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A novel integrated model to measure supplier performance considering qualitative and quantitative criteria used in the supplier selection process

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Keywords

novel, selection, criteria, used, quantitative, process, qualitative, considering, performance, supplier, measure, model, integrated

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A Novel Integrated Model to Measure Supplier Performance Considering Qualitative and Quantitative Criteria used in the Supplier Selection Process

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Abstract

Supplier evaluation has become a significant topic over the past few decades, as companies have become more outsourced oriented. However, previous research on this topic has not paid adequate attention to the limitations associated with the availability of accurate and reliable data relating to the performance of potential suppliers. In an attempt to address this issue, this paper proposes a novel supplier evaluation model that can handle imprecise quantitative and qualitative data. Additionally, Decision Maker's judgement regarding both qualitative and quantitative criteria are incorporated into this model so that a more comprehensive and realistic assessment of supplier performance can be achieved. The model combines five separate methods that have specific capabilities to handle multiple limitations in the existing methods: first, Fuzzy Analytical Hierarchy Process and Fuzzy TOPSIS (Technique for Order Preference by Similarity to Ideal Solution) method are used to analyse qualitative criteria/data; second, Analytical Hierarchy Process and Axiomatic Design are used to analyse quantitative criteria/data, with a particular focus on handling variability in performance data; and third, Data Envelopment Analysis is used to integrate the results of the two approaches above to arrive at a comparative assessment of supplier performance. The proposed integrated model is verified using a numerical example.

Keywords: Supplier Selection, Analytical Hierarchy Process, Fuzzy TOPSIS, Axiomatic Design, Data Envelopment Analysis.

1. Introduction

Today's competitive business environment forces companies to continuously optimise their business processes to maintain a strategic advantage in global markets. However, competition increasingly occurs at the level of supply chains rather than at the firm level. Therefore, companies must cooperate and collaborate with their supply chain partners towards enhancing the performance of the overall supply chain. To this end, supplier selection has an important role to play as the performance of individual suppliers directly affects the performance of the whole supply chain.

There are many aspects of supplier performance that need to be considered in supplier selection and these can be broadly divided into qualitative and quantitative criteria. Both qualitative and quantitative criteria are important measures in selecting suppliers as the effects of these factors are often complementary [16]. Despite these complementarities, there seems to have been a strong disparity in the way researchers have used such criteria, especially, between those who have different disciplinary backgrounds. For example, researchers with an operations research background have traditionally focused on quantitative criteria in their solutions while those with a business management background have emphasised the significance of qualitative criteria[16]. Such singular-perspective treatment can lead to increased potential errors in suppler selection decisions. Numerous methods have also been used to measure supplier performance, but they suffer from similar drawbacks. For example, Data Envelopment Analysis (DEA), a widely used method, when applied on its own heavily relies on quantitative data. While recognising this limitation, some researchers have used Imprecise Data Envelopment Analysis (IDEA) and Augmented Imprecise Data Envelopment Analysis (AIDEA), using ordinal data while

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others have combined other methods with DEA to analyse qualitative data, such as Analytical Hierarchy Process (AHP), Fuzzy Analytical Hierarchy Process (FAHP) and Fuzzy TOPSIS method [24];[28];[30]. However, these studies do not consider imprecise quantitative data comprehensively.

The aim of this paper is to present a comprehensive, yet practically feasible supplier selection model capable of dealing with imprecise qualitative and quantitative data in measuring supplier performance. The proposed model considers Decision Maker (DM)'s judgment based on both qualitative and quantitative data. The paper will begin by identifying the applications, issues and limitations of current methods used for measuring supplier performance in the supplier selection process. It then proposes a model to address these issues followed by a numerical example that illustrates the utility of the model. The paper concludes with a brief discussion about the limitations of the proposed model and directions for future research.

2. Literature Review

Supplier selection is a multi-criteria decision-making problem, as there are many factors that need to be considered in the selection of a supplier. These criteria can be of two types; qualitative and quantitative criteria [16]. Considering only one type of criteria in the decision-making process increases the risk of partial treatment of supplier performance and may not identify other important aspects that contribute to a successful buyer-supplier relationship. For this reason, a number of researchers have applied Multi Criteria Decision Making (MCDM) methods. For example, Barbarosoglu and Yazgac [2] applied AHP to solve the supplier selection problem in a Turkish Electric company. Akarte *et al*. [1] proposed a web based AHP approach to analyse qualitative and quantitative criteria. Muralidharan *et al*. [22] constructed an AHP model to solve supplier selection problem, assigning weights to incorporate the level of importance of each criteria based on decision makers' opinion. Liu and Hai [20] developed a voting AHP model to evaluate the performance of suppliers taking into account the opinions of sixty managers. Hou and Su [15] defined a set of criteria with respect to SWOT (Strength, Weakness, Opportunity and Threat) and PEST (Political, Economical, Social, and Technological) analysis, and these criteria were then evaluated using AHP. Bayazit [3] developed an Analytical Network Process (ANP) - based model to select suppliers considering both supplier's performance and supplier's capabilities. Gencer and Gurpinar [12] developed an ANP model to select the best supplier for an electronic company in Turkey. Although these methods have been widely cited in literature, they rely too heavily on qualitative data and are therefore highly subjective and context-specific [14].

Another popular qualitative method used to solve the supplier selection problem is Fuzzy Set Theory (FST). In particular, this method has been utilised to handle uncertainty in the supplier selection process. For example, Bevilacqua and Petroni [4] proposed a Fuzzy model to select the best supplier out of ten suppliers involving four decision makers. Chen *et al*. [10] proposed a FST model using the concept of TOPSIS to obtain a Fuzzy Positive/Negative Ideal Solution. Sarkar and Mohapatra [25] developed a FST model to evaluate the performance and the capability of suppliers. FST, however, can also result in inconsistent results because it relies on fuzzy numbers, which are not selected based on a commonly agreed basis.

Some authors have integrated FST and AHP to address some of these issues. Kahraman *et al.* [17] proposed Fuzzy AHP to select a suitable supplier for a Turkish white goods manufacturing company. Chan and Kumar [8] also utilised Fuzzy AHP to deal with the supplier selection issue for global supply risks. Kilincci and Onal [18] applied Fuzzy AHP to solve supplier selection problem in a Turkish Washing Machine Company. Furthermore, Fuzzy AHP has been combined with some MCDM methods. Bottani and Rizzi [5]for example, combined Fuzzy AHP with cluster analysis to evaluate the performance of suppliers. Mohammady and Amid [21] integrated Fuzzy AHP and Fuzzy VIKOR (VlseKriterijumska Optimizacija I Kompromisno Resenje) to address supplier selection issues. Chamodrakas *et al.* [9] integrated Fuzzy Preference Programming and Fuzzy AHP to evaluate the performance of suppliers and to select preferred suppliers. Even though these studies can be useful in measuring supplier performance, based on qualitative criteria, the major drawback is that they do not consider quantitative data.

There are many methods available to handle quantitative data in selecting suppliers. One of these methods is Axiomatic Design. This method is particularly useful for analysing imprecise quantitative data and to obtain decision maker's judgement regarding quantitative aspects. You [29] applied Axiomatic Design to solve supplier selection issues using imprecise quantitative data

in a company. Another method, which has been widely used to measure supplier performance utilising quantitative data in the literature of supplier selection, is DEA [14]. Liu *et al*. [20] proposed DEA to select a preferred supplier using a criterion involving three inputs and two outputs. Talluri and Sarkis [27] suggested a DEA model to measure performance of eighteen suppliers incorporating four outputs and two inputs. The disadvantage of using DEA for supplier selection is its dependence on quantitative data only. However, DEA is not capable of handling qualitative criteria.

To be able to consider qualitative criteria, some authors have combined other methods with DEA. Ha and Krishnan [13] proposed a combined AHP-DEA- Neural Network (NN) approach to address the specific issues as follows. AHP was used to account for qualitative criteria, and the scores which were obtained in AHP were transferred into DEA and NN, and these scores and quantitative criteria were then analysed in DEA and NN. By comparison, Zeydan *et al*.[30] proposed a model, which included Fuzzy AHP, Fuzzy TOPSIS and DEA. Fuzzy AHP and Fuzzy TOPSIS were used to analyse qualitative criteria, and the scores which were obtained in Fuzzy AHP and Fuzzy TOPSIS were fed into DEA, and these scores and quantitative criteria were then analysed in DEA. Although these studies assist in the analysis of qualitative criteria in the evaluation of supplier performance, they do not consider imprecise quantitative data. As imprecise data reflects variations in real world conditions, incorporating methods to deal with such variations is necessary to enhance supplier selection decisions.

Some authors have used a modified DEA to analyse imprecise quantitative and qualitative data in selecting suppliers. Saen [24], for example, proposed IDEA to analyse imprecise quantitative and qualitative data in evaluating supplier performance. Wu *et al*. [28] proposed AIDEA to examine imprecise quantitative and qualitative data to distinguish between inefficient and efficient suppliers. Even though these studies analysed qualitative and imprecise quantitative data, the Decision Maker's judgement was not reflected in the analysis of quantitative data. Thus, these papers did not enable the decision maker to consider more qualitative and imprecise quantitative data with respect to the Decision Maker's judgement.

In short, there are many methods to select appropriate suppliers advocated through literature. Some methods (IDEA, AIDEA) consider qualitative and quantitative (imprecise) criteria, however; these methods are insufficient to obtain the requirements of Decision Maker. Additionally, these methods do not consider the importance degree of criteria with respect to the judgement of Decision Maker in evaluating the performance of suppliers. Furthermore, some integrated models (Fuzzy AHP- TOPSIS- DEA) were used to solve supplier selection problem considering qualitative and quantitative (non-imprecise) criteria. However, these methods do not focus on the requirement of the Decision Maker and imprecise quantitative criteria. In this paper, the requirement of the Decision Maker was considered in measuring of the performance of supplier by using of Axiomatic Design . AHP ,Fuzzy AHP, VIKOR, TOPSIS do not focus on the requirement of the Decision Maker, however; Axiomatic Design considers this requirement of Decision Maker. Additionally, in this paper, separate weighting systems (AHP- Fuzzy AHP) for type of criterion (qualitative and quantitative) was used to select the preferred supplier, this provides systematic way in solution.

3. Design Of The Integrated Model

This paper advocates a structured, comprehensive and practically feasible approach to measuring supplier performance in the supplier selection process. Table 1 summarises the supplier selection criteria that will be applied in this study. The criteria are divided into the two types of data: qualitative and quantitative, and have been compiled based on the literature informing this research.

Table 1: Supplier Selection Criteria used in the Integrated Model

Criteria	Definition	Authors	Qualitative/Quantitative
Cost Reduction Activities	Activities aimed at improving cost effectiveness, including typical discounts, such as quantity discounts	[2]	Qualitative
Compliance with sectoral price	Offering prices within sectoral price	[2]	Qualitative
Reputation	Perceived brand image and market position of the supplier in the industry	[7]; [23];[25] ;[26]	Qualitative
Technical Assistance	Ability to provide training and information in addressing technical issues to meet the needs of buyers	[11]	Qualitative

Communication	The flow of information between buyer and supplier being adequate and efficient	[7];[23];[8];[11]	Qualitative
Technological Capabilities	Supplier's potential to adapt high-end technologies in its processes	[6];[25]	Qualitative
Past Experience	The success of past activities and performance of the supplier	[7]	Qualitative
Quality Process Improvement	Level of continuous quality improvement endeavours of the supplier	[2]	Qualitative
Defect Ratio	The ratio of rejected parts in the received order	[30]	Quantitative
Conforming to Standards	The percentage of orders received within the required engineering specifications	[15]	Quantitative
Complete Quantity	Percentage of orders received complete	[16]	Quantitative
Commit Delivery	Percentage of orders received on commit date	[16]	Quantitative

4. Proposed Model

4.1. Overview of the Model

The model proposed in this paper combines qualitative and quantitative criteria in an integrated and practically feasible way, while addressing the limitations of existing methods reported in literature, as illustrated in Figure 1. The methodology starts with the analysis of quantitative criteria using the Analytical Hierarchy Process (AHP) and Axiomatic Design (AD). AHP is used to compare the quantitative criteria and AD will be used to analyse imprecise quantitative data relating to supplier performance using decision maker's requirements. Second, Fuzzy-AHP and Fuzzy-TOPSIS are used to compare the qualitative criteria using weights assigned by the decision maker. As a result, qualitative criteria are compared against each other using qualitative data. Score for each supplier will be obtained from the analysis of qualitative data in Fuzzy TOPSIS and the other score will be obtained from the analysis of quantitative data from AD. These scores will then be used in the next stage for Data Envelopment Analysis (DEA). In DEA, these scores will be analysed as output variables, and one input will be used as dummy, which equals to 1. Overall, this methodology will distinguish between inefficient and efficient suppliers.

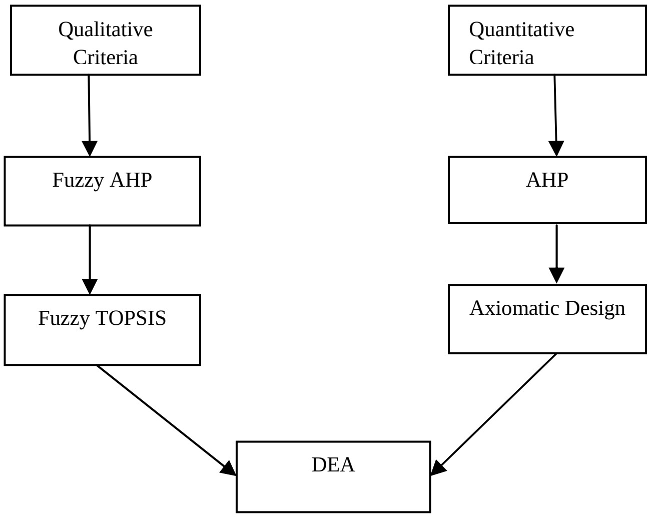

Figure 1: The Proposed Integrated Approach to Evaluate Suppliers

The following sections details the steps involved in the aforementioned supplier selection methodology.

Table 2: Notations

G	Goal set
X	Elements of Decision Matrix
S	Suppliers
C	Criteria
$\tilde{X}$	Fuzzy Elements of Decision Matrix
i	Criteria Number
j	Supplier Number
$\tilde{r}_{ij}$	Normalised Fuzzy decision Matrix
$\tilde{V}$	Weighted Normalised Fuzzy decision Matrix
A^{+}	Positive Ideal Solution
A^{-}	Negative Ideal Solution
w_i	Weight
D_j^{+}	Distance from Positive Ideal Solution
D_j^{-}	Distance from Negative Ideal Solution
$M_{m\times n}$	Normalised Decision Matrix for AHP
k_{ij}	Element of Normalised Decision Matrix in AHP
I_i	Information Content
β	Efficiency Score
$\otimes$	N-Ary Circled Times Operator
a_{ij}	The Lowest value for fuzzy numbers
b_{ij}	Medium value for fuzzy numbers
c_{ij}	The Highest value for fuzzy numbers

4.2. Analysis of Qualitative Criteria

In this section qualitative criteria are analysed using Fuzzy AHP and Fuzzy TOPSIS. The analysis of qualitative criteria is started with the following definitions as;

(i) a set of m possible suppliers called $S = \{S_1, S_2, \dots, S_j, \dots . S_m\}$;

(ii) a set of *n* criteria, $C = \{C_1, C_2, \dots, C_i, \dots . C_n\}$;

(iii) a set of performance ratings of S_j ($j = 1,2,3,\dots,m$) with regard to criteria C_i($i = 1,2,3,\dots,n$) called $\tilde{X} = \{\tilde{x}_{ij}, i = 1,2,3,\dots,n; j = 1,2,3,\dots,m\}$.
(iv) a set of importance weights of each criterion w_i($i = 1,2,3,\dots,n$). These weights were found in Fuzzy AHP using Eqn 2.

Fuzzy-AHP is used to establish priority among qualitative criteria. These qualitative criteria were shown in Table 1. In a supplier selection problem, let $X = \{x_1, x_2, \dots, x_n\}$ represent the elements of each supplier as an object set and let $G = \{g_1, g_2, \dots, g_m\}$ represent the elements of the supplier selection criteria as a goal set. According to the extended analysis of Chang (1992) where each object is taken and extent analysis for each goal is performed respectively. Thus, m extent analysis values for each object can be obtained with using the following mathematical notations:

$$M_{g_i}^1, M_{g_i}^2, \dots, M_{g_i}^m, \quad i = 1,2,\dots,n \tag{1}$$

where $M_{g_i}^j (\forall\, j = 1,2,\dots,m)$ are triangular fuzzy numbers. The steps of this method will be explained as following:

The value of the Fuzzy Synthetic Extent with respect to the i^{th} object is defined as

$$w_i = \sum_{j=1}^{m} M_{g_i}^j \otimes \left[\sum_{i=1}^{n}\sum_{j=1}^{m} M_{g_i}^j\right]^{-1} \tag{2}$$

where $\sum_{j=1}^{m} M_{g_i}^j$ is obtained by performing fuzzy addition operation of m extent analysis values for a particular matrix such that,

$$\sum_{j=1}^{m} M_{g_i}^j = \left(\sum_{i=1}^{m} l_j, \sum_{i=1}^{m} m_j, \sum_{i=1}^{m} u_j\right) \tag{3}$$

And $\left[\sum_{i=1}^{n}\sum_{j=1}^{m} M_{g_i}^j\right]^{-1}$ is obtained by performing the fuzzy addition operation of $M_{g_i}^j (j = 1,2,\dots,m)$ values such that

$$\sum_{i=1}^{n}\sum_{j=1}^{m} M_{g_i}^j = \left(\sum_{i=1}^{n} l_i, \sum_{i=1}^{n} m_i, \sum_{i=1}^{n} u_i\right) \tag{4}$$

Once Eqn. (4) is evaluated, then the inverse of this fuzzy value is computed as,

$$\left[\sum_{i=1}^{n}\sum_{j=1}^{m} M_{gi}^j\right]^{-1} = \left(\frac{1}{\sum_{i=1}^{n} u_i}, \frac{1}{\sum_{i=1}^{n} m_i}, \frac{1}{\sum_{i=1}^{n} l_i}\right) \tag{5}$$

Once Eqn.(2) is evaluated, the weights of criteria are obtained. Fuzzy weights in Table 2 are used in Fuzzy-AHP.

Table 3: Fuzzy Weights

Linguistic Variables	Fuzzy Numbers
Equal Importance	(1,1,1)
Preferred Equal Importance	(1,2,3)
A Little More Important	(2,3,4)
Preferred A Little More Important	(3,4,5)
Strongly Important	(4,5,6)
Preferred Strongly Important	(5,6,7)
More Strongly Important	(6,7,8)
Preferred More Strongly Important	(7,8,9)
Totally Important	(8,9,9)

After obtaining the weights of each criterion, Purchase Manager (Decision Maker) will assign a linguistic rating, as presented in Table 3, to each supplier under the different criteria using Fuzzy TOPSIS. Supplier selection problem can be described by following sets:

As stated above, fuzzy decision matrix format can be expressed as follows:

$$\tilde{X} = \begin{bmatrix} \tilde{x}_{11} & \cdots & \tilde{x}_{1n} \\ \vdots & \ddots & \vdots \\ \tilde{x}_{m1} & \cdots & \tilde{x}_{mn} \end{bmatrix} \text{(obtained from Table 3)}$$

(6)

Considering the different importance values of each criterion, the normalised fuzzy decision matrix ($\tilde{r}_{ij}$) is structured as:

$$\tilde{V} = \left[\tilde{v}_{ij}\right]_{nxm} \quad i = 1,2,\dots,n, \quad j = 1,2,\dots,m \tag{7a}$$

$$\text{where } \tilde{v}_{ij} = \left[\tilde{r}_{ij}\right] \otimes w_i \tag{7b}$$

According to the fuzzy theory above, fuzzy TOPSIS steps can be outlined as follows:

Step1: Choose the linguistic ratings $(\tilde{x}_{ij}, i = 1,2,3\dots,n;\ j = 1,2,3,\dots,m)$ for suppliers with regard to criteria. To obtain normalised decision matrix $\tilde{r}_{ij}$, let $\tilde{x}_{ij} = (a_{ij}, b_{ij}, c_{ij}), \tilde{x}_j^- = (a_j^-, b_j^-, c_j^-)$ and $\tilde{x}_j^+ = (a_j^+, b_j^+, c_j^+)$($a_{ij}$, is the lowest value; b_{ij}, is the medium value; c_{ij}, is the highest value for fuzzy numbers) we have

$$\tilde{r}_{ij} = \begin{Bmatrix} \dfrac{\tilde{x}_{ij}}{\tilde{x}_j^+} = \left(\dfrac{a_{ij}}{a_j^+}, \dfrac{b_{ij}}{b_j^+}, \dfrac{c_{ij}}{c_j^+}\right) \\ \dfrac{\tilde{x}_j^-}{\tilde{x}_{ij}} = \left(\dfrac{a_j^-}{a_{ij}}, \dfrac{b_j^-}{b_{ij}}, \dfrac{c_j^-}{c_{ij}}\right) \end{Bmatrix} \tag{8}$$

Step 2: Calculate the weighted normalised fuzzy decision matrix. The weighted normalised value $\tilde{v}_{ij}$ is calculated by Eqn. (6).

Step 3: Identify positive ideal (A^+) and negative ideal (A^-) solutions. The fuzzy positive-ideal solution $(FPIS, A^+)$ and the fuzzy negative-ideal solution $(FNIS, A^-)$ are indicated in Eqns. (9) and (10) respectively.

$$A^+ = \{\tilde{v}_1^+, \dots, \tilde{v}_i^+\} = \left\{\max v_{ij} \,\middle|\, i \in I\right\} i = 1,2,\dots,n, \quad j = 1,2,\dots,m \tag{9}$$

$$A^- = \{\tilde{v}_1^-, \dots, \tilde{v}_i^-\} = \left\{\min v_{ij} \,\middle|\, i \in I\right\} i = 1,2,\dots,n, \quad j = 1,2,\dots,m \tag{10}$$

where I is the criteria.

Step 4: Calculate the distance (D_j^+, D_j^-) of each alternative from $A^+$and A^- using Eqns. (11) and (12) respectively.

$$D_j^+ = \sum_{j=1}^{n} d\,(\tilde{v}_{ij}, \tilde{v}_i^+) \quad j = 1,2, \dots, m \tag{11}$$

$$D_j^- = \sum_{j=1}^{n} d\,(\tilde{v}_{ij}, \tilde{v}_i^-) \quad j = 1,2, \dots, m \tag{12}$$

Step 5: Calculate similarities to ideal solution.

$$CC_j = \frac{D_j^-}{D_j^- + D_j^+} \quad j = 1,2,3 \dots\dots, n \tag{13}$$

Table 4: Fuzzy Ratings

Linguistic Variables	Fuzzy Numbers
Very Good	(9,10,10)
Good	(7,9,10)
Medium Good	(5,7,9)
Fair	(3,5,7)
Medium Poor	(1,3,5)
Poor	(0,1,3)
Very Poor	(0,0,1)

4.3. Analysis of Quantitative Criteria

As discussed in Section 4.1, AHP will be used to determine weightings of quantitative criteria showed in Table 1. AHP will be calculated by Expert Choice. Steps of this method will be described for supplier selection problem as follows:

Step 1: Structure decision matrix to assign weight to each supplier regarding quantitative criteria. If the number of suppliers is *m* and the number of criteria is *n* then decision matrix will be as follows:

$$M_{m\times n} = \begin{bmatrix} a_{11} & \cdots & a_{1n} \\ \vdots & \ddots & \vdots \\ a_{m1} & \cdots & a_{mn} \end{bmatrix} \tag{14}$$

where an element a_{ij} of the decision matrix $M_{m\times n}$ represents the actual value of the i^{th} supplier in terms of j^{th} decision criteria.

Step 2: Normalise decision matrix. An element k_{ij} of the normalised decision matrix *R* is calculated as follows:

$$k_{ij} = \frac{a_{ij}}{\left[\sum_{i=1}^{m} (a_{ij})^2\right]^{0.5}} \tag{15}$$

Step 3: Structure a pair-wise comparison matrix of criteria using a scale of relative importance. For *n* criteria, the size of this comparison matrix will be *n*x*n* and the entry t_{ij} will denote the comparative importance of criteria *i* with respect to criteria *j*. In the matrix $t_{ij} = 1$ when $i = j$ and $t_{ji} = 1/t_{ij}$. The pair-wise comparison matrix (T_1) of criteria is shown below:

$$T_1 = \begin{bmatrix} 1 & t_{12} & \cdots & t_{1n} \\ \vdots & \vdots & \ddots & \vdots \\ t_{m1} & t_{m2} & \cdots & 1 \end{bmatrix} \tag{16}$$

The principal eigen vector (λ_{max}) of the above matrix represents the relative weights of the decision matrix of the decision criteria and it is calculated as follows:

The normalised weight or importance of the i^{th} criteria (Y_i) is determined by calculating the geometric mean of i^{th} row (GM_i) of the above matrix and then normalising the geometric means of rows. This can be represented as follows:

$$GM_i = \left\{\prod_{j=1}^{n} t_{ij}\right\}^{1/n} \text{ and } Y_i = GM_i / \sum_{i=1}^{n} GM_i \tag{17}$$

Matrix T_3 and T_4 are then calculated such that $T_3 = T_1 \times T_2$ and $T_4 = T_3 / T_2$, where

$$T_2 = [Y_1, Y_2, \dots . Y_n] \tag{18}$$

The principal eigen vector $(\lambda_{max})$of the original pair-wise comparison matrix (T_1) is calculated from the average of matrix T_4.To check the consistency in pair-wise comparison judgement, consistency index (CI) and consistency ratio $(CR)$are calculated using the following equations:

$$CI = (\lambda_{max} - n)/(n - 1) \text{ and } CR = CI/RCI \tag{19}$$

where RCI is random consistency index. If the value of CR is 0.1 or less than the judgement is considered to be consistent and therefore acceptable.

After obtaining weights from AHP, imprecise quantitative data will be examined in Axiomatic Design (AD). In Axiomatic Design, there are two different axioms: ‘independence’ and ‘information’. In this study, we will use the ‘information’ axiom. ‘Information’ is defined in terms of the information content, *I*, that is related in its simplest form to the probability of satisfying the given FR (Functional Requirements). Information content, *I*, for a given FR is defined as follows;

$$I_i = \log(1/p_i) \tag{20}$$

Where $p_i$the probability of achieving the functional requirement FRi and the logarithm is taken to base 2 (with the unit of bits)(Suh,2001).In any situation, the probability of success is given by what designer wishes to achieve in terms of tolerance (i.e., design range) and what the system is capable of delivering (i.e., system range) (Suh, 2001). The overlap between the designer-specified “design range” and the system capability range “system range” is the

region where the acceptable solution exists. This region is called common range. Figure 2 will indicate system range, design range and common range. The design including the smallest information content is the best design.

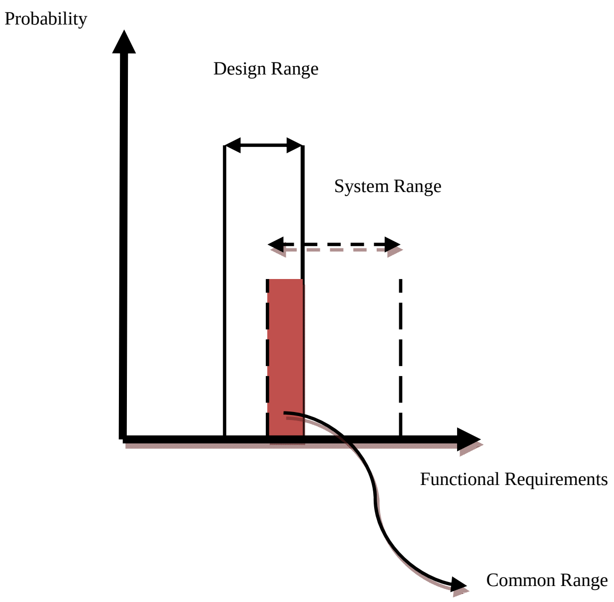

Figure 2: System Range, Design Range and Common Range

Therefore, in the case of the uniform probability distribution function, p_i may be written as:

$p_i = ((common\,range)/(system\,range))$ (21)

So, the information content is equal to:

$I_i = log_2((system\,range)/(common\,range))$ (22)

Steps of AD is follows :

- determining the design range (designer-specified), according to DM's tolerance and objective imprecise value
- determining the system range (supplier's range), according to DM's tolerance and objective imprecise value
- calculating the information content (I_i) for each criterion using Eqn. 21.
- multiplying each information content (I_i) and each criterion weight (Y_i, obtained from AHP), thus, I_{wi}(weighted information content) will be calculated as follows:

$I_{wi} = I_i \times Y_i$ (23)

- calculating the total weighted information content (I_{twi}) for each supplier using Eqn.23 as follows:

$I_{twi} = \sum_i^n I_{wi}$ (24)

After analysing qualitative and quantitative criteria based on Section 4.2 and 4.3, two values $(CC_j\ and\ I_{twi})$ will be obtained. The application of Fuzzy AHP and Fuzzy TOPSIS will provide CC_j for each of the supplier and this value is called "Qualitative Performance Value (QTPV)". Furthermore, the results of application of AHP and AD are I_{twi} for each supplier and this value is called "Quantitative Performance Value (QPV)". In order to make a balance between quantitative and qualitative performance values, we will assign 100 as the highest value for Qualitative Performance Value of supplier (as highest value in Fuzzy TOPSIS is the most precious value) and 100 as the smallest value in qualitative performance value of supplier (as the smallest value in AD is the most suitable value). Direct proportion will be used to calculate other supplier's score for QTPV. Indirect proportion will be used to calculate other supplier's score for QPV. As Fuzzy TOPSIS is a ranking method, supplier, which has the highest value, is the best supplier. On the other hand, AD is a method to reduce variance between system range and design range. For this reason, supplier, which has the smallest value, is the best supplier for AD.

4.4.Data Envelopment Analysis

QPV and QTPV will be used as output and input (dummy) for the DEA output-oriented BCC model in this section. The efficiency score of each supplier will be calculated using DEA mathematical model below. DEA output-oriented BCC model is summarised as follows:

Objective function $\acute{E_k} = Max\acute{\beta} + \varepsilon \sum_{\iota=1}^{m} s_\iota^- + \varepsilon \sum_{i=1}^{p} s_r^+$ (25)

Subject to:

$\sum_{j=1}^{n} b_{ij}\,\lambda_j + s_i^- - b_{ik} = 0,\ \ i = 1, \ldots\ldots, m$ (26)

$\sum_{j=1}^{n} e_{rj}\,\lambda_j - s_r^+ - \beta e_{rk} = 0,\ \ r = 1, \ldots\ldots, p$ (27)

$\sum_{j=1}^{n} \lambda_j = 1$ (28)

$\lambda_j \geq 0,\ j = 1, \ldots., n$ (29)

$s_i^- \geq 0, i = 1, \ldots., m,\quad s_r^+ \geq 0,\ r = 1, \ldots., p$ (30)

where, β is the efficiency score; e_{rj} is the output r for supplier j; b_{ij} is the input i for supplier j; s_i^-, s_r^+ are slack and surplus corresponding to input i, and output r, respectively; λ_j is the weights attached to inputs and and outputs of supplier j; b_{ij}, e_{rj} are inputs (i) and outputs (j) of the particular supplier (for k) whose efficiency is being evaluated and ε is a non-archimedean small and positive number.

5. Computational Results

Company X, which is a suit manufacturer, is supplied with fabric from five suppliers. The firm would like to reduce its supply base. To this end, the company will evaluate the performance of these suppliers. The company will select the most efficient suppliers for fabric supply. The Purchase

Manager (PM) of company has assigned a value to each supplier and identified the requirements of the company. Firstly, PM will compare criteria to obtain weight for each criterion. Table 5 shows PM's weights for qualitative criteria.

Table 5: PM's weights for Qualitative Criteria

Criteria / Criteria	Cost Reduction Activities	Compliance with sectoral prices	Reputation	Technical Assistance	Communication	Technological Capability	Past Experience	Quality Process Improvement
Cost Reduction Activities	(1,1,1)	(1/4,1/3,1/2)	(2,3,4)	(4,5,6)	(4,5,6)	(5,6,7)	(5,6,7)	(1/4,1/3,1/2)
Compliance with sectoral prices	(2,3,4)	(1,1,1)	(2,3,4)	(2,3,4)	(4,5,6)	(5,6,7)	(5,6,7)	(2,3,4)
Reputation	(1/4,1/3,1/2)	(1/4,1/3,1/2)	(1,1,1)	(2,3,4)	(2,3,4)	(4,5,6)	(2,3,4)	(1/4,1/3,1/2)
Technical Assistance	(1/6,1/5,1/4)	(1/4,1/3,1/2)	(1/4,1/3,1/2)	(1,1,1)	(1/4,1/3,1/2)	(4,5,6)	(2,3,4)	(1/4,1/3,1/2)
Communication	(1/6,1/5,1/4)	(1/6,1/5,1/4)	(1/4,1/3,1/2)	(2,3,4)	(1,1,1)	(2,3,4)	(2,3,4)	(2,3,4)
Technological Capability	(1/7,1/6,1/5)	(1/7,1/6,1/5)	(1/6,1/5,1/4)	(1/6,1/5,1/4)	(1/4,1/3,1/2)	(1,1,1)	(1/4,1/3,1/2)	(1/4,1/3,1/2)
Past Experience	(1/7,1/6,1/5)	(1/7,1/6,1/5)	(1/4,1/3,1/2)	(1/4,1/3,1/2)	(1/4,1/3,1/2)	(2,3,4)	(1,1,1)	(1/4,1/3,1/2)
Quality Process Improvement	(2,3,4)	(1/4,1/3,1/2)	(2,3,4)	(2,3,4)	(1/4,1/3,1/2)	(2,3,4)	(2,3,4)	(1,1,1)

In first step, the weights of criterion was calculated. Fuzzy AHP was used to determine the degree importance of each criterion using these weights (see Eqn.2). Table 6 shows results of Fuzzy AHP. These results will be aggregated in Fuzzy TOPSIS. The weights of cost reduction activities and compliance with sectoral price were calculated as below:

w_{cra}= (21.50,26.67,32.00) ⊗ (1/153.55,1/122,1/92.15) = (0.140,0.219,0.347)

w_{csp}= (23.00,30.00,37.00) ⊗ (1/153.55,1/122,1/92.15) = (0.150,0.247,0.401)

Table 6: Fuzzy Weights of Qualitative Criteria

Criteria	**Fuzzy Weights**
Cost Reduction Activities	(0.140, 0.219,0.347)
Compliance with sectoral prices	(0.150, 0.247,0.401)
Reputation	(0.077, 0.132,0.222)
Technical Assistance	(0.053,0.087, 0.144)
Communication	(0.062,0.113,0.195)
Technological Capability	(0.015,0.022,0.037)
Past Experience	(0.028,0.044,0.080)
Quality Process Improvement	(0.075,0.137,0.239)

Table 6 shows fuzzy weights for each criterion obtained in Fuzzy AHP. PM used linguistic rating variables (Table 3) to assign value for each supplier with regard to each criterion. Table 7 shows linguistic rating variables for suppliers.

Table 7: PM's Weights for Suppliers

Criteria	Cost Reduction Activities	Compliance with Sectoral Price	Reputation	Technical Assistance	Communication	Technological Capacity	Past Experience	Quality Process Improvements

Suppliers								
Supplier 1	Medium Good	Good	Medium Good	Medium Good	Medium Good	Medium Good	Medium Good	Medium Good
Supplier 2	Good	Very Good	Good	Good	Medium Good	Good	Good	Good
Supplier 3	Good	Good	Medium Good	Medium Good	Good	Medium Good	Good	Good
Supplier 4	Good	Good	Very Good	Medium Good	Good	Good	Good	Good
Supplier 5	Medium Good	Good	Good	Medium Good	Medium Good	Medium Good	Medium Good	Medium Good

Linguistic variables were converted into fuzzy numbers (see Table 3) to construct the fuzzy decision matrix. Fuzzy Decision matrix was indicated as Table 8.

Table 8: Fuzzy Decision Matrix

Criteria / Suppliers	Cost Reduction Activities	Compliance with Sectoral Price	Reputation	Technical Assistance	Communication	Technological Capacity	Past Experience	Quality Process Improvements
Supplier 1	(5,7,9)	(7,9,10)	(5,7,9)	(5,7,9)	(5,7,9)	(5,7,9)	(5,7,9)	(5,7,9)
Supplier 2	(7,9,10)	(9,10,10)	(7,9,10)	(7,9,10)	(5,7,9)	(7,9,10)	(7,9,10)	(7,9,10)
Supplier 3	(7,9,10)	(7,9,10)	(5,7,9)	(5,7,9)	(7,9,10)	(5,7,9)	(7,9,10)	(7,9,10)
Supplier 4	(7,9,10)	(7,9,10)	(9,10,10)	(5,7,9)	(7,9,10)	(7,9,10)	(7,9,10)	(7,9,10)
Supplier 5	(5,7,9)	(7,9,10)	(7,9,10)	(5,7,9)	(5,7,9)	(5,7,9)	(5,7,9)	(5,7,9)

In second step, maximum value for each column was obtained. This value for each column is 10 and this was divided into each fuzzy value to provide normalised fuzzy decision matrix (see Eqn.7a). For example, fuzzy values of supplier 1 with respect to Cost Reduction Activities are (5, 7, and 9). These values were divided by 10 and normalised fuzzy values, which are (0.5, 0.7, and 0.9), were obtained. Table 9 indicates normalised decision matrix and the weights of each criterion (obtained using Fuzzy AHP).

Table 9: Normalised Fuzzy Decision Matrix

Criteria / Suppliers	Cost Reduction Activities	Compliance with Sectoral Price	Reputation	Technical Assistance	Communication	Technological Capacity	Past Experience	Quality Process Improvements
Supplier 1	(0.5,0.7,0.9)	(0.7,0.9,1)	(0.5,0.7,0.9)	(0.5,0.7,0.9)	(0.5,0.7,0.9)	(0.5,0.7,0.9)	(0.5,0.7,0.9)	(0.5,0.7,0.9)
Supplier 2	(0.7,0.9,1)	(0.9,1,1)	(0.7,0.9,1)	(0.7,0.9,1)	(0.5,0.7,0.9)	(0.7,0.9,1)	(0.7,0.9,1)	(0.7,0.9,1)
Supplier 3	(0.7,0.9,1)	(0.7,0.9,1)	(0.5,0.7,0.9)	(0.5,0.7,0.9)	(0.7,0.9,1)	(0.5,0.7,0.9)	(0.7,0.9,1)	(0.7,0.9,1)
Supplier 4	(0.7,0.9,1)	(0.7,0.9,1)	(0.9,1,1)	(0.5,0.7,0.9)	(0.7,0.9,1)	(0.7,0.9,1)	(0.7,0.9,1)	(0.7,0.9,1)
Supplier 5	(0.5,0.7,0.9)	(0.7,0.9,1)	(0.7,0.9,1)	(0.5,0.7,0.9)	(0.5,0.7,0.9)	(0.5,0.7,0.9)	(0.5,0.7,0.9)	(0.5,0.7,0.9)
Weights	(0.140,0.219, 0.347)	(0.150,0.247, 0.401)	(0.077,0.132, 0.222)	(0.053,0.087, 0.144)	(0.062,0.113, 0.195)	(0.015,0.022, 0.037)	(0.028,0.044, 0.037)	(0.075,0.137, 0.239)

In third step, normalised fuzzy values were multiplied by the weights of criterion (see Eqn. 7b). For example, normalised fuzzy values of supplier 1 are (0.5, 0.7, and 0.9) with respect to Cost Reduction Activities and the fuzzy weights of this criterion are (0.140,0.219,0.347). The calculation of these fuzzy values was shown as below:

$\tilde{v}_{cra}$= (0.5,0.7,0.9) ⊗ (0.140, 0.219, 0.347) = (0.070,0.153,0.313)

Table 10: Weighted Normalized Matrix

Criteria / Supplier	Cost Reduction Activities	Compliance with Sectoral Price	Reputation	Technical Assistance	Communication	Technological Capacity	Past Experience	Quality Process Improvements
Supplier 1	(0.070, 0.153,0.313)	(0.105, 0.222,0.401)	(0.038, 0.092,0.200)	(0.027, 0.061,0.129)	(0.031, 0.079,0.176)	(0.008, 0.016,0.033)	(0.014, 0.031,0.072)	(0.037, 0.096,0.205)
Supplier 2	(0.098, 0.197,0.347)	(0.135, 0.247,0.401)	(0.054, 0.118,0.222)	(0.037, 0.078,0.144)	(0.031, 0.079,0.176)	(0.011, 0.020,0.037)	(0.020, 0.039,0.080)	(0.052, 0.123,0.239)
Supplier 3	(0.098, 0.197,0.347)	(0.105, 0.222,0.401)	(0.038, 0.092,0.200)	(0.027, 0.061,0.129)	(0.044, 0.102,0.195)	(0.008, 0.016,0.033)	(0.020, 0.039,0.080)	(0.052, 0.123,0.239)
Supplier 4	(0.098, 0.197,0.347)	(0.105, 0.222,0.401)	(0.069, 0.132,0.222)	(0.027, 0.061,0.129)	(0.044, 0.102,0.195)	(0.011, 0.020,0.037)	(0.020, 0.039,0.080)	(0.052, 0.123,0.239)
Supplier 5	(0.070, 0.153,0.313)	(0.105, 0.222,0.401)	(0.054, 0.118,0.222)	(0.027, 0.061,0.129)	(0.031, 0.079,0.176)	(0.008, 0.016,0.033)	(0.014, 0.031,0.072)	(0.037, 0.096,0.205)

Closeness of coefficient (CC) values, which were calculated using Eqn.13, and score of each supplier are indicated in Table 11. For calculation of CC, distances from positive ideal solution and negative ideal solution should be calculated. For example, the distance from positive ideal solution and negative ideal solution of supplier 1 can be calculated respectively as below:

$$\left.\begin{array}{l}\sqrt{\frac{1}{3}\text{x}[(1-0.070)^2+(1-0.153)^2+(1-0.313)^2]} = 0.8275 \\ \vdots \\ \sqrt{\frac{1}{3}\text{x}[(1-0.037)^2+(1-0.096)^2+(1-0.205)^2]} = 0.8901\end{array}\right\} \quad D_j^{+}=7.1548$$

$$\left.\begin{array}{l}\sqrt{\frac{1}{3}\text{x}[(0-0.070)^2+(0-0.153)^2+(0-0.313)^2]} = 0.2052 \\ \vdots \\ \sqrt{\frac{1}{3}\text{x}[(0-0.037)^2+(0-0.096)^2+(0-0.205)^2]} = 0.1324\end{array}\right\} \quad D_j^{-}=1.0052$$

and CC for supplier 1 can be calculated as follows:
CC = 1.0052/(1.0052+7.1548) = 0.1232

Table 11: Closeness of Coefficient of Qualitative Criteria

Suppliers	**CC**	**Ranks of Suppliers**	**Scores**
Supplier 1	0.1232	5	90.05
Supplier 2	0.1368	1	100
Supplier 3	0.1329	3	97.13
Supplier 4	0.1365	2	99.79
Supplier 5	0.1259	4	92.02

After obtaining results for qualitative criteria, quantitative criteria compared using AHP in Expert Choice 13.0. Table 12 indicates weights of quantitative criteria. Scores of each supplier in Table 11 will be used as output (QTPV) in DEA.

Table 12: Weights of Quantitative Criteria

Criteria	Weights

Defect Ratio	0.514
Conformance to Standards	0.278
Complete Quantity	0.159
Complete Delivery	0.05

Table 13 shows PM’s opinion regarding quantitative criteria and imprecise quantitative criteria for each supplier.

Table 13: PM’s opinion and Imprecise Quantitative Criteria

Alternatives / Criteria	Purchase Manager	Supplier 1	Supplier 2	Supplier 3	Supplier 4	Supplier 5
Defect Ratio	1-5%	4-6%	2-8%	3-6%	2-6%	1-7%
Conformance to Standards	95-100 %	94-96%	93-99%	94-97%	94-98%	94-97%
Complete Quantity	96-100%	95-97%	94-98%	92-98%	96-99%	92-97%
Complete Delivery	97-100%	96-99%	95-98%	96-99%	96-98%	94-99%

Imprecise quantitative criteria analysed in Axiomatic Design (AD) to obtain the information content of each supplier by using PM’s opinion (see Eqn.22). For example, the information content of supplier 1 was calculated with respect to defect ratio as follows:

log_2 = (6-4)/(6-5)=1.00

Table 14 indicates results of AD.

Table 14: Results of Analysis of Quantitative Data

Criteria / Suppliers	Defect Ratio	Complete Delivery	Complete Quantity	Conformance to Standards
Supplier 1	1.00	1.00	1.00	0.58
Supplier 2	1.00	0.58	1.00	1.58
Supplier 3	0.58	0.58	1.58	0.58
Supplier 4	0.42	0.42	0.00	1.00
Supplier 5	0.58	0.58	2.32	1.32

Weights obtained in AHP multiplied by results obtained in AD. Table 15 indicates weighted results, total value and scores of each supplier. The score of each supplier in Table 15 will be used as output (QPV) in DEA.

Table 15: Overall Score for Quantitative Data

Criteria / Suppliers	Defect Ratio	Complete Delivery	Complete Quantity	Conformance to Standards	Total	Score
Supplier 1	0.51	0.28	0.16	0.03	0.98	38.63
Supplier 2	0.51	0.16	0.16	0.08	0.91	41.40
Supplier 3	0.30	0.16	0.25	0.03	0.74	50.86
Supplier 4	0.21	0.12	0.00	0.05	0.38	100.00
Supplier 5	0.30	0.16	0.37	0.07	0.90	42.15

Scores of qualitative and quantitative criteria were examined as two outputs (QPV and QTPV) in Output-oriented DEA in which dummy input was used. Output-oriented DEA was calculated by Frontier Analyst 4, which is software for DEA. The solution of DEA is sensitive with regard to the number of variables (inputs and outputs), so output-oriented DEA was used to measure supplier performance with two outputs and one dummy input. Table 16 shows QTPV (scores from qualitative assessment),QPV (scores from quantitative assessment), Input, efficiency score, inefficient and efficient suppliers.

Table 16: Overall Results

Suppliers	QTPV (Output)	QPV(Output)	Input (Dummy)	Efficiency Score	Inefficient/Efficient
Supplier 1	90.05	38.63	1	90.1	Inefficient
Supplier 2	100	41.40	1	100	Efficient
Supplier 3	97.13	50.86	1	97.2	Inefficient
Supplier 4	99.79	100.00	1	100	Efficient
Supplier 5	92.02	42.15	1	92	Inefficient

Based on these results, PM will select Supplier 2 and Supplier 4 for supplying fabric.

The model proposed in this paper fills several gaps found in existing literature regarding evaluating supplier performance. As per the results of the numerical example, the overall performance of Supplier 2 and Supplier 4 is considerably high. In particular, the reputation of supplier 4 is significantly higher than that of others. Similarly, the performance of supplier 2 is considerably high in terms of compliance with sectoral price. Therefore, the score of supplier 2 is the highest score with respect to qualitative criteria. However, the score of supplier 2 is significantly low with respect to quantitative criteria. Although the score of supplier 2 is considerably low for quantitative criteria, the efficiency score of supplier 2 is higher than supplier 1, supplier 3 and supplier 5. The underlying reason is that the supplier 2 had the highest score for qualitative criteria. Saen [24]has dealt with imprecise quantitative data for measuring supplier performance in the supplier selection process; however he has only used ordinal numbers to evaluate supplier performance. In comparison, the model proposed in this paper allows analysing both qualitative and imprecise quantitative data comprehensively. Therefore, this model is suitable for problems including imprecise quantitative and qualitative data. Imprecise data can also be suitable for other selection problems, such as weapon selection, location selection and facility selection. As such, the decision support model proposed in this paper can be extended for solving such problems.

6.Discussion And Conclusions

In the context of today's competitive environment, companies are increasingly focusing on their supply chain performance. Purchasing from suitable suppliers will ensure enhanced supplier-buyer relationships and this enhancement of supplier-buyer relationship in turn will improve supply chain performance. For this reason, selecting appropriate suppliers is an important business activity for practitioners and academicians alike. There are many methods to select appropriate suppliers advocated through literature. Even though most of these methods are useful in evaluating the performance of suppliers, they do not focus on both qualitative and imprecise quantitative data to measure supplier performance. This can lead to decision makers selecting inappropriate suppliers. In this paper, a supplier selection model comprising techniques capable of analysing imprecise qualitative and quantitative data were presented and discussed. To take into account the differences between organisations and the circumstances in which each organisation make their supplier selection decisions, qualitative and quantitative criteria were treated separately. Imprecise quantitative data was analysed by using Decision Maker's opinion and qualitative data was analysed using weights from Decision Maker. Two values for each supplier, one qualitative and one quantitative, along with dummy inputs were placed in output-oriented DEA. After this process, preferred suppliers were identified. The proposed model provides a suitable solution for Decision Makers as qualitative and quantitative data are analysed based on the priorities (weightings) assigned by decision makers to each criteria. The model dealt with imprecise quantitative criteria using AHP and Axiomatic Design, thus considering decision maker's opinion regarding quantitative criteria/data. Additionally, Fuzzy AHP and Fuzzy TOPSIS were used to analyse qualitative data and to obtain decision maker's judgement regarding qualitative criteria/data. As such, the approach proposed in this paper comprehensively addresses the limitations of existing approaches to supplier selection.

Even though this model addresses the analysis of qualitative and imprecise quantitative data, it does not consider order allocation from efficient suppliers. Order allocation from suppliers is the final but an important step in the supplier the selection process, and this is significantly affected by variability in demand. Variation of demand also causes purchase costs and inventory costs. Therefore, this variability should be considered in the supplier selection process. Additionally, suppliers may not be able to meet the increased demand from manufacturers due to limitation of their capacity. This can lead to disruptions in manufacturer's production process. Therefore, the capacity of suppliers should also be considered in the supplier selection in future research.

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