregate rank $\widetilde{R_i} = (\widetilde{p_i}, \widetilde{q_i}, \widetilde{r_i}, \widetilde{s_i})$ corresponding to i^{th} criterion is obtained as follows.

For $\forall\ k \in (1,2, \dots K)\ and\ i \in (1,2, \dots n)$;

$\widetilde{p_i} = Min\{p^k\}$,

$\widetilde{q_i} = \frac{1}{k}\sum_{k=1}^{K} q^k$,

$\widetilde{r_i} = \frac{1}{k}\sum_{k=1}^{K} r^k$,

$\widetilde{s_i} = Min\{s^k\}$

Step 5: Calculation of α-cut

Once the Aggregate rank of each criterion is obtained, α-cut for each fuzzy number is obtained. For a given value of $\alpha \in [0, 1]$, α-cut of a fuzzy number P will be $P^\alpha = \{x_i: \mu_P(x_i) \geq \alpha, x_i \in X\}$. The symbol P^α represents a non-empty bounded interval contained in X, which can be denoted by $P^{\alpha} = [P_L^{\alpha}, P_U^{\alpha}]$, P_L^{α} and P_U^{α} are the lower and upper bounds of the closed interval, respectively (Kaufmann & Gupta, 1991; Zimmermann, 1992).

Step 6: Defuzzification

In order to obtain crisp value corresponding to each fuzzy number, center of gravity (COG) method can be applied (Zimmermann, 1992). Leekwijck & Kerre, (1999) shows that center of gravity method provides the highly practical property of continuity. Let P be a trapezoidal fuzzy number with membership function $\mu_P(x)$. Then crisp value corresponding to this fuzzy number P can be calculated as:

$$COG(P) = \frac{\int_a^b \mu(xi).x\, dx}{\int_a^b \mu(xi) dx}$$

Step 7: Weight of criteria

Once the crisp rank of each criterion is obtained, its weight is determined by dividing the rank of criterion by the total rank of all criteria.

Phase 2: Fuzzy Goal Programming Approach

Goal programming is an efficient method to solve multi objective decision making problems (Charnes, Cooper, & Ferguson, 1955). It refers to the minimization of positive (over achievement) and negative deviation (under achievement) from the target value set by the decision makers. Application of goal programming can be seen in several works (Charnes & Cooper, 1957; Ignizio, 1985; Lee, 1972; Romero, 2001; Tamiz, Jones, & Romero, 1998) for the multi objective decision making problems. Bellman & Zadeh (1970) introduced the fuzzy multi criteria decision making problem to capture the uncertainty, which became the building block for the fuzzy goal programming approach. Fuzzy goal programming strives to achieve maximum aspiration level (membership grade) rather than strictly satisfying the constraints (Zimmermann, 1978). Various researchers used fuzzy goal programming approach to capture uncertainty (Amid et al., 2011; Kumar et al., 2004, 2006; Liao & Kao, 2011; Lin, 2012; Shaw et al., 2012). Due to ambiguous nature of some parameters in real life supplier selection problem, the evaluation of suppliers cannot be performed with deterministic models. Therefore, fuzzy goal programming plays an important role to capture the ambiguity (Kumar et al., 2006).

In this phase, a fuzzy goal programming model is proposed to capture the real life supplier selection problem. The proposed model uses the hyperbolic membership function in order to retain continuity and differentiability of objective functions. Following steps describe the model in detail:

Step 1: Collection of necessary data

For the evaluation of suppliers, collect the relevant data from the experts and suppliers; and transform the linguistic variables into their respective crisp value (as given in phase 1).

Step 2: Problem formulation

Formulate the mathematical model for the multiple objectives and constraints for the supplier selection problem.

$$Maximize\ or\ Minimize\ Z_i(x) \qquad \forall\, i \in (1,2,\dots n) \tag{1}$$

Subject to

Demand Constraint:

$$\sum_{i=1}^{n} x_{ij} \geq D_j \qquad \forall\, j \in (1,2,\dots P') \tag{2}$$

Capacity constraint:

$$\sum_{j=1}^{P'} x_{ij} \leq C_j \qquad \forall\, i \in (1,2,\dots n) \tag{3}$$

$$x_{ij} \geq 0 \qquad \forall\, i \in (1,2,\dots n), j \in (1,2,\dots P') \tag{4}$$

Equation (1) represents the i^{th} objective function for the maximization or minimization of goal; equation (2) enforces that, total quantity supplied by n suppliers of product $j \in P'$ should be greater than or equal to D_j units, where P' is the set of products; equation (3) represents the capacity constraint of suppliers: it shows that for i^{th} supplier, the total quantity supplied of product $j \in P'$, should not be greater than the capacity C_i; equation (4) stands for the non-negative order quantities.

An equivalent weighted goal programming model for the above mathematical model can be represented as:

$$Minimize \begin{cases} \sum_{i=1}^{n} w_i * (\Delta_i^+ + \Delta_i^-) \\ \qquad OR \\ \sum_{i=1}^{n} w_i * |Z_i(x) - g_i| \end{cases} \tag{5}$$

Subject to

$$Z_i(x) - \Delta_i^+ + \Delta_i^- = g_i \qquad \forall\, i \in (1,2, \dots n) \tag{6}$$
$$\sum_{i=1}^{n} x_{ij} \geq D_j \qquad \forall\, j \in (1,2, \dots P') \tag{7}$$
$$\sum_{j=1}^{P'} x_{ij} \leq C_j \qquad \forall\, i \in (1,2, \dots n) \tag{8}$$
$$x_{ij} \geq 0 \qquad \forall\, i \in (1,2, \dots n), j \in (1,2, \dots P') \tag{9}$$

In the above goal programming model, equation (5) minimizes the total weighted positive (over achievement) and negative deviations (under achievement) of all goals; equation (6) represents the goal programming constraint for i^{th} goal, in case of over achievement $\Delta_i^- = 0$ and for the under achievement $\Delta_i^+ = 0$; equation (7), (8) and (9) are same as described in the previous mathematical model.

Step 3: Solve the Multi-objective supplier selection problem as a single objective problem using only one objective at a time (ignore all others) and obtain the optimal order quantity QO_i^* for i^{th} objective.

Step 4: Calculate the value of all objective functions at the optimal ordered quantities ($QO_1^*, QO_2^*, \dots QO_n^*$) obtained in the previous step and construct a pay-off matrix (POM) (as shown below), where the diagonal of pay-off matrix constitute individual optimum values for the all objective functions. The rows and columns in the matrix are corresponding to $QO_1^*, QO_2^*, \dots QO_n^*$ and $Z_{1(QO)}, Z_{2(QO)}, \dots Z_{m(QO)}$ respectively.

$$\text{POM} = \begin{array}{c} \\ QO_1^* \\ QO_2^* \\ \vdots \\ QO_n^* \end{array} \begin{array}{c} \begin{matrix} Z_{1(QO)} & Z_{2(QO)} & \cdots & Z_{m(QO)} \end{matrix} \\ \begin{bmatrix} Z_{11} & Z_{12} & \cdots & Z_{1m} \\ Z_{21} & Z_{22} & \cdots & Z_{2m} \\ \cdots & \cdots & \cdots & \cdots \\ Z_{n1} & Z_{n2} & \cdots & Z_{nm} \end{bmatrix} \end{array}$$

Step 5: Find the upper and lower bound corresponding to each objective function from the pay-off matrix obtained in the previous step. The upper and lower bound for an objective function shows its highest and lowest possible aspiration level.

Step 6: Transform the fuzzy objective functions formulated in step 2 into membership grades with the help of hyperbolic membership function. The hyperbolic membership function satisfies the property of both continuity and differentiability which helps to closely map the approximate solution in the interval $[0, 1]$. Membership grade for the minimization type objective is described as follows:

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Fig. 4 Hyperbolic membership function for minimization type objective

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$$\mu_i[Z_i(x)] = \begin{cases} 1, & \mathrm{Z_i(x)} \leq \mathrm{L_i} \\ \frac{1}{2} + \frac{1}{2}\tanh\left(\left(\frac{U_i+L_i}{2} - Z_i(x)\right)\gamma_i\right), & \mathrm{L_i} < Z_i(x) < U_i \\ 0, & \mathrm{Z_i(x)} \geq \mathrm{U_i} \end{cases}$$

Membership grade for maximization type objective is described as follows:

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Fig. 5 Hyperbolic membership function for maximization type objective

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$$\mu_i[Z_i(x)] = \begin{cases} 0, & \mathrm{Z_i(x)} \leq \mathrm{L_i} \\ \frac{1}{2} + \frac{1}{2}\tanh\left(\left(\mathrm{Z_i(x)} - \frac{U_i+\mathrm{L_i}}{2}\right)\gamma_i\right), & \mathrm{L_i} < Z_i(x) < U_i \\ 1, & \mathrm{Z_i(x)} \geq \mathrm{U_i} \end{cases}$$

Where $\mu_i[Z_i(x)]$ is the membership grade of i^{th} objective function, $\mathrm{L_i}$ and U_i are the lower and upper bound respectively (obtained in step 4), γ_i is a parameter, where $\gamma_i = \frac{6}{U_i - \mathrm{L_i}}$.

The equivalent fuzzy goal programming model for the supplier selection problem as described in step 2, can be re-formulated as:

$$Maximize \sum_{i=1}^{n} w_i * \lambda_i \tag{10}$$

Subject to

$$\mu_i[Z_i(x)] \geq \lambda_i \qquad \forall\, i \in (1,2, \dots n) \tag{11}$$

$$\sum_{i=1}^{n} x_{ij} \geq D_j \qquad \forall\, j \in (1,2, \dots P') \tag{12}$$

$\sum_{j=1}^{P'} x_{ij} \leq C_j \quad \forall\, i \in (1,2, \dots n) \quad (13)$

$x_{ij} \geq 0 \quad \forall\, i \in (1,2, \dots n), j \in (1,2, \dots P') \quad (14)$

The solution of above linear programming problem guarantees to provide highest attainable value λ_i of each objective. Where, λ_i represents the highest membership value or satisfaction level achieved by i^{th} goal.

5. Case Study

The robustness of the model is examined through a case study conducted for an Indian automobile equipment manufacturing company namely *Entropy Innovations Pvt. Ltd.,* which manufactures automatic bike cleaning machines. The machine guarantees to wash dirtiest of the bikes and scooters within 5 minutes. The company procures the raw material from different suppliers and produces bike cleaning machines in its Mumbai based plant in India. Subsequently, the final product is sold in the market through company/franchisee outlets for the bike wash stations. Procurement of raw material starts after receiving the orders from customers (i.e. pull demand system) using lean practices. Due to increasing pressure from the government and customers' interest in environment protection, company has started focusing on sustainability. The management has realized the need of sustainable suppliers to deal with economic and environmental challenges. For this purpose, a special team of managers from various functional areas such as production, purchasing, quality control and marketing department was formed. For the manufacturing of sustainable products, the company needed several kinds of material and finished components in large quantities on long term basis. Specific problems that were faced by the company in the procurement included:

- Higher delivery lead time
- Ambiguity in supplier selection criterion
- Rejection of the lots having inferior quality
- Higher transportation cost
- Environmental specification
- Appearance of low quality or damaged parts in production

In order to overcome these problems, management realized the need of effective supplier selection system based on quantitative and qualitative criterion. The company considered a pool of four suppliers for outsourcing four items (such as raw material or finished components) and all the suppliers were eligible to supply any of these four items. The company required 10,000 units of each item. Suppliers had enough production capacity of these items except the followings:

- Supplier 4 can supply a maximum of 6000 units of item 1
- Supplier 4 can supply a maximum of 3000 units of item 2
- Supplier 2 can supply a maximum of 7000 units of item 3
- Supplier 3 can supply a maximum of 4500 units of item 4

Phase 1: Determination of weights

Step 1: Selection of supplier

It is observed that there are multiple suppliers (domestic and international) willing to supply the required four items. Evaluation of all the suppliers for the specific item and its management becomes very complex and time consuming task.

Step 2: Determination of criteria

In order to determine preference of supplier selection criteria for the company, three meetings were held by a team of managers from various functional areas. As an outcome of these meetings, four major criteria (economic aspects, lean practices, sustainability and after sales services) and thirteen sub-criteria were identified. Table 2 presents the criteria and sub criteria that company uses for the evaluation of suppliers.

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Table 2: Supplier selection criteria

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Step 3: Ranking of criteria

In order to determine the priority of each criterion, five purchasing specialists were asked to rank each criterion in linguistic form according to its importance while evaluating suppliers. Table 3 provides the response of five decision makers for the priority of criterion, where linguistic variable L, M, MH, H, VH denote 'Lower', 'Medium', 'Medium High', 'High' and 'Very High' respectively.

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Table 3: Responses of decision makers

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Step 4: Aggregation of responses

After obtaining responses from the decision makers, linguistic variables were transformed into trapezoidal fuzzy number and aggregate fuzzy response was calculated. Table 4 shows the aggregate fuzzy response of decision makers.

Step 5: Calculation of α-cut

In order to increase the compactness of fuzzy number, α-cut for the value of 0.5 is obtained, where α-cut for a fuzzy number *P* can be denoted as $P^{\alpha} = \{x_i : \mu_P(x_i) \geq \alpha, x_i \epsilon X\}$ for $\alpha \in [0,1]$. Table 4 provides the α-cut (for $\alpha = 0.5$) for each aggregate fuzzy number obtained in the previous step.

Step 6: Defuzzification

After obtaining α-cut of aggregate fuzzy responses in the previous step, defuzzification of trapezoidal fuzzy numbers was performed with the help of center of gravity method. Table 4 shows the crisp value corresponding to each fuzzy number (α-cut).

Step 7: Weight of criteria

After obtaining the crisp value corresponding to each criterion, the weights were obtained by dividing crisp response of each criterion by the total crisp responses of all criteria. Table 4 Shows that the high importance was given to criteria '(Z_3) UDLP' whereas low weight was given to '(Z_{11}) REC' by the decision makers.

Insert

Table 4: Response of experts corresponding to each criterion

about here

Phase 2: Fuzzy Goal Programming Approach

Steps 1 & 2: Collection of necessary data and performance measures

In order to select the best supplier from the pool of suppliers for the multiple items, relevant data on the basis of past experience was collected and performance measures were calculated. Table 5 and 6 gives the collected data and performance measures respectively.

Insert

Table 5: Data Collection

Table 6: Performance measures

about here

Step 3: Problem formulation

The supplier selection problem for the case of *Entropy Innovations Pvt. Ltd.* is formulated as linear programming model. Proposed model attempts to find optimal supplier for each item from the given set of suppliers. The linear programming model for the evaluation of suppliers can be restated as follows.

$$Z_1 = Min \sum_{i=1}^{4} \sum_{j=1}^{4} URP_{ij} * QO_{ij} \quad (15)$$

$$Z_2 = Min \sum_{i=1}^{4} \sum_{j=1}^{4} UDLP_{ij} * QO_{ij} \quad (16)$$

$$Z_3 = Min \sum_{i=1}^{4} \sum_{j=1}^{4} PC_{ij} * QO_{ij} \quad (17)$$

$$Z_4 = Max \sum_{i=1}^{4} \sum_{j=1}^{4} CUR_{ij} * QO_{ij} \quad (18)$$

$$Z_5 = Min \sum_{i=1}^{4} \sum_{j=1}^{4} TC_{ij} * QO_{ij} \quad (19)$$

$$Z_6 = Max \sum_{i=1}^{4} \sum_{j=1}^{4} FDC_{ij} * QO_{ij} \quad (20)$$

$$Z_7 = Max \sum_{i=1}^{4} \sum_{j=1}^{4} WR_{ij} * QO_{ij} \quad (21)$$

$$Z_8 = Max \sum_{i=1}^{4} \sum_{j=1}^{4} JIT_{ij} * QO_{ij} \quad (22)$$

$$Z_9 = Max \sum_{i=1}^{4} \sum_{j=1}^{4} TECH_{ij} * QO_{ij} \quad (23)$$

$$Z_{10} = Max \sum_{i=1}^{4} \sum_{j=1}^{4} REC_{ij} * QO_{ij} \quad (24)$$

$$Z_{11} = Max \sum_{i=1}^{4} \sum_{j=1}^{4} GRP_{ij} * QO_{ij} \quad (25)$$

$Z_{12} = Max\ \sum_{i=1}^{4}\sum_{j=1}^{4} EMT_{ij} * QO_{ij}$ (26)

$Z_{13} = Max\ \sum_{i=1}^{4}\sum_{j=1}^{4} CR_{ij} * QO_{ij}$ (27)

Subject to

$\sum_{j=1}^{4} QO_{ij} \geq RO_i \quad for\ i = 1, 2, \dots 4$ (28)

$QO_{ij} \leq AC_{ij} \quad for\ i = 1, 2, \dots 4, j = 1, 2, \dots 4$ (29)

$QO_{ij} \geq 0 \quad \forall\ i, j$ (30)

Where, QO_{ij} denote the quantity of product i to be purchased from supplier j, RO_i denote the required quantities of item i. AC_{ij} represents the annual capacity of supplier j for item i.

In the above model, equation (15) minimizes the unit rejection rate; equation (16) minimizes the rate of units delivered late; equation (17) minimizes the total cost of all items; equation (18) maximizes the capacity utilization ratio; equation (19) minimizes the total transportation cost; equation (20) maximizes the demand flexibility of supplier; equation (21) focuses on maximizing the waste reduction practices; equation (22) focuses on maximizing Just-in-time practices; equation (23) emphasizes on maximizing technological capability of suppliers; equation (24) focuses on maximizing recycling of the product; equation (25) emphasizes on following Green packaging; equation (26) stresses for eco-friendly material and technology and equation (27) focuses on maximizing the conflict resolution index of supplier, whereas equation (28), (29) and (30) stand for demand, capacity, and non-negativity constraints of variables.

Step 4: Solve the multi-objective supplier selection problem by taking each time only one objective function (ignoring all others). Table 7 shows the individual solution of all objectives, QO_1^* refers to the optimal order quantity for objective (goal) one, QO_2^* for objective function (goal) two and so on.

Insert

Table 7: Individual optimal solution

about here

Step 5: In order to generate a payoff matrix, values of objective functions are determined on all the optimal ordered quantities (QO_1^*, QO_2^*... QO_{13}^*) obtained in step 4 . Table 8 shows the pay-off matrix for the supplier selection problem.

Insert

Table 8: Pay-off Matrix

about here

Step 6: After generating the pay-off matrix, upper and lower bound of each objective function is obtained which shows the minimum and maximum achievable value corresponding to each objective (goal). Table 9 shows the upper and lower bound for each objective function.

Insert

Table 9: Lower and upper bound corresponding to each objective

about here

Step 7: Fuzzy programming with hyperbolic membership function

The linear programming model (as shown in the step 3) is transformed into fuzzy programming model with the help of hyperbolic membership function. The transformed model can be stated as follows:

$Minimize \sum_{i=1}^{13} w_i * \lambda_i$

Subject to

$Z_i + \frac{\varphi_i}{\alpha_i} \leq \left(\frac{U_i+L_i}{2}\right)$ $\quad for\ i = 1,2,3,5$

$Z_i - \frac{\varphi_i}{\alpha_i} \geq \left(\frac{U_i+L_i}{2}\right)$ $\quad for\ i = \ 4,6,7,8,9,10,11,12,13$

Demand Constraints:

$\sum_{j=1}^{4} QO_{ij} \geq RO_i$ $\quad for\ i = 1,2, \dots 4$

Capacity Constraint:

$QO_{ij} \leq AC_{ij}$ $\quad for\ i = 1,2, \dots 4, j = 1,2, \dots 4$

$QO_{ij} \geq 0$ $\quad \forall\ i,j$

$\lambda_i \geq 0$ $\quad \forall\ i$

Where, $\varphi_i = tanh^{-1}(2\lambda_i - 1)$, $\alpha_i = \frac{6}{U_i - L_i}$

Since $tanh$ and $tanh^{-1}$ are strictly increasing functions and $\lambda_i = \frac{\tanh(\varphi_i)+1}{2}$, so an equivalent problem by replacing λ_i with φ_i is solved to find optimal solution.

6. Results and Discussion

The proposed fuzzy goal programming model for the evaluation of suppliers is solved using a commercial optimization software, LINGO. The proposed model gives the optimum order quantities (QO_{ij}), that should be allocated to each supplier (say, a demand of QO_{ij} units of item i should be placed to supplier j) for the sustainable supply chain. The proposed model is also compared with the traditional models of supplier selection (Jadidi, Zolfaghari, & Cavalieri, 2014; Ozkok & Tiryaki, 2011; Zimmermann, 1978) and was found to be better, as it achieves higher aspiration level for most of the objectives. Table 10 shows the comparison of optimal values and aspiration level of criterion with the traditional methods.

Ozkok & Tiryaki, (2011) extended the model of Zimmermann (1983) and proposed a compensatory fuzzy method for the multi objective linear supplier selection problem. The basic assumption of this model is that the membership function for the fuzzy objectives is taken to be linear and compensatory parameter is decided by the decision makers. In real life, finding the value of this parameter is a complex task to reflect decision maker's preference. In this paper, the solution obtained through the proposed model is compared with the solution obtained through Ozkok & Tiryaki, (2011) model for $\gamma = 0.9$ (compensatory parameter) and the solution obtained by the proposed model is found to be more optimal with higher membership grades. Jadidi et al., (2014) proposed a normalized goal programming approach to achieve some levels of consistency among the objectives. In this model a solution is said to be consistent if the achieved objectives have a proportional distance from their goals. Whereas in the proposed model the objectives achieve higher aspiration level (membership grade) for most of the objectives with the help of hyperbolic membership function.

It can be observed from Table 10 that the proposed approach achieves higher membership grade for most of the criteria as compared to the traditional methods, and thereby gives more optimal value for the objective functions (highlighted in Table 10). For example, in the proposed model

'Recycling practices (Z_{10})' goal achieves the aspiration level 0.99 against the 0.55, 0.75 and 0.56 values obtained through the traditional models which show that the suppliers selected through the proposed approach, follows the 'Recycling practices' to its highest level as compared to other aproaches. The average membership grades under the criteria; economical, lean, environmental and service are 0.62, 0.62, 0.82 and 0.90 respectively, which show that the selected supplier stands good for the services and follow the practices of sustainablity.

It can be observed from Table 11 that according to the proposed model supplier 1 is good for items 1 and 4. While supplier 2 is good for items 2 and 3, as it supplies higher number of units for the respective items. Supplier 1 supplies the complete order of item 1. The zero entry corresponding to each supplier for the particular item shows that the supplier achieves low score in economical, lean, environmental constraints as compared to other suppliers; thereby a quantity zero is assigned to that supplier.

Insert

Table 10: Optimal value and aspiration level of objective functions

Table 11: Optimal order quantity

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7. Conclusion

Supplier selection is a complex multi criteria decision making problem. Evaluation of suppliers on the basis of both quantitative and qualitative data becomes a complex task for the decision makers due to many conflicting criteria. It can be seen in the literaurture that many researchers have used linear, triangular and trapezoidal membership functions to capture the uncertainty but very few of the researchers have used non-linear membership due to complexity of the problem. In this paper, a fuzzy goal programming approach integrating hyperbolic membership function is proposed to solve complex problem of supplier selection.

Ever increasing concern towards sustainability has forced decision makers to evaluate suppliers on the basis of environmental performances. Various researchers separately considered economic aspect, lean practices and sustainable development. This study integrates all the three aspects together in the supplier evaluation. In this paper, the proposed approach of supplier selection is divided into two phases. In the first phase, a criterion ranking model is proposed to obtain the weights of ambiguous supplier evaluation criterion. Phase two introduces a fuzzy goal programming approach integrating hyperbolic membership function to find the best supplier for the items to be purchased. The non-linear hyperbolic membership function maintains the continuity and differentiability of objective function and truly transform the values into membership grade.

A case study presented in this paper is used to check the robustness and validity of the proposed approach. Results obtained through the proposed approach is compared with the traditional approaches (Jadidi et al., 2014; Ozkok & Tiryaki, 2011; Zimmermann, 1978) of supplier selection and was found to be optimal as it achieves higher aspiration level (membership grade).

The proposed model is adaptive to solve real world problems of supplier selection as all criterion do not possess the same weights, so the managers can change the criterion and their weights according to their requirement. The priority of each criterion can easily be calculated with the help of proposed approach (as shown in phase one) and the model can be applied to various multi objective supplier selection problem with quantitative, qualitative or both type of criterion.

Limitations and Future work

In this paper, phase one determines the weights of criterion based on the responses of the experts. The responses obtained from the experts are in linguistic form. Hence, a membership function should be carefully selected to cover all the possible variation in the responses. The model proposed in this paper can further be extended to incorporate the constraints on the membership grades. Further, objective functions with lower membership grades can be set to a minimum threshold limit. For example, the degree of membership grade of green packaging goal (Z_{11}) is obtained as 0.5. This aspiration level (membership grade) may not be sufficient to satisfy decision makers' objective of high green packaging standards. In real life, one cannot compromise with the poor performance of one criteria and good performance of other criterion. To incorporate this, the proposed model can be reformulated by including an additional condition on the aspiration level (membership grade).

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Table 1: Summary of literature review

Category	Paper(s)	Description
Literature Review	Aissaoui et al., (2007)	Review
	Choi & Hartley (1996)	
	De Boer et al., (2001)	
	Ho et al., (2010)	
	Wilson (1994)	
Framework for supplier selection criteria	Dickson (1966)	Proposed 23 criterion of supplier selection
	Chang et al., (2014)	Multi-segment and multi-aspiration criterions
	Amin & Zhang (2012)	Supplier, parts and process, reverse logistic
	Yadav & Sharma (2016)	Quality, cost, delivery, service, flexibility and long term relationship
	Singh & Sharma (2014a)	Highlighted the importance of 'flexibility' and 'long term relationship'
Supplier selection problem + Sustainability	Humphreys ae al., (2003)	Considered chemical waste, solid waste, air emission, energy and water waste disposal
	Hsu & Hu (2009)	Hazardous substance management
	Erol et al., (2011)	Environmental sustainability, social sustainability and economic sustainability
	Noci (1997)	Green competencies, current environmental efficiency, supplier's green image and net life cycle cost
	Humphreys & McCloskey (2006)	Categorized criteria into quantitative and qualitative environmental criteria
	Sarkis (1998)	Design for the environment, life cycle analysis, total quality environmental management and green supply chain
	Kuo et al., (2010)	Cost, quality delivery, environment, service and corporate social responsibility.

Methodology	Paper(s)	Description

AHP/FAHP	Ghodsypour & O'Brien (1998)	AHP + Linear programming
	Shaw et al., (2012)	Fuzzy AHP + Linear programming
	Singh & Sharma (2014b)	Fuzzy AHP + extent analysis
ANP/FANP	Lin (2012)	FANP + Linear Programming
	Lin (2009)	Combination of association rule and set theory
	Tseng et al., (2009)	Choquet integral
	Noci (1997)	Green vendor rating system
Fuzzy Linear programming	Lin (2012)	ANP + Linear programming
	Wu (2009)	A hybrid model for classification and prediction
	Kumar etal., (2006)	Cost-minimization, quality & delivery-maximization
	Ng (2008)	A simple weighted LP
	Lin (2012)	FANP + Linear Programming
	Ghodsypour & O'Brien (1998)	AHP + Linear programming
Goal Programming	Charnes & Cooper (1957)	Management Models and Industrial Applications
	Ignizio (1985)	Algorithm to solve goal programming
	Lee (1972)	
	Romero (2001)	Extended lexicographic goal programming
	Tamiz et. Al., (1998)	
	Charnes et al., (1955)	Optimal Estimation of Executive Compensation
Fuzzy Goal programming	Amid et al., 2011	Weighted max–min fuzzy decision model
	Kumar et al., (2004, 2006)	Vendor selection for cost-minimization, quality-maximization and maximization of on-time-delivery,
	Liao & Kao (2011)	(Group) Multi-choice goal programming
	Tsai & Hung (2009)	Fuzzy GP; Green SCM
	Jadidi et al., (2014)	Normalized Goal Programming
	Shaw et al., (2012)	Low carbon SCM
	Kumar et al., (2006)	Cost-minimization, quality & delivery-maximization
Hybrid Approach	Liao & Kao (2011)	TOPSIS + Goal Programming
	Yadav & Sharma (2015a, 2015c)	DEA +AHP
	Amid et al., (2011)	AHP + Weighted Max-Min fuzzy model
	Ghodsypour & O'Brien (1998)	AHP + Linear programming

	Shaw et al., (2012)	Fuzzy AHP + Linear programming
	Lin (2012)	ANP + Linear programming

Membership Function	**Paper(s)**	**Description**
Linear	Jadidi et al., (2014)	Normalized Goal Programming
	Kumar et al., (2004, 2006)	Parameters have been treated as vague with a linear membership function of fuzzy type
Triangular	Büyüközkan & Çifçi, (2011)	Green SCM
	Lee et al., (2009)	The Delphi method + Fuzzy AHP
	Lu et al., (2007)	Analytical hierarchy process
	Şen et. Al., (2010)	
	Shaw et al., (2012)	Low carbon SCM
Trapezoidal	Bai & Sarkis (2010)	Grey system and rough set methodologies
	Labib (2011)	Fuzzy linguistic expression, Fuzzy logic
Non-Linear	Díaz-Madroñero et al., (2010)	S- Curve Membership function

Table 2: Supplier selection criteria

Criteria	Sub-criteria	Description
Economic Aspect	Cost	Z_3: Minimize the cost of product (PC)
	Quality	Z_1: Minimize the rate of rejection (URP)
	Delivery/Lead Time	Z_2: Minimize the units delivered late (UDLP)
	Capacity	Z_4: Maximize the capacity utilization ratio (CUR)
	Transportation cost	Z_5: Minimize the transportation cost (TC)
Lean Practices	Waste Reduction	Z_7: Maximize the waste reduction practices (WR)
	Just in Time approach	Z_8: Maximize the JIT practices (JIT)
	Technological Capability	Z_9: Maximize the Technological Capability (TEC)
Sustainability	Recycling	Z_{10}: Maximize the recycling practices adopted by the suppliers (REC)
	Green Packaging	Z_{11}: Maximize the green packaging practices (GRP)
	Eco-friendly material and technology	Z_{12}: Maximize the Eco-friendly material and technological practices (EMT)
Services	Conflict Resolution	Z_{13}: Maximize the conflict resolution index (CR)
	Flexibility in demand change	Z_6: Maximize the flexibility in demand change (FDC)

Table 3: Responses of decision makers

	Decision Maker				
Criterion	**1**	**2**	**3**	**4**	**5**
(Z_1) URP	MH	M	VH	H	H
(Z_2) UDLP	H	MH	H	H	H
(Z_3) PC	VH	H	MH	L	L
(Z_4) CUR	VH	L	M	H	M
(Z_5) TC	H	H	M	H	MH
(Z_6) FDC	MH	H	H	MH	M
(Z_7) WR	M	MH	MH	H	M
(Z_8) JIT	H	MH	H	MH	H
(Z_9) TECH	M	H	L	H	MH
(Z_{10}) REC	L	H	H	L	MH
(Z_{11}) GRP	MH	H	MH	H	M
(Z_{12}) EMT	H	MH	M	MH	H
(Z_{13}) CR	H	MH	M	H	M

Table 4: Response of experts corresponding to each criterion

(Goal) Criterion	Aggregate Fuzzy response	α-Cut (for $\alpha = 0.5$)	Crisp Response	Weight
(Z1) URP	(0.3, 0.68, 0.74, 1)	(0.49, 0.68, 0.74, 0.87)	0.7	0.088161
(Z2) UDLP	(0.5, 0.72, 0.8, 0.9)	(0.61, 0.72, 0.8, 0.85)	0.75	0.094458
(Z3) PC	(0.1, 0.53, 0.59, 1)	(0.31, 0.53, 0.58, 0.79)	0.55	0.06927
(Z4) PUR	(0.1, 0.53, 0.58, 1)	(0.31, 0.53, 0.58, 0.79)	0.55	0.06927
(Z5) TC	(0.3, 0.58, 0.62, 0.9)	(0.44, 0.58, 0.62, 0.76)	0.59	0.074307
(Z6) FDC	(0.3, 0.62, 0.66, 0.9)	(0.46, 0.62, 0.66, 0.78)	0.63	0.079345
(Z7) WR	(0.3, 0.55, 0.57, 0.9)	(0.42, 0.55, 0.57, 0.73)	0.56	0.070529
(Z8) JIT	(0.5, 0.69, 0.75, 0.9)	(0.59, 0.69, 0.75, 0.82)	0.71	0.089421
(Z9) TECH	(0.1, 0.54, 0.59, 0.9)	(0.32, 0.54, 0.59, 0.74)	0.55	0.06927
(Z10) REC	(0.1, 0.5, 0.56, 0.9)	(0.3, 0.5, 0.56, 0.73)	0.5	0.062972
(Z11) GRP	(0.3, 0.62, 0.66, 0.9)	(0.46, 0.62, 0.66, 0.78)	0.63	0.079345
(Z12) EMT	(0.3, 0.62, 0.66, 0.9)	(0.46, 0.62, 0.66, 0.78)	0.63	0.079345
(Z13) CR	(0.3, 0.58, 0.62, 0.9)	(0.44, 0.58, 0.62, 0.76)	0.59	0.074307

Table 5: Data Collection

	Supplier 1 Items				Supplier 2 Items				Supplier 3 Items				Supplier 4 Items			
	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4
…es received	10800	21950	10920	21890	10905	20916	10870	21930	10900	21807	10876	21790	10704	21904	10732	21594
…s delivered late	302	507	253	652	500	700	207	456	505	832	360	418	206	101	169	351
…s rejected	210	360	154	168	1350	198	129	213	164	217	345	377	135	485	164	156
…oduct Cost	113	171	145	211	115	168	146	215	110	174	141	218	114	170	147	222
…early productivity	14000	30000	18000	28000	15000	30000	15000	30000	20000	25000	16000	26000	14000	30000	16000	25000
…ansportation Cost/unit	17	23	22	26	19	21	25	25	20	19	27	21	17	22	23	25
…exibility in demand	MH	MH	H	M	M	H	MH	H	L	L	M	M	L	H	MH	H
…aste Reduction	M	M	M	M	VH	VH	VH	VH	H	H	H	H	VH	VH	VH	VH
…st in Time approach	H	H	H	H	MH	MH	MH	MH	M	M	M	M	M	M	M	M
…chnological Capability	H	H	H	H	MH	MH	MH	MH	MH	MH	MH	MH	H	H	H	H
…ecycling	H	VH	MH	VH	MH	VH	MH	M	M	L	L	M	L	L	M	M
…reen Packaging	H	H	H	H	MH	MH	MH	MH	VH	VH	VH	VH	M	M	M	M
…o-friendly …aterial/technology	MH	M	MH	M	H	VH	H	MH	MH	M	M	L	MH	M	MH	M
…onflict Resolution	H	H	H	H	MH	MH	MH	MH	M	M	M	M	M	M	M	M

Table 6: Performance measures

	Supplier 1				Supplier 2				Supplier 3				Supplier 4			
…erion	Item 1	Item 2	Item 3	Item 4	Item 1	Item 2	Item 3	Item 4	Item 1	Item 2	Item 3	Item 4	Item 1	Item 2	Item 3	Item 4
	0.019	0.016	0.017	0.008	0.012	0.010	0.012	0.010	0.015	0.010	0.032	0.017	0.013	0.022	0.015	0.007
…P	0.028	0.023	0.023	0.030	0.046	0.034	0.019	0.021	0.046	0.038	0.033	0.019	0.019	0.046	0.016	0.016
	0.250	0.250	0.250	0.244	0.254	0.246	0.252	0.248	0.243	0.255	0.244	0.252	0.252	0.249	0.254	0.256
	0.771	0.732	0.607	0.782	0.727	0.697	0.725	0.731	0.545	0.872	0.680	0.838	0.765	0.730	0.671	0.864
	0.233	0.271	0.227	0.268	0.260	0.247	0.258	0.258	0.274	0.224	0.278	0.216	0.233	0.259	0.237	0.258
…OC	0.610	0.610	0.780	0.410	0.410	0.780	0.610	0.780	0.220	0.220	0.410	0.410	0.220	0.780	0.610	0.780
…R	0.410	0.410	0.410	0.410	0.910	0.910	0.910	0.910	0.780	0.780	0.780	0.780	0.910	0.910	0.910	0.910
	0.780	0.780	0.780	0.780	0.610	0.610	0.610	0.610	0.410	0.410	0.410	0.410	0.410	0.410	0.410	0.410
…CH	0.780	0.780	0.780	0.780	0.610	0.610	0.610	0.610	0.610	0.610	0.610	0.610	0.780	0.780	0.780	0.780
…C	0.780	0.910	0.610	0.910	0.610	0.910	0.610	0.410	0.410	0.220	0.220	0.410	0.220	0.220	0.410	0.410
…RP	0.780	0.780	0.780	0.780	0.610	0.610	0.610	0.610	0.910	0.910	0.910	0.910	0.410	0.410	0.410	0.410
…MT	0.610	0.410	0.610	0.410	0.780	0.910	0.780	0.610	0.610	0.410	0.410	0.220	0.610	0.410	0.610	0.410
…R	0.780	0.780	0.780	0.780	0.610	0.610	0.610	0.610	0.410	0.410	0.410	0.410	0.410	0.410	0.410	0.410

Table 7: Optimal solution

Supplier	Quantity Ordered	QO_1^*	QO_2^*	QO_3^*	QO_4^*	QO_5^*	QO_6^*	QO_7^*	QO_8^*	QO_9^*	QO_{10}^*	QO_{11}^*	QO_{12}^*	QO_{13}^*
1	QO_{11}	0	4000	0	10000	4000	10000	0	10000	4000	10000	0	0	10000
	QO_{12}	0	10000	0	0	0	0	0	10000	7000	0	0	0	10000
	QO_{13}	0	0	0	0	10000	10000	0	10000	0	3000	0	0	10000
	QO_{14}	0	0	10000	0	0	0	0	10000	0	10000	5500	0	10000
2	QO_{21}	10000	0	0	0	0	0	4000	0	0	0	0	10000	0
	QO_{22}	10000	0	10000	0	0	7000	7000	0	0	10000	0	10000	0
	QO_{23}	7000	0	0	7000	0	0	7000	0	0	7000	0	7000	0
	QO_{24}	0	0	0	0	0	0	0	0	0	0	0	10000	0
3	QO_{31}	0	0	10000	0	0	0	0	0	0	0	10000	0	0
	QO_{32}	0	0	0	10000	10000	0	0	0	0	0	10000	0	0
	QO_{33}	0	0	10000	3000	0	0	0	0	0	0	10000	0	0
	QO_{34}	0	0	0	0	4500	0	0	0	0	0	4500	0	0
4	QO_{41}	0	6000	0	0	6000	0	6000	0	6000	0	0	0	0
	QO_{42}	0	0	0	0	0	3000	3000	0	3000	0	0	0	0
	QO_{43}	3000	10000	0	0	0	0	3000	0	10000	0	0	3000	0
	QO_{44}	10000	10000	0	10000	5500	10000	10000	0	10000	0	0	0	0

Table 8: Pay-off Matrix

(Goal) Criterion	Optimal Order Quantities												
	QO_1^*	QO_2^*	QO_3^*	QO_4^*	QO_5^*	QO_6^*	QO_7^*	QO_8^*	QO_9^*	QO_{10}^*	QO_{11}^*	QO_{12}^*	QO_{13}^*
(Z_1) URP	420.2	542.2	559	533	538.65	566.8	459.2	603	559.3	499.7	687.2	445.2	603
(Z_2) UDLP	1137.1	778.2	1224	1220	1017.25	1047.8	1014.7	1041	847.2	1115.6	1426.3	1182.1	1041
(Z_3) PC	10094	10119	9765	9989	10108	10036	10090	9944	10115	9913	9889	10013	9944
(Z_4) PUR	29965	30335	27037	32187	30985	29489	30289	28915	30330	29397	29041	28637	28915
(Z_5) TC	10166	9983	10674	10257	9224	9680	10037	9983	9948	9964	10207	10166	9983
(Z_6) FDC	25800	23760	20200	22100	19895	29500	24660	24100	24270	24610	12600	25800	24100
(Z_7) WR	36400	29400	20100	21400	27515	26400	36400	16400	30900	24900	29165	36400	16400
(Z_8) JIT	21800	21580	27500	29500	21580	25200	20000	31200	20470	28310	18435	23800	31200
(Z_9) TECH	26610	31200	29500	29500	28735	30010	28140	31200	31200	28310	25335	24910	31200
(Z_{10}) REC	24800	21740	28400	30400	16840	25030	20390	32100	19670	32100	15350	24800	32100
(Z_{11}) GRP	21800	21580	32500	29500	28830	25200	20000	31200	20470	28310	35685	23800	31200
(Z_{12}) EMT	28290	20400	20400	22100	19545	23900	25770	20400	20400	26590	17545	30290	20400
(Z_{13}) CR	21800	21580	27500	29500	21580	25200	20000	31200	20470	28310	18435	23800	31200

Table 9: Lower and upper bounds corresponding to each objective

(Goal) Criterion	Lower Bound	Upper Bound
(Z_1) URP	420.2	687.2
(Z_2) UDLP	778.2	1426.3
(Z_3) PC	9765	10119
(Z_4) PUR	27037	32187
(Z_5) TC	9224	10674
(Z_6) FDC	12600	29500
(Z_7) WR	16400	36400
(Z_8) JIT	18435	31200
(Z_9) TECH	24910	31200
(Z_{10}) REC	15350	32100
(Z_{11}) GRP	20000	35685
(Z_{12}) EMT	17545	30290
(Z_{13}) CR	18435	31200

Table 10: Optimal value and aspiration level of objective functions

(Goal) Criteria	Proposed Method		Zimmermann (1983) Approach		Ozkok & Tiryaki (2011) (for γ= 0.9)		Jadidi et al., (2014)	
	Objective Value	Membership Grade	Objective Value	Membership Grade	Objective Value	Membership Grade	Objective Value	Membership Grade
(Z_1) URP	514.51	0.85	546.07	0.55	557.16	0.49	536.69	0.56
(Z_2) UDLP	1078.82	0.60	1080.56	0.55	1078.48	0.54	1059.13	0.57
(Z_3) PC	9940.86	0.5	9859.15	0.55	9942.63	0.50	9925.45	0.55
(Z_4) PUR	29613.29	0.5	29493.03	0.55	29547.44	0.49	28589.89	0.30
(Z_5) TC	9874.50	0.65	9847.93	0.55	9823.61	0.59	9863.76	0.56
(Z_6) FDC	24782.96	0.93	21335.62	0.55	23011.26	0.62	24438.12	0.70
(Z_7) WR	26400.10	0.5	26699.95	0.55	27987.23	0.58	28989.75	0.63
(Z_8) JIT	27002.31	0.88	25047.10	0.55	24651.89	0.49	25087.29	0.52
(Z_9) TECH	28055.00	0.50	27984.54	0.55	27973.39	0.49	27825.05	0.46
(Z_{10}) REC	30602.83	0.99	26702.88	0.55	27850.72	0.75	24794.40	0.56
(Z_{11}) GRP	27842.31	0.5	27939.60	0.55	27639.01	0.49	26381.70	0.41
(Z_{12}) EMT	26238.38	0.9	23872.48	0.55	24807.61	0.57	26293.23	0.69
(Z_{13}) CR	27002.31	0.88	25047.10	0.55	24651.89	0.56	25087.29	0.52

Table 11: Optimal order quantity

Supplier	Quantity Ordered	Proposed Method	Zimmermann (1983) approach	Ozkok & Tiryaki (2011) (for γ= 0.9)	Jadidi et. al. (2014)
1	QO_{11}	10000	6433	8663.83	4000
	QO_{12}	0	849	0	0
	QO_{13}	2121	1853	0	6019.318
	QO_{14}	7442	8215	6608.41	4128.09
2	QO_{21}	0	0	0	0
	QO_{22}	9987	7434	9527.59	10000
	QO_{23}	6833	4319	3478.21	1391.872
	QO_{24}	0	0	0	5871.91
3	QO_{31}	0	0	594.82	0
	QO_{32}	13	1416	472.41	0
	QO_{33}	0	2584	1515.42	2588.81
	QO_{34}	1667	1785	3391.59	0
4	QO_{41}	0	3567	741.35	6000
	QO_{42}	0	0	0	0
	QO_{43}	1046	1245	5006.38	0
	QO_{44}	891	0	0	0

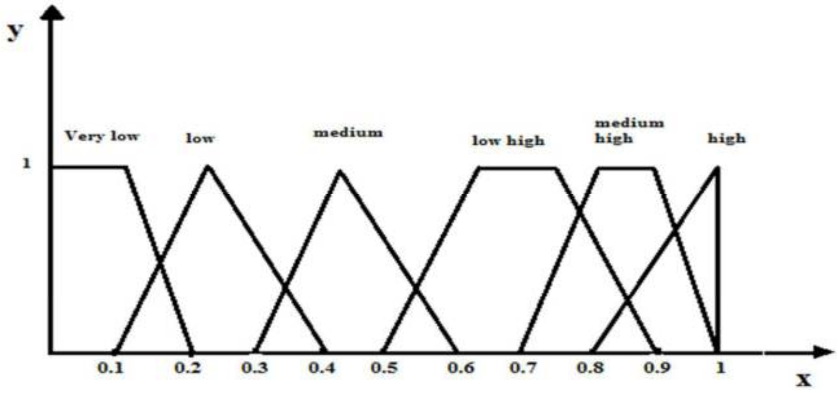

Figure 1: Membership grades of linguistic variable

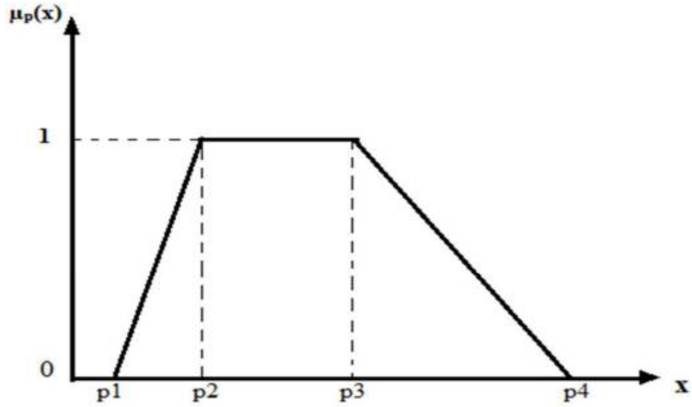

Figure 2: Trapezoidal membership function

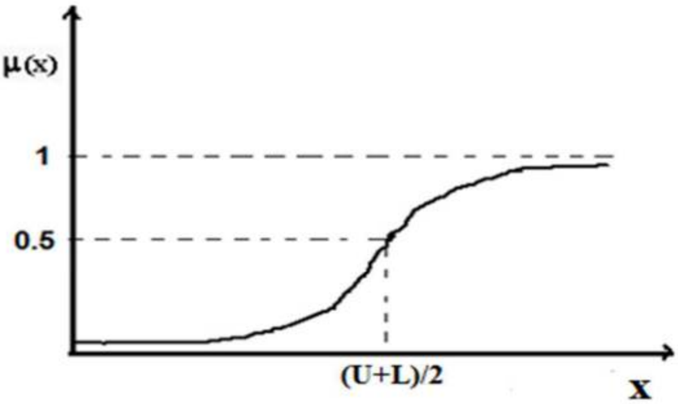

Figure 3: Hyperbolic membership function

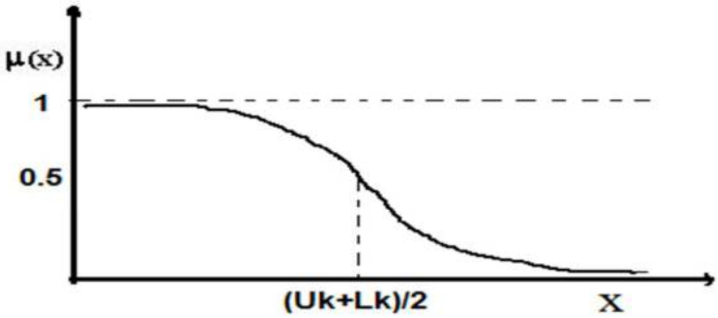

Figure 4: Hyperbolic membership function for minimization type objective

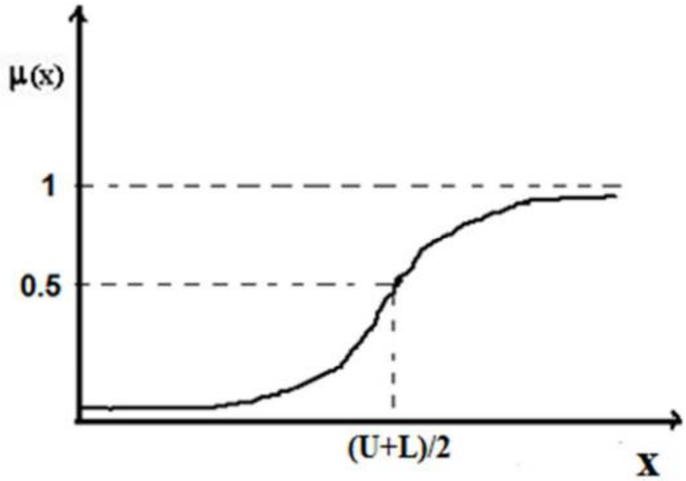

Figure 5: Hyperbolic membership function for maximization type objective