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An integrated fuzzy multiple criteria supplier selection approach and its application in a welding company

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ABSTRACT

Supplier selection is a strategic decision-making task for any company, as it engages multiple criteria for the evaluation and selection of alternate suppliers. So, multi-criteria decision making (MCDM) is a necessary approach in this domain. When both the qualitative and quantitative criteria are available and required to be evaluated simultaneously in decision making process for the supplier selection, a proper integrated approach is necessary to be adopted in order to select the best supplier and to find out the interrelationship structure within criteria. To address these issues, this paper proposes a unique integrated multi-attribute decision making (MADM) and mathematical programming (MP)-based model in a mixed environment (i.e., considering qualitative and quantitative criteria together) by combining decision making trial and evaluation laboratory (DEMATEL)-based on analytic network process (ANP), i.e., DANP, fuzzy technique for order of preference by similarity to ideal solution, i.e., FTOPSIS and multiple segment goal programming (MSGP). Network relationship map (NRM) is used to outline the interrelationships among the dimensions and criteria. The novelty of the proposed supplier selection approach lies with the fact that both the qualitative and quantitative criteria have been considered in it. Sensitivity analysis has also been carried out to validate the result of our proposed methodology. In addition, the result of our proposed method is supported by DANP-based fuzzy VIseKriterijumska Optimizacija I Kompromisno Resenje (FVIKOR) technique and the best supplier has been identified. Delivery schedule and environmental collaboration are revealed to be the most and least important dimensions, respectively.

1. Introduction

Now-a-days, enterprises have been experiencing a huge competition in their supply chain. To remain competitive in the market, manufacturing organization should primarily focus on decreasing production costs and manufacturing cycle time. Under these circumstances, organizations need to outsource their many components of the product to various suppliers, whose performances decide the degree of success of supply chain of the organization, and enable the management to achieve the products of higher quality at a reduced cost with the satisfaction of downstream customer. To achieve these goals, selection of suppliers has become a critical aspect and a key strategic issue [1] of any organization. However, the main objectives of this selection include the reduction of purchase risk, value addition to the purchasers, and establishment of the proximity and long-term relationships between the purchasers and suppliers [2]. Supplier selection is operationally a pure decision-making process under certain conditions that helps the decision makers to select the potential suppliers among many [3]. Thus, decision is usually taken based on many qualitative and quantitative criteria related to the suppliers that ultimately make it a multi-criteria decision making (MCDM) process. The decision making, however, involves a high level of imprecision, vagueness or fuzziness in its process itself. However, to measure this fuzziness, traditional approaches are found to be ineffective. Therefore, there is a need for robust analytical methods and decision support tools, which could offer a fine trade-off among multiple criteria [4]. To tackle this situation effectively, fuzzy set theory has been widely used in supplier selection process [5], as it enables us to model the whole MCDM process using imprecise

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information of decision makers (DMs). Basically, this MCDM process consists of two categories: (i) multi-attribute decision making (MADM), and (ii) multi-objective decision making (MODM). MADM processes include various methods like technique for order of preference by similarity to ideal solution (TOPSIS), analytic network process (ANP), multi-attribute utility theory (MAUT), outranking methods, and others, which limit the number of alternatives, whereas MODM can determine the solutions for both single and multiple objectives subjected to specific constraints. It includes linear programming (LP), goal programming (GP), data envelopment analysis (DEA) etc. Therefore, when both the qualitative and quantitative data are available for the purpose of evaluation of suppliers, an integration of these MADM and MODM methods is required for better assessment of the performance of the suppliers in this mixed environment. Therefore, the aim of this study is set to propose a new integrated method combining decision making trial and evaluation laboratory (DEMATEL), ANP, fuzzy TOPSIS (FTOPSIS), and multi-segment goal programming (MSGP) in supplier selection problem under the fuzzy environment and identification of interrelationships among criteria and dimensions.

The remainder of the paper is organized as follows: Section 2 presents a brief review on existing literature of the supplier selection. Section 3 outlines the approaches, namely DEMATEL, ANP, FTOPSIS, Fuzzy VIKOR and MSGP. A case study addressed in this study has been demonstrated in Section 4. Results are stated and discussed in Section 5. Finally, in Section 6, conclusions are drawn and the scopes for future study have been suggested.

2. Review of literature

The research on supplier selection in supply chain management (SCM) has been getting matured since 1960s. A large number of approaches had been used by many researchers, academicians, practitioners and others. These approaches can be grouped into four categories [6] as follows: (i) MADM; (ii) mathematical programming (MP); (iii) artificial intelligence (AI); and (iv) hybrid approaches.

2.1. MADM approaches

Among many other MADM techniques, analytic hierarchy process (AHP) and ANP are the most popular ones to deal with the multiple criteria, which involve qualitative aspects [7,8]. These two methods are used to evaluate the criteria weights using pairwise comparison matrix and experts' judgments. They are much popular for effectively treating qualitative factors than other models. AHP can only be employed in hierarchical decision cases. However, in most of the real-world problems of decision making, there hardly exists hierarchical structure. Instead, a network structure of interdependency is mostly adopted in those cases. To deal with this situation, ANP, which is a generalization of AHP, is used considering dependencies between the elements in hierarchy. Usually, it is observed that ANP is used very often in combination with other methods like DEMATEL [9,10], TOPSIS [11] etc. However, some of the previous studies took an assumption that each cluster in ANP structure has equal weight to obtain weighted super matrix [10,12]. Moreover, a combination of DEMATEL and ANP (i.e., DANP) was used to evaluate the weights of criteria utilizing network relationship map (NRM) [7]. Other MADM techniques used in supplier selection literature include Elimination Et Choix Tradusant La Réalite (ELECTRE) [13,14], preference ranking organization method for enrichment evaluations (PROMETHEE) [15,16], TOPSIS [17], VIKOR [18], simple multi-attribute rating technique (SMART) [19], grey relational analysis (GRA) [20] etc. The fuzzy MCDM application in supplier selection domain had attained the interest of many researchers. Some of them include fuzzy TOPSIS [1,21], fuzzy VIKOR [22,23], fuzzy PROMETHEE [24], fuzzy DEMATEL [25,26], fuzzy AHP [27], fuzzy ANP [28,29], and so forth. However, those approaches could not handle the combined qualitative and quantitative criteria for the supplier selection tasks.

2.2. MP approaches

In mathematical programming models used in supplier selection problem, data envelopment analysis (DEA) is the popular one [30,31]. Other than DEA models, single objective mathematical programming, like linear programming, non-linear programming, mixed integer programming were used, where, in most of the cases, cost was set as only one objective function and other criteria were considered as the constraints [32]. On the other hand, some researchers used multi-objective mathematical programming to solve the supplier selection problem. For instance, Yeh & Chuang used multi-objectives Genetic Algorithms (GA) to obtain the Pareto front of solutions, while dealing with four objectives simultaneously, namely quality, green score, time and cost [33]. Fuzzy multi-objective linear programming model was used by Shaw et al. for supplier selection [34]. Kannan et al. utilized fuzzy MCDM and multi-objective programming for order allocation and green supplier selection [35]. Genetic programming (GP), a powerful multi-objective MP model, had been used by many researchers in this problem. Among those studies, Karpak et al. used GP to allocate purchase orders by minimizing the product costs and maximizing the quality of product and reliability of delivery [36]. Kumar et al. used fuzzy GP in their study for selecting the suppliers [37]. Tsai & Hung implemented fuzzy GP for the selection of green suppliers by considering the cost and performance evaluation in the associated supply chain structure [38]. Later on, in order to handle the vagueness of goals and constraints, fuzzy multi-objective linear model was used by allowing the DMs to select different weight values on various objectives [37,39]. In line with this, fuzzy multiple GP model was also found to be useful for downstream supplier selection problems [40].

Moreover, this GP model could enable the DMs to fix their levels of aspiration for each of the goals with an objective to reduce the deviation between the achievement of the goals and their corresponding aspiration levels. In 2007, Chang declared that DMs sometimes take decisions on the problems with the goal that can be achieved from some particular aspiration levels [41]. Here, the application of multi-choice GP (MCGP) became useful. Recently, Karimi & Attarpour proposed a multi-aspiration GP (MAGP) model, which could combine both MCGP and multi-segment GP (MSGP) [42]. The concept of using MSGP in supplier selection paradigm was the multi-objective planning. In that case, the objectives of the DMs were so diverse that they could not be merged into a single goal. But, DMs attempted to achieve the acceptable solution to the problem of a multi-segment aspiration level, where they were interested to minimize the deviation between the achievement of the goal and the aspiration levels of the variable co-efficients of decision.

2.3. Artificial intelligence (AI) approaches

In the supplier selection literature, AI techniques had also been used rapidly. Basically, AI is the study of intelligent agents, which perceives its surroundings and accordingly take actions that can maximize its chances of success [43]. For examples, artificial neural network (ANN), GA, data mining approaches, grey system theory were used for supplier selection [44–46]. Choy et al. used ANN model to select potential partners in a consumer product firm in Hong Kong [47]. Suppliers were also evaluated by predicting their performances in a supply chain. For examples, Lee & Ou-Yang utilized ANN-based predictive decision model to evaluate the suppliers' performances [48]. Adaptive neuro-fuzzy system (ANFIS)-based model was used by Guneri et al. to tackle the multi-objective issues (criteria selection, and performance evaluation of the suppliers) [49]. Cui used an improved GA approach for supplier selection by incorporating customer flexibility [50]; Kumar et al. tried to solve the bi-objective vendor selection problem under multi-sourcing strategy using an improved GA with a multi-parent crossover operator [51]. Another important and advanced technique like data mining has been now-a-days applied by many researchers, academicians, or practitioners. For instance, Jain et al. used data mining technique to extract knowledge in order to explore hidden relationships among the suppliers' parameters in an uncertain environment [52]. Kuo et al. applied association rule mining for selecting the important suppliers [53].

In the domain of supplier selection, some of the applications based on grey theory, which has been found to have a strong capability of handling the uncertain information within data, include grey DEMATEL approach for logistic provider solution [54], combined grey system theory and uncertainty theory [55], FAHP combined grey relational analysis (GRA) [56], grey-based decision making model [20], and so forth. Fuzzy logic applications are also found in this domain of supplier selection. For example, Mahmoudi et al. used fuzzy logic for group multi-attribute decision making [57]; Soroor et al. utilized fuzzy logic to make the smart module in order to get the best supplier bid automatically [58].

2.4. Hybrid approaches

Hybrid approaches had been developed for supplier selection by a number of researchers in order to overcome the limitation(s) of a simple technique and take the merits of two or more techniques. For instances, AHP combined DEA is one of methods used by various researchers to deal with such problems [59–61]. To name a few, Sevkli et al. used AHP-DEA approach [61]; Kuo et al. utilized fuzzy AHP and fuzzy DEA approach in their respective supplier selection problems [60]. Along with the application of AHP, intelligent approaches, such as ANN, and ANFIS have recently been applied in this domain [62]. Among other hybrid MCDA techniques, DEMATEL and ANP had been used more frequently due to the fact that the combined model not only evaluates the weights of the criteria but also explores the interrelationship structure among the factors [7,53,63,64]. Kuo et al. used DEMATEL-based ANP (DANP) and VIKOR for green supplier selection [53]. Apart from these, there are other hybrid approaches like ANP combined GP [14], Gene Expression Programming (GEP) combined DEA [65], etc., which were also found to be much more effective in this domain of research. Ayhan & Kilic used FAHP for calculating the weights for five different products and then, applied mixed-integer linear programming for distributing the ordered amounts among six suppliers [66]. In addition, some other investigators developed hybrid techniques by using GP with either ANP [67–69] or AHP [70,71] to obtain the best supplier.

2.5. Research gap and contribution of the present study

Based on the above literature review, it can be concluded that, till date, hardly there has been any study reported, which deals with both the qualitative and quantitative aspects of supplier selection simultaneously. Most of the studies concentrated on using either qualitative data or quantitative data for supplier selection problem. Although a considerable amount of work had been carried out in this field, some important aspects are still ignored, e.g., supplier selection based on qualitative and quantitative data together, exploration of the interrelationship among the criteria, dimensions used for supplier selection etc.

To address these issues, DEMATEL, ANP, FTOPSIS and MSGP methods have been used together in this study to provide the solution to the company. DEMATEL has been used to find out the interrelationship among the criteria. Thereafter, ANP has been performed to compute the weight of each of the criteria. Using these weights, FTOPSIS is done, which is able to generate the ranking of the suppliers. In order to use the quantitative data relative to supplier selection, MSGP approach has been combined to DANP-FTOPSIS method in this study. To the best of the authors' knowledge, no work has been reported on solving the supplier selection problem by utilizing an integrated method of DEMATEL, ANP (i.e., DANP), fuzzy TOPSIS, and MSGP. Results of the present study have been validated using sensitivity analysis and compared to that of fuzzy VIKOR technique. Therefore, the contributions of the present study on supplier selection can be summarized as follows:

(i) This study proposes a novel integrated model using MADM (i.e., DANP and FTOPSIS) and MP (i.e., MSGP) approach that simultaneously considers both the qualitative and quantitative data of suppliers' *selection of a welding manufacturing industry in India.*
(ii) It not only attempts to resolve the supplier selection problem by providing ranking, but also explores the interrelationships among the evaluation criteria and dimensions.

3. Methodology

In this section, the process starting from data collection to final decision making has been discussed in brief. In the *first stage*, a decision-making team consisting of five experts of a welding manufacturing company (in India) validates the evaluation criteria and dimensions obtained from a series of experts' meeting and review of literature, and then, ten potential suppliers associated with them are identified. In the *second stage*, DEMATEL is used to get the interrelationship of the criteria and dimensions. Then, to obtain the weights of criteria, ANP is performed in the *third stage*. In the *fourth* and *fifth stages*, FTOPSIS and MSGP are used to obtain the final optimal ranking of the suppliers, respectively. The result is validated by DANP-based FVIKOR, and sensitivity analysis is carried out in the *sixth stage*. Finally, comparison between the two algorithms has been made and the best supplier has been identified in *seventh stage*. The methods and the overall steps of this integration are depicted through a flowchart, as shown in Fig. 1.

3.1. Dematel

DEMATEL is used due to its capability of describing the complex systems through the identification of cause-effect influences among criteria or dimensions for evaluation. The method can be explained in four steps, as given below [7].

Step 1: Calculation of the average matrix

At first, a five-point influence scale is selected: "No influence (0)", "Low influence (1)", "Medium influence (2)", "High influence (3)" and "Very high influence (4)". Then, all the experts (say, H experts) are asked to make pairwise comparison in terms of influence between two criteria, from which direct relationship matrix

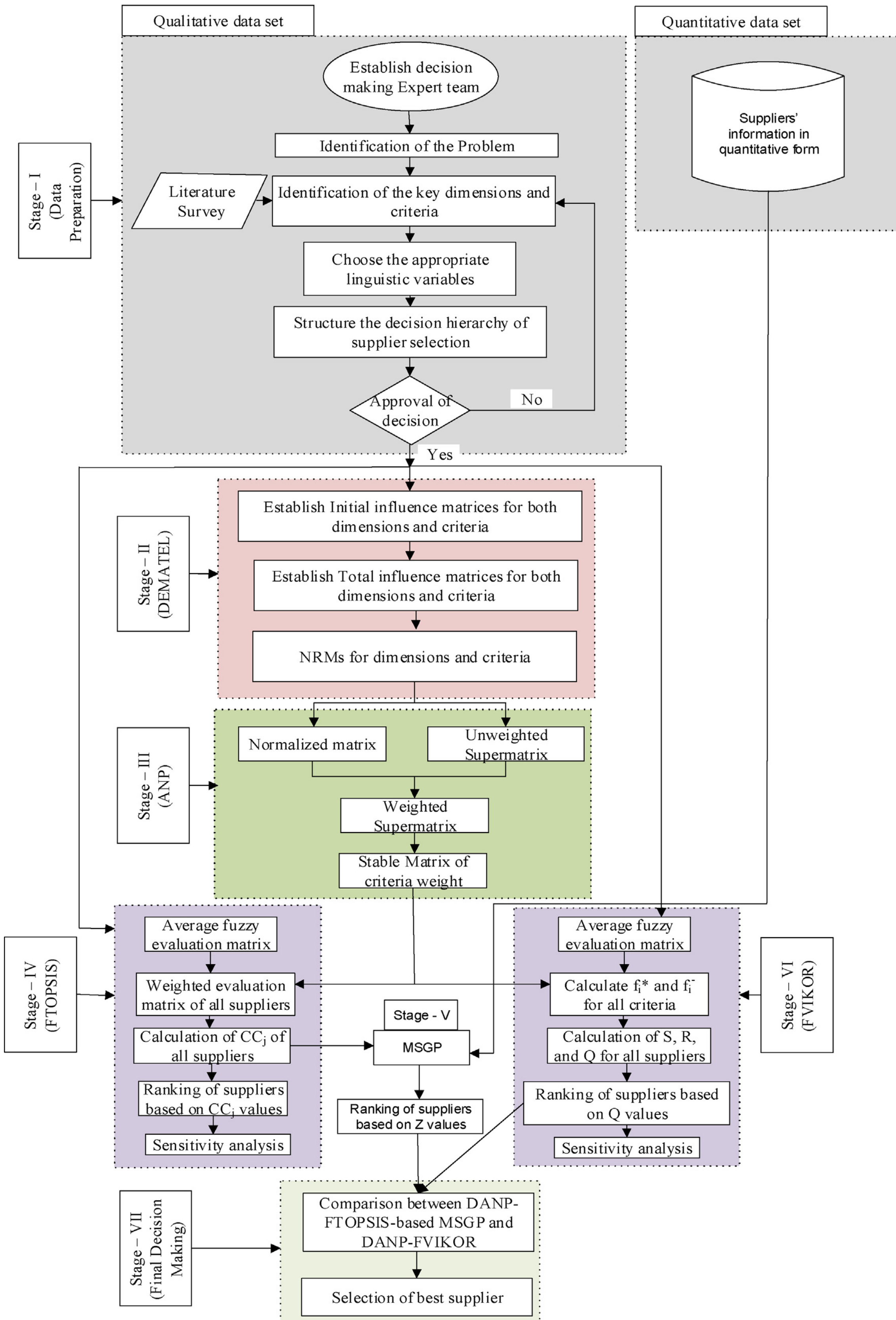

Fig. 1. The flowchart of the proposed methodology.

for them is formed. Then, average matrix A (i.e., $[a_{ij}]_{n'\times n'}$) is calculated using Eq. (1).

$$a_{ij} = \frac{1}{H}\sum_{k=1}^{H} c_{ij}{}^{k}, \tag{1}$$

where a_{ij} is called the degree of influence of the criteria from i to j, and n' is the number of criteria.

Step 2: Calculation of the normalized direct influence matrix

Normalized direct influence matrix can be computed utilizing Eqs. (2)–(3). D is a matrix obtained by Eq. (3), in which the sum of all principal diagonal elements is kept equal to zero and $\lim_{k\to\infty} D^k = [0]_{n' x n'}$.

$$S_1 = \max\left(\max_{1\le i\le n'}\sum_{j=1}^{n'} a_{ij}, \max_{1\le j\le n'}\sum_{i=1}^{n'} a_{ij}\right) \tag{2}$$

So,

$$D = \frac{A}{S_1} \tag{3}$$

Step 3: Computation of the total influence matrix (T)

Total influence or relation matrix, T can be computed through Eq. (4), where I denotes the identity matrix. The parameters: r and s are the summations of the row and column elements of T matrix and can be calculated using Eqs. (5) and (6), respectively.

$$T = [t_{ij}] = D + D^2 + \ldots + D^k = D(I-D)^{-1} \text{when} \lim_{k\to\infty} D^k = [0]_{n'\times n'}, \text{where} i \text{and} j = 1, 2, \ldots, n', \tag{4}$$

Here,

$$D = \left[c'_{ij}\right]_{n'\times n'}, 0 \le c'_{ij} \le 1 \text{and } 0 \le \sum_i c'_{ij} \le 1 \text{or } 0 \le \sum_j c'_{ij} \le 1$$

$$r = [r_i]_{n'\times 1} = \left(\sum_{j=1}^{n'} t_{ij}\right)_{n'\times 1}, \text{ and} \tag{5}$$

$$s = [s_j]_{n'\times 1} = Transpose\left(\sum_{i=1}^{n'} t_{ij}\right)_{1\times n'} \tag{6}$$

Here, it is noteworthy to mention that r_i denotes the total effects (direct and indirect) of factor i on the other factors (or, criteria). Similarly, s_j implies the total effects received by the factor j from other factors. In addition, with a certain condition $j = i$, the value of $(r_i + s_i)$ denotes the index of strength of influences given and received, and the value of $(r_i - s_i)$ expresses the net effect, which is provided by the factor i to the problem. Now, if the value of $(r_i - s_i)$ be positive, it means that factor i is affecting other factors, otherwise, the factor i is being affected by the presence of other factors [72].

Step 4: Development of Network Relationship Map (NRM)

In order to establish the relationship structure between the criteria and dimensions with less complexity, a threshold value α has been set. The elements of T having the higher values than α are selected only, and are considered in network relationship map (NRM).

3.2. DEMATEL-based analytic network process (DANP)

To solve the problems of dependency among the criteria, Saaty proposed ANP [8]. The steps of ANP are described as follows [72]:

Step 1: Develop an unweighted supermatrix

From DEMATEL, the total influence matrix for criteria, T is obtained. Then, the elements of each column of T will be summed up in order to determine their normalized values. Here, $T_C = [t_{ij}]_{nxn}$ (where n denotes the number of dimensions (clusters)), as shown in Eq. (7) and influence matrix for dimension $T_D = [t_{ij}^D]_{mxm}$ is determined by the dimensions (here, clusters) from T_C. Then, normalization of T_C is performed to get the ANP weights for dimensions by utilizing T_D. It is to be noted that i-th dimension (i.e., D_i) consists of m_i number of criteria.

$$T_C = \begin{array}{cc|ccccc|}
 & & D_1 & & D_j & & D_n \\
 & & c_{11}\ldots c_{1m_1} & \cdots & c_{j1}\ldots c_{jm_j} & \cdots & c_{n1}\ldots c_{nm_n} \\
D_1 & c_{11} & T_C^{11} & \cdots & T_C^{1j} & \cdots & T_C^{1n} \\
\vdots & \vdots & \vdots & & \vdots & & \vdots \\
 & c_{i1} & \vdots & & \vdots & & \vdots \\
D_i & \vdots & T_C^{i1} & \cdots & T_C^{ij} & \cdots & T_C^{in} \\
\vdots & c_{im_i} & \vdots & & \vdots & & \vdots \\
 & c_{n1} & \vdots & & \vdots & & \vdots \\
D_n & \vdots & \vdots & & \vdots & & \vdots \\
 & c_{nm_n} & T_C^{n1} & \cdots & T_C^{nj} & \cdots & T_C^{nn}
\end{array} \tag{7}$$

A new matrix T_C^α is obtained through normalizing T_C by dimensions (clusters) using Eq. (8).

$$T_C^\alpha = \begin{array}{cc|ccccc|}
 & & D_1 & & D_j & & D_n \\
 & & c_{11}\ldots c_{1m_1} & \cdots & c_{j1}\ldots c_{jm_j} & \cdots & c_{n1}\ldots c_{nm_n} \\
D_1 & c_{11} & T_C^{\alpha 11} & \cdots & T_C^{\alpha 1j} & \cdots & T_C^{\alpha 1n} \\
\vdots & \vdots & \vdots & & \vdots & & \vdots \\
 & c_{i1} & \vdots & & \vdots & & \vdots \\
D_i & \vdots & T_C^{\alpha i1} & \cdots & T_C^{\alpha ij} & \cdots & T_C^{\alpha in} \\
\vdots & c_{im_i} & \vdots & & \vdots & & \vdots \\
 & c_{n1} & \vdots & & \vdots & & \vdots \\
D_n & \vdots & \vdots & & \vdots & & \vdots \\
 & c_{nm_n} & T_C^{\alpha n1} & \cdots & T_C^{\alpha nj} & \cdots & T_C^{\alpha nn}
\end{array} \tag{8}$$

Here, an explanation for the normalization method is given using Eqs. (9) and (10).

$$d_{ci}^{11} = \sum_{j=1}^{m_1} t_{cij}^{11}, \quad i = 1, 2, \ldots, m_1. \tag{9}$$

$$T_C{}^{\alpha 11} = \begin{bmatrix} t_{c11}^{11}/d_{c1}^{11} & \cdots & t_{c1j}^{11}/d_{c1}^{11} & \cdots & t_{c1m_1}^{11}/d_{c1}^{11} \\ \vdots & & \vdots & & \vdots \\ t_{ci1}^{11}/d_{ci}^{11} & \cdots & t_{cij}^{11}/d_{ci}^{11} & \cdots & t_{cim_1}^{11}/d_{ci}^{11} \\ \vdots & & \vdots & & \vdots \\ t_{cm_11}^{11}/d_{cm_1}^{11} & \cdots & t_{cm_1j}^{11}/d_{cm_1}^{11} & \cdots & t_{cm_1m_1}^{11}/d_{cm_1}^{11} \end{bmatrix} = \begin{bmatrix} t_{c11}^{\alpha 11} & \cdots & t_{c1j}^{\alpha 11} & \cdots & t_{c1m_1}^{\alpha 11} \\ \vdots & & \vdots & & \vdots \\ t_{ci1}^{\alpha 11} & \cdots & t_{cij}^{\alpha 11} & \cdots & t_{cim_1}^{\alpha 11} \\ \vdots & & \vdots & & \vdots \\ t_{cm_11}^{\alpha 11} & \cdots & t_{cm_1j}^{\alpha 11} & \cdots & t_{cm_1m_1}^{\alpha 11} \end{bmatrix} \quad (10)$$

The unweighted supermatrix W is derived by transposing T_C^α by dimensions (clusters) (refer to Eq. (11). Here, $W = (T_C^\alpha)'$.

$$W = (T_C^\alpha)' = \begin{array}{cc|ccccc|} & & \begin{matrix} D_1 \\ c_{11}\ldots c_{1m_1} \end{matrix} & \cdots & \begin{matrix} D_i \\ c_{i1}\ldots c_{im_i} \end{matrix} & \cdots & \begin{matrix} D_n \\ c_{n1}\ldots c_{nm_n} \end{matrix} \\ \hline D_1 & c_{11} & W^{11} & \cdots & W^{i1} & \cdots & W^{n1} \\ \vdots & \vdots & \vdots & & \vdots & & \vdots \\ & c_{j1} & \vdots & & \vdots & & \vdots \\ & c_{j2} & \vdots & & \vdots & & \vdots \\ D_j & \vdots & W^{1j} & \cdots & W^{ij} & \cdots & W^{nj} \\ \vdots & c_{jm_j} & \vdots & & \vdots & & \vdots \\ \vdots & \vdots & \vdots & & \vdots & & \vdots \\ & c_{n1} & \vdots & & \vdots & & \vdots \\ & c_{n2} & \vdots & & \vdots & & \vdots \\ D_n & \vdots & \vdots & & \vdots & & \vdots \\ & c_{nm_n} & W^{1n} & \cdots & W^{in} & \cdots & W^{nn} \end{array} \quad (11)$$

If the matrix W^{11} is found to be blank or null or 0 (as expressed as Eq. (12)), the matrix between the clusters or criteria becomes completely independent, and the other W^{nn} values are obtained by Eq. (12) as follows:

$$W^{11} = \begin{array}{c|ccccc|} & c_{11} & \cdots & c_{1i} & \cdots & c_{1m_1} \\ \hline c_{11} & t_{c11}^{\alpha 11} & \cdots & t_{ci1}^{\alpha 11} & \cdots & t_{cm_11}^{\alpha 11} \\ \vdots & \vdots & & \vdots & & \vdots \\ \vdots & \vdots & & \vdots & & \vdots \\ c_{1j} & t_{c1j}^{\alpha 11} & \cdots & t_{cij}^{\alpha 11} & \cdots & t_{cm_1j}^{\alpha 11} \\ \vdots & \vdots & & \vdots & & \vdots \\ \vdots & \vdots & & \vdots & & \vdots \\ c_{1m_1} & t_{c1m_1}^{\alpha 11} & \cdots & t_{cim_1}^{\alpha 11} & \cdots & t_{cm_1m_1}^{\alpha 11} \end{array} \quad (12)$$

Step 2: Calculation of the weighted supermatrix

Once the matrix T_C is obtained from input pair-wise comparison matrix, the average is calculated for the elements of the criteria under a particular dimension. This average value is considered as the element of the corresponding dimension. Similarly, all the elements in T_D matrix can be computed by averaging the corresponding elements of criteria in T_C. Now, the total influence matrix for dimension T_D (refer to Eq. (13)) is normalized and a new matrix T_D^α is obtained, and this is shown in Eq. (14), where, $t_D^{\alpha ij} = t_D^{ij}/d_i$. Here, $d_i$represents the sum of i-th row of $T_D$matrix. Now, the normalized total influence matrix T_D^α is to be multiplied by the unweighted supermatrix $W$to get the weighted super matrix W^α (refer to Eq. (15)).

Total influence matrix for dimension

$$= T_D = \begin{bmatrix} t_D^{11} & \cdots & t_D^{1j} & \cdots & t_D^{1n} \\ \vdots & & \vdots & & \vdots \\ t_D^{i1} & \cdots & t_D^{ij} & \cdots & t_D^{in} \\ \vdots & & \vdots & & \vdots \\ t_D^{n1} & \cdots & t_D^{nj} & \cdots & t_D^{nn} \end{bmatrix} \quad (13)$$

$$\text{Normalized } \mathrm{T}_D = T_D^\alpha = \begin{bmatrix} t_D^{11}/d_1 & \cdots & t_D^{1j}/d_1 & \cdots & t_D^{1n}/d_1 \\ \vdots & & \vdots & & \vdots \\ t_D^{i1}/d_i & \cdots & t_D^{ij}/d_i & \cdots & t_D^{in}/d_i \\ \vdots & & \vdots & & \vdots \\ t_D^{n1}/d_n & \cdots & t_D^{nj}/d_n & \cdots & t_D^{nn}/d_n \end{bmatrix} = \begin{bmatrix} t_D^{\alpha 11} & \cdots & t_D^{\alpha 1j} & \cdots & t_D^{\alpha 1n} \\ \vdots & & \vdots & & \vdots \\ t_D^{\alpha i1} & \cdots & t_D^{\alpha ij} & \cdots & t_D^{\alpha in} \\ \vdots & & \vdots & & \vdots \\ t_D^{\alpha n1} & \cdots & t_D^{\alpha nj} & \cdots & t_D^{\alpha nn} \end{bmatrix} \quad (14)$$

$$\text{Weighted supermatrix} = W^\alpha = \quad T_D^\alpha . * W = \begin{bmatrix} t_D^{\alpha 11} \times W^{11} & \cdots & t_D^{\alpha i1} \times W^{i1} & \cdots & t_D^{\alpha n1} \times W^{n1} \\ \vdots & & \vdots & & \vdots \\ t_D^{\alpha 1j} \times W^{1j} & \cdots & t_D^{\alpha ij} \times W^{ij} & \cdots & t_D^{\alpha nj} \times W^{nj} \\ \vdots & & \vdots & & \vdots \\ t_D^{\alpha 1n} \times W^{1n} & \cdots & t_D^{\alpha in} \times W^{in} & \cdots & t_D^{\alpha nn} \times W^{nn} \end{bmatrix} \quad (15)$$

It is to be noted that $T_D^\alpha . * W$ denotes element-wise multiplication of T_D^α and W.

Step 3: Limit the weighted supermatrix

The global priority vectors (that is, DANP weights, w_i) of all criteria can be obtained by raising W^α to a large power g, till it converges and becomes a stable long-term supermatrix, that is, it is represented by $\underset{g\to\infty}{Lim} (W^\alpha)^g$.

3.3. Fuzzy TOPSIS method

TOPSIS is a very popular and powerful tool in the domain of MCDM techniques.

Say, there is a set of J alternatives called as $A = \{A_1, A_2, \ldots, A_j, \ldots, A_J\}$, and n' criteria as $C = \{C_1, C_2, \ldots, C_i, \ldots, C_{n'}\}$. The performance rating of $A_j$with respect to criterion C_i is taken as$\tilde{X} = \{\tilde{x}_{ij},\ \ i = 1, 2, \ldots, n';\ \ and\ \ j = 1, 2, \ldots, J\}$. A set of importance weight of each criterion is also considered as$w_i\ \ (i = 1, 2, \ldots, n')$.

According to Onut & Soner [73], fuzzy TOPSIS can be illustrated stepwise as follows:

Step 1: Choosing of linguistic values

Choosing the appropriate linguistic values $(\tilde{x}_{ij})$ for alternatives with respect to criteria is done. The property of the fuzzy linguistic rating $(\tilde{x}_{ij})$ defines the ranges of normalized triangular fuzzy numbers (TFN) from 0 to 1. Thus, there is no need for further normalization. Here, $i = 1, 2, \ldots, n'$ and $j = 1, 2, \ldots, J$. The linguistic values, that is, very low (VL), low (L), medium (M), high (H), very high (VH), and excellent (E) are given as fuzzy numbers (0,0,0.2), (0,0.2,0.4), (0.2,0.4,0.6), (0.4,0.6,0.8), (0.6,0.8,1.0), and (0.8, 1.0,1.0), respectively, manually (based on the experts' opinion) by assuming symmetrical triangular membership function distributions. Here, the distance between two fuzzy numbers is calculated by vertex method using Eq. (16), as shown below.

$$d(\tilde{a}, \tilde{b}) = \sqrt{\frac{1}{3}[(a_1 - b_1)^2 + (a_2 - b_2)^2 + (a_3 - b_3)^2]}. \tag{16}$$

where the two triangular fuzzy numbers (TFNs) are $\tilde{a}$ and $\tilde{b}$. Here, $\tilde{a} = (a_1, a_2, a_3)$ and $\tilde{b} = (b_1, b_2, b_3)$.

Step 2: Computation of the weighted normalized fuzzy decision matrix

The weighted normalized fuzzy decision matrix $\tilde{V}$ can be calculated by Eq. (17) as follows:

$$\tilde{V} = [\tilde{v}_{ij}]_{n'xJ}, \quad \text{where } i = 1, 2, \ldots, n'; \text{ and } j = 1, 2, \ldots, J. \tag{17}$$

where $\tilde{v}_{ij} = \tilde{x}_{ij}(\bullet) \quad w_i$.

Step 3: Identification of fuzzy positive ideal solution (FPIS) and fuzzy negative ideal solution (FNIS)

The FPIS and FNIS can be calculated using Eq. (18) as follows:

$$\begin{aligned} A^* &= \{\tilde{v}_1^*, \tilde{v}_2^*, \tilde{v}_3^*, \ldots, \tilde{v}_{n'}^*\} = \{(\max_j \ v_{ij} | \ i \in I'), (\min_j \ v_{ij} | \ i \in I'')\}, \text{ and} \\ A^- &= \{\tilde{v}_1^-, \tilde{v}_2^-, \tilde{v}_3^-, \ldots, \tilde{v}_{n'}^-\} = \{(\min_j \ v_{ij} | \ i \in I'), (\max_j \ v_{ij} | \ i \in I'')\}. \end{aligned} \tag{18}$$

Here, I' *and* I'' are associated with the benefit and non-benefit criteria, respectively. It is to be noted that $\tilde{x}_{ij}$ and w_i have been considered as decision variables of Eqs. (17) and (18).

Step 4: Computation of distance

Here, the distance of each alternative from $A*$ and A^- is calculated by following Eq. (19):

$$\begin{aligned} D_j^* &= \sum_{j=1}^{n'} d(\tilde{v}_{ij}, \tilde{v}_i^*), \text{ where j = 1,2,..., J, and} \\ D_j^- &= \sum_{j=1}^{n'} d(\tilde{v}_{ij}, \tilde{v}_i^-), \text{ where j = 1,2,..., J.} \end{aligned} \tag{19}$$

Step 5: Calculation of the relative closeness values

Last of all, relative closeness (CC_j) is calculated by using Eq. (20).

$$CC_j = \frac{D_j^-}{D_j^* + D_j^-}, \quad \text{where } j = 1, 2 \ldots, J. \tag{20}$$

Step 6: Rank the alternatives.

The alternative with maximum CC_j is ranked first and then, the other alternatives are chosen as second, third, etc. according to the descending order of CC_j.

3.4. Fuzzy VIKOR

The algorithm of fuzzy VIKOR method is illustrated below in steps [74]:

Step 1: Creation of fuzzy decision matrix

Create a fuzzy decision matrix (FDM) consisting of a set of criteria and alternatives with the corresponding normalized weight of each criterion (which is obtained here by ANP). It shows the experts' average aggregated evaluation in terms of TFN linguistic scale used. An FDM of $(J \times n')$ dimensions can be defined as follows (refer to Eq. (21)) (where J and n' are the number of alternatives and number of criteria, respectively):

$$FDM = A_j \begin{bmatrix} A_j\tilde{x}_{11} \ldots \tilde{x}_{1i} \ldots \tilde{x}_{1n'} \\ A_j\tilde{x}_{j1} \ldots \tilde{x}_{ji} \ldots \tilde{x}_{jn'} \\ A_j\tilde{x}_{J1} \ldots \tilde{x}_{Ji} \ldots \tilde{x}_{Jn'} \end{bmatrix}_{(J \times n')}, \tag{21}$$

where $\tilde{x}_{ji} = (x_{ji1}, x_{ji2}, x_{ji3})$ is an aggregated fuzzy rating of alternatives(*i.e.*, a_j, *where* $j = 1, 2, \ldots, J$)with respect to each criterion($i = 1, 2, \ldots, n'$).

Step 2: Defuzzification of fuzzy decision matrix

Defuzzification is usually used to determine the best non-fuzzy performance (BNP) value. In this paper, for defuzzification of fuzzy decision matrix, center of area (COA) method has been used to determine the best non-fuzzy performance (BNP) due to its simplicity. The BNP value of TFN $\tilde{k}_j = (lk_j, mk_j, uk_j)$ can be computed using Eq. (22):

$$x_j = \quad lk_j + \frac{(uk_j - lk_j) + (mk_j - lk_j)}{3}, \quad \forall j \tag{22}$$

where x_j is the BNP value of j-th alternative, lk_j, mk_j, and uk_j are the lower, medium and upper values of fuzzy decision of j-th alternative, respectively.

Step 3: Determination of the best positive ideal solution (f^*) and the worst negative ideal solution (f^-) values for all criteria

The best f_i^* and the worst f_i^- for i-th criterion are calculated using Eq. (23), as follows:

$$f_i^* = \max\left(f_{ji}\right) \quad ; \quad f_i^- = \min\left(f_{ji}\right) \tag{23}$$

where f_{ji} denotes the positive or negative ideal solution.

Step 4: Calculation of the values of S_j and R_j

The values of S_j and R_j are calculated utilizing Eq. (24).

$$S_j = \sum_{i=1}^{n'} \frac{w_i(f_i^* - f_{ji})}{(f_i^* - f_i^-)}; R_j = \max_i\left(\frac{w_i(f_i^* - f_{ji})}{(f_i^* - f_i^-)}\right), \tag{24}$$

where w_i is the weight of $i - th$ criterion and S_j,R_j are considered as the distance rates of j-th alternative to positive and negative ideal solutions, respectively.

Step 5: Calculation of the values of Q_j

The Q_j value can be computed by following Eq. (25), as follows:

$$\begin{aligned} &S^- = \max_j(S_j); \quad S^* = \min_j(S_j); \quad R^- = \max_j(R_j); \\ &R^* = \min_j(R_j); \quad Q_j = v\left\{\frac{(S_j - S^*)}{(S^- - S^*)}\right\} + (1 - v)\left\{\frac{(R_j - R^*)}{(R^- - R^*)}\right\} \quad , \end{aligned} \tag{25}$$

where v and $(1 - v)$are the weights of strategy for maximum group utility and individual regret, respectively.

Step 6: Generation of the ranking table

The ranking table of suppliers by sorting Q_j values (calculated in step (5)) in an ascending order is generated.

Step 7: Checking the compromise solution

A compromise solution is proposed that implies that alternative $A^{(1)}$ is the best ranked by the Q measure (that is, minimum), if both the two conditions are satisfied simultaneously, that is,

(i) **C1: Acceptable advantage:** It shows that $Q(A^{(2)}) - Q(A^{(1)}) \geq (1/J - 1)$, where J is the number of alternatives, and $A^{(2)}$ is an alternative having the second position in ranking list; and

(ii) **C2: Acceptable stability in decision making:** From S or/and R values, $A^{(1)}$ must be the best ranked. This solution (compromise) is stable within a range of decision making process, i.e., 'with veto ($v < 0.5$)', or 'by consensus $v \approx 0.5$', or 'by majority rule $v > 0.5$'.

3.5. Multiple segment goal programming (MSGP)

GP is a very popular approach in multi-objective optimization scenario, as it gives optimal solutions in various decision-making issues. In this GP problems, targets have been assigned to all attributes and non-achievement of the corresponding goal has to be minimized [75]. MSGP, proposed by Liao [76], is a special type of GP problem. It is intended to solve the multi-segment aspiration levels (MSAL) problem, where the DMs could set their multiple levels of aspiration to each segment goal level. Therefore, the achievement function can be formulated, as shown in Eq. (26).

$$\begin{aligned}
&\textit{Minimize}Z = \sum_{i=1}^{n_2} w^*{}_i(d_i^+ + d_i^-)\\
&\text{subject to } f_i(x) + d_i^+ - d_i^- = g_i, [i = 1,2,\ldots, n_2]\\
&f_i(x) = \sum_{j=1}^{m_2} S_{ij}B_{ij}(b) \bullet x_i,\\
&S_{ij}B_{ij}(b) \in R_i(x), [i = 1,2,\ldots, n_2; j = 1, 2,\ldots, m']\\
&d_i^+, d_i^- \geq 0, [i = 1,2,\ldots, n_2; X \in F \text{ (where F = Feasible set)}]
\end{aligned} \quad , \tag{26}$$

where $f_i(x)$is the linear function of the i-th goal, g_i is the aspiration level of the $i-th$ goal, $w^*{}_i$represents the weight attached to the deviation; $d_i$denotes the deviation from the target value g_i; $d_i^+ = \max(0, f_i(x)\text{-}g_i)$, which indicates the under-achievement of the $i-th$ goal; $d_i^- = \max(0, g_i\text{-}f_i(x))$, which represents over-achievement of the $i-th$ goal; S_{ij} denotes the decision variable co-efficient representing multi-segment aspiration levels of $j-th$ segment of $i-th$goal; $B_{ij}(b)$ represents the function of a binary serial number; $R_i(x)$ denotes the function of resource limitation.

However, the MSGP model can be rewritten, as shown in Eq. (27) [41]:

$$\begin{aligned}
&\textit{Minimize } S_1 = w^*{}_i((d_i^+ + d_i^-) + (e_i^+ + e_i^-))\\
&\text{subject to} \sum_{j=1}^{m'} S_{ij}B_{ij}(b) \bullet x_i + d_i^+ - d_i^- = g_i,\\
&\frac{1}{L_i}\{b_i S_{ij}^{\max} + (1-b_i)S_{ij}^{\min}\} - e_i^+ + e_i^- = 1 + \frac{1}{L_i}(S_{ij}^{\max} or S_{ij}^{\min}),\\
&\quad \text{where } L_i = (S_{ij}^{\max} - S_{ij}^{\min}),\\
&S_{ij}B_{ij}(b) \in R_i(x)\\
&b_i \in \{0,1\}\\
&d_i^+, d_i^-, e_i^+, e_i^- \geq 0\\
&X \in F
\end{aligned} \tag{27}$$

where $i = 1, 2, \ldots, n_2$ and $j = 1,2, \ldots m'$.

4. A case study

In this paper, the problem related to supplier selection of SCM of a welding company has been addressed. The company under study has been undergoing a serious problem related to suppliers in terms of their process capability, lead time of product, delivery time, quality of product, and other important aspects. Of them, lead time is one of the most serious issues. Most of the time, vendors exceed their lead time period in supplying products to the company, thus putting the company under trouble for further delivery to its customer. Sometimes, to maintain lead time, the quality of products becomes poor or sub-standard that automatically results in escalating rejection rate during the inspection carried out by the company. Moreover, the company has not followed any systematic approach for the selection of supplier, while both qualitative and quantitative data are available simultaneously for each of the suppliers. Thus, in these circumstances, if supplier selection is to be done using either qualitative or quantitative information, the evaluation may be partial or incomplete to judge a supplier appropriately. Moreover, the company is also interested to figure out the weak criteria or dimensions maintained by the available suppliers. Therefore, there exists a requirement of an appropriate system that not only helps DMs in selecting the best supplier, but also explores the interrelationship structures within the evaluation criteria. In fact, it is observed more often in manufacturing industries in developing countries like India of not having a proper system capable of appropriate selection of suppliers, which, in turn, creates difficulty in supply chain network. In addition, the management of the welding company often receives different levels of profits from varying markets based on the objectives set by the managers. Thus, these objectives are so different that they cannot be combined into a single goal. The situation raised in company basically triggers the use of multi-segment aspiration levels by setting an aggregated goal, where the decision makers will be interested to minimize the deviation between the achievement of the goal and their aspiration levels. Consequently, the motivation behind this study is to propose a scalable and generalizable hybrid model to resolve the current problems in the company by providing not only ranking of the suppliers but also interrelationships among the different criteria. In order to achieve the goals, DANP-based FTOPSIS and MSGP models have been used and its effectiveness has been tested in producing the desired outputs, which will be directly helpful to the company's perspective for profit and growth. Hence, the steps including data collection from the industry experts and the data set collected are discussed below.

4.1. Data collection

A questionnaire-based survey has been conducted to collect data (i.e., qualitative) from the experts of the case company. Some limited quantitative data related to the suppliers are also provided. The experts consist of production manager, factory manager, deputy manager of purchase, deputy manager of production and deputy manager of quality assurance (QA) cell. In this study, qualitative data set has been generated based on only five experts' opinions.

4.2. Data set and description

Data set obtained from the company consists of qualitative and quantitative information. Qualitative data is based on questionnaire survey and quantitative data is gathered from the statistics maintained by the company. In qualitative data, six dimensions and twelve criteria are considered, which are denoted by$D_1, D_2, D_3, D_4, D_5, D_6$, and $C_1, C_2, \ldots, C_{11}$ and C_{12}, respectively. Ten suppliers or vendors have been considered in this study, as denoted by $A_1, A_2 \ldots A_{10}$. The hierarchy of the supplier selection is depicted in Fig. 2. In this figure, all the dimensions and criteria, which are selected for the evaluation of the best supplier, have been displayed. In this hierarchy, there are ten alternatives, that is, suppliers, twelve criteria, six dimensions, and only one goal, that is, selection of the best supplier among the available ten alternate suppliers. From the discussion and review of literature, all the criteria, dimensions are selected for the preparation of questionnaire survey [72,76–78]. In the quantitative data set, information related to delivery time, average purchase cost, and number of environmental friendly items used for each of the suppliers are provided in Table 1.

The meanings of the attributes used for both the cases (i.e., qualitative and quantitative) in this study are given below.

For the qualitative study, the following twelve attributes have been used:

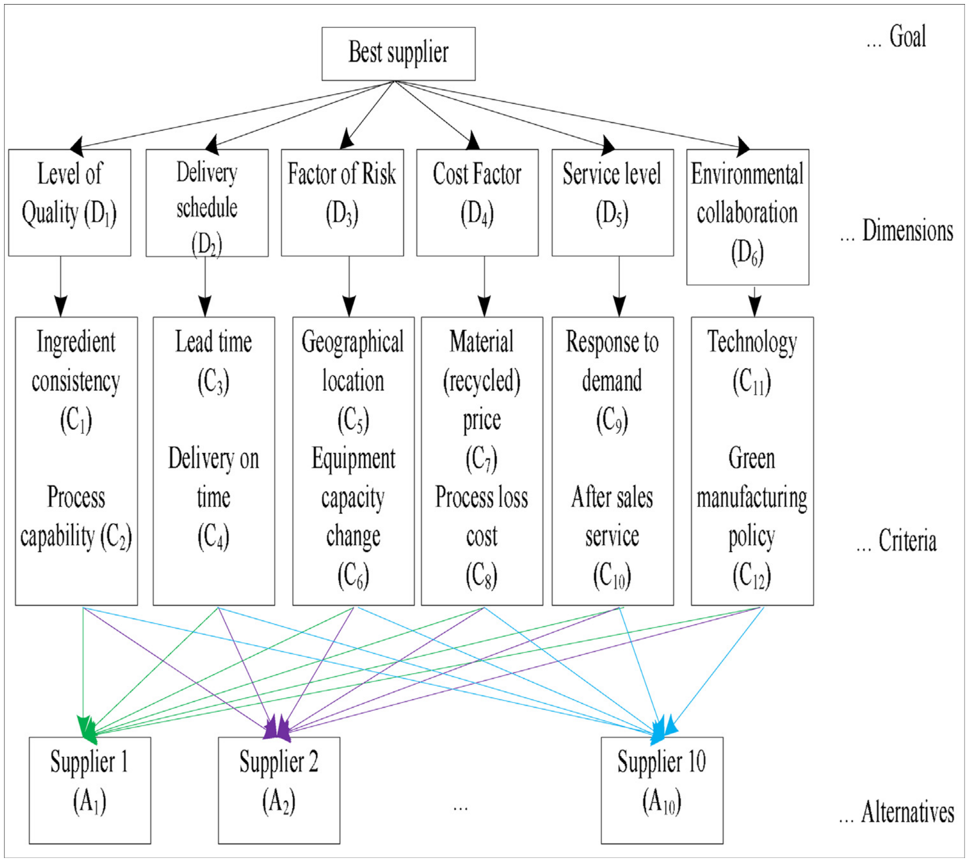

Fig. 2. The hierarchy of supplier selection.

Table 1
Data set used for MSGP model.

Suppliers (G_1)	Avg. delivery time (G_2) (day)	Average purchase cost (per month) (G_3) (Rs.)	Average environmental friendly items produced (per month) (G_4) (number)
A1	4	15000	2
A2	2	14500–15000	2
A3	1–4	13500	3
A4	2–4	13750–15250	4
A5	1–3	13500–14000	4
A6	1–2	12500–13500	5
A7	5	13475	2
A8	5	14500	2
A9	2–4	14500	3
A10	6	13500	1

(i) Ingredient consistency (C_1) – It implies that the source of all materials which are recycled should be unique; *(ii) Process capability (C_2)* – It indicates that how the vendors can produce the products according to the company's desired specification.; *(iii) Lead time (C_3)* – It means the time spent between the placing an order and its delivery to the customer.; *(iv) Delivery on time (C_4)* – It implies the delivery of the products from the vendors to their customer (here, our case company) on time scheduled at the beginning of the placement of the order; *(v) Geographical location (C_5)* – It indicates how far the vendor's premise is located from the company; *(vi)Equipment capacity change (C_6)* – It denotes the ability of the vendor to tackle any form of change in the supply chain with its existing machineries or equipment. *(vii) Material (recycled) price (C_7)* – It indicates the price associated with the recycled materials provided their source is unique; *(viii) Process loss cost (C_8)* – It implies the cost associated with the loss of quality due to recycling of the materials; *(ix) Response to demand (C_9)* – It is a significant key feature of the vendor's performance. It shows how promptly a vendor could respond to a change in demand in supply chain; *(x) After sales service (C_{10})* – It is another key performance indicator that indicates the level of service provided by the vendor after the sales of recycled products. To increase this level of service, they may provide warranty against the products to the customers; *(xi) Technology (C_{11}) used for recycling processes* – It implies how much advanced and developed technology is used by the vendor for recycling materials to meet the demand of the customer or company; and *(xii) Green manufacturing policy (C_{12})* – It indicates the policy that helps the vendor to follow the environmental norms while producing the environment friendly products for its customer.

For the performance assessment of the suppliers, quantitative data of a similar product are recorded from the monthly records of the company in terms of the following attributes:

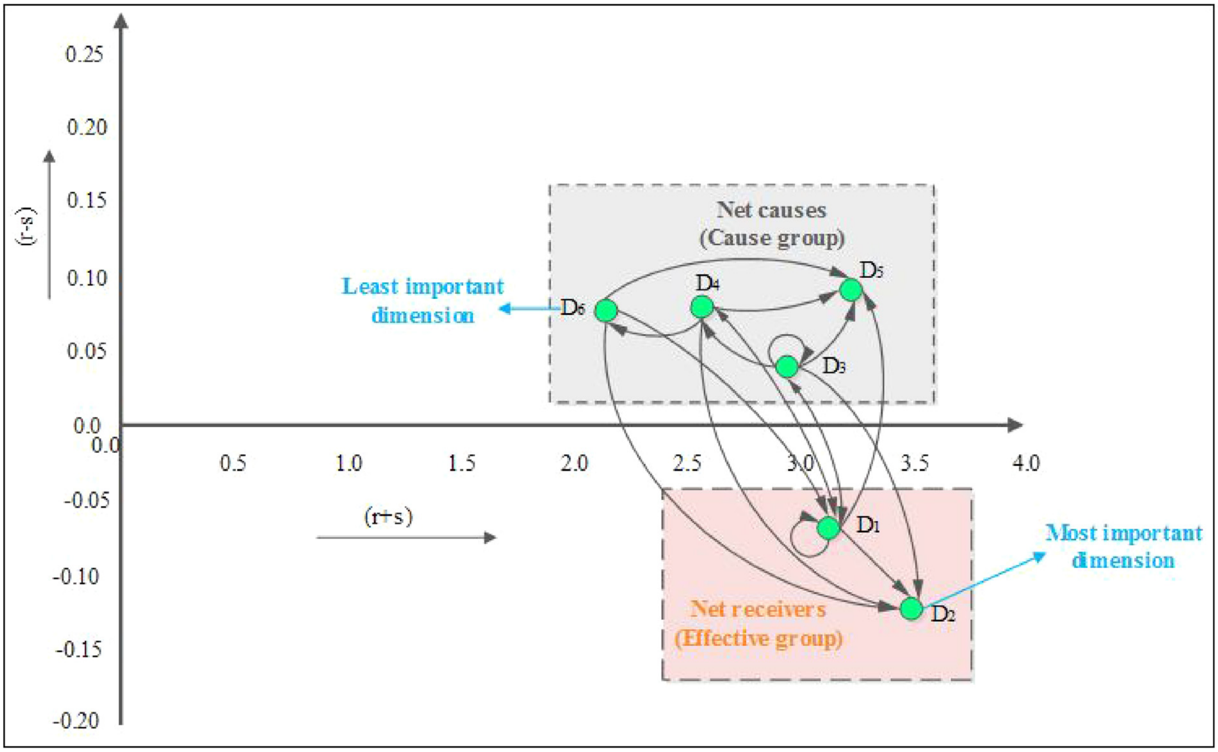

Fig. 3. Network relationship map of the dimensions based on the threshold value, α=0.20.

(i) Average delivery time (G_2) – It denotes the average time taken (in day) by the suppliers for a particular product; *(ii) Average purchase cost (G_3)* – It indicates the average product cost per month including material cost, maintenance cost, cost related to logistics etc.; *(iii) Average environmental friendly items produced (G_4)*- It implies the average number of environmental friendly items produced by the suppliers.

5. Results and discussion

In this section, some of the important results and findings from the analyses of DEMATEL, ANP, sensitivity analysis, MSGP, and FVIKOR techniques are described below.

(i) From the DEMATEL model, it is clear to understand interrelationships and interdependence among the dimensions, which are shown in Fig. 3. Depending upon the threshold value of $\alpha = 0.20$ (as decided by the experts), the relationships, i.e., NRMs among the dimensions and the criteria are evaluated and shown in Figs. 3 and 4, respectively. From Tables 2 and 3, the importance of the six dimensions have been calculated and prioritized as D_2 (3.951) > D_1 (3.356) > D_5 (3.252) > D_3 (2.967) > D_4 (2.605) > D_6 (2.369) based on $(r+s)$values. This result indicates that delivery schedule (D_2) is the most important dimension with the value of 3.951, while environmental collaboration (D_6) is the least important dimension with the value of 2.369. So, the company needs much more attention towards the environment-friendly activities. In contrast to the importance, risk (D3), cost (D4), service level (D5) and environmental factors (D_6) dimensions are the net causes and are classified in the cause group. On the other hand, quality (D_1) and delivery schedule (D_2) are the net receivers and are classified in effect group based on (r-s) values. Service level is found to have the greatest direct impact on the other dimensions.

Cost and environmental collaboration are found to have very close impact factors. On the other hand, risk has very less impact on others. Delivery is found out to be a factor, which is the most affected one by the other factors. From Fig. 4, C_4 is found to be the most important criterion with the $(r+s)$value of 7.950, and C_7 seems to be the least important criterion with the $(r+s)$value of 3.950. It is important to note that $(r+s)$value helps to identify the most or least important criterion, as it represents the index of strength of influences given and received by the criteria (refer to Section 3.1). This is due to the fact that delivery rate on time (C_4) plays a vital role for the company and management has been trying to maintain it, as it is related to customers' satisfaction and reliability. The price of recycled materials (C_7) is the least important one, as the suppliers are sometimes less interested in recycling product, as it takes more time and thus, in turn, making this criterion least important from the suppliers' perspective. In this figure, C_7 is seen to be uninfluenced by any other criterion, which indicates that C_7 is the least important factor. In Fig. 3, environmental factors (D_6) are influencing service level (D_5), delivery on time (D_2), quality of product (D_1); risk (D_3) influences service level (D_5), cost (D_4), quality of product (D_1), and delivery on time (D_2). This information actually helps the management to take clear and judicious decision for the improvement of their supply chain. Environmental factor is the key dimension for the purpose of supplier selection. So, to improve the supply chain efficiency, suppliers should improve green manufacturing policy (C_{12}).

(ii) According to the results of DANP, the weights of the criteria from the stable supermatrix are computed, i.e., 0.0835, 0.0820, 0.0836, 0.0827, 0.0799, 0.0857, 0.0607, 0.1073, 0.0890, 0.0773, 0.0835, and 0.0851 for C_1, C_2, C_3, …, C_{12}, respectively and with FTOPSIS model, we can observe the relative closeness rating (i.e.,CC_j) of the ten suppliers. The higher value of CC_jindicates the better supplier over the others. Thus, supplier A_6 is ranked first and A_{10} has got the rank of ten. The following results are obtained from the analysis: A_6 (0.50411) > A_5 (0.50112) > A_3 (0.49864) > A_4 (0.49842) > A_9 (0.49781) > A_2

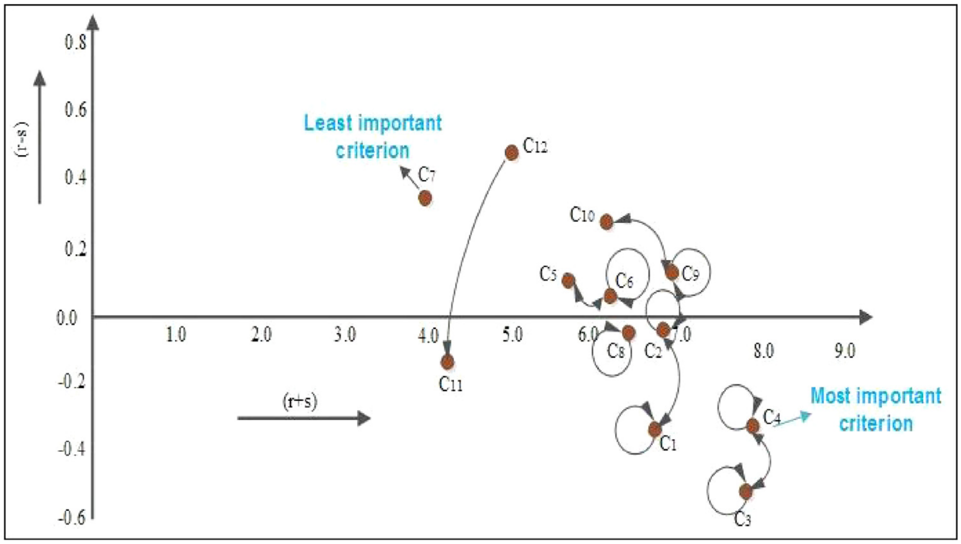

Fig. 4. Network relationship map of the criteria within dimensions based on the threshold value, α=0.20.

Table 2
The initial influence matrix*A*for criteria.

Criteria	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9	C_{10}	C_{11}	C_{12}	Sum
C_1	0.0	2.4	2.0	2.8	0.8	1.6	0.6	2.2	1.4	0.6	0.6	0.8	15.8
C_2	2.6	0.0	2.4	2.0	1.0	2.2	0.6	2.4	1.0	1.4	1.0	0.6	17.2
C_3	1.8	2.0	0.0	3.0	2.0	2.0	1.0	1.4	2.4	1.8	0.8	0.6	18.8
C_4	2.6	2.2	3.0	0.0	2.6	1.6	0.6	1.6	2.2	1.6	1.0	0.6	19.6
C_5	1.2	0.8	2.4	2.0	0.0	0.6	0.6	1.6	1.2	2.0	1.4	1.0	14.8
C_6	1.2	1.2	2.6	2.6	1.2	0.0	0.2	1.6	2.2	1.0	0.6	0.8	15.2
C_7	0.8	0.4	1.0	0.8	0.6	0.2	0.0	1.2	1.0	0.8	2.6	2.2	11.6
C_8	2.4	2.8	1.6	1.6	0.4	1.8	1.0	0.0	1.6	1.0	0.6	1.6	16.4
C_9	1.8	1.6	2.8	2.6	1.4	1.6	0.8	0.8	0.0	2.2	1.0	1.2	17.8
C_{10}	1.0	1.2	2.0	1.8	1.8	1.4	1.4	1.6	1.8	0.0	1.2	1.4	16.6
C_{11}	1.0	1.4	0.8	1.0	0.8	0.6	1.0	0.6	0.8	1.2	0.0	1.8	11.0
C_{12}	1.0	1.0	0.8	0.8	1.6	1.4	1.6	1.8	1.6	1.4	1.8	0.0	14.8
Sum	17.4	17.0	21.4	21.0	14.2	15.0	9.4	16.8	17.2	15.0	12.6	12.6	

Table 3
The total influence matrix $T_D$and influences given/received for dimensions.

Dimensions	D_1	D_2	D_3	D_4	D_5	D_6	r	(r + s)	(r-s)
D_1	0.296	0.388	0.267	0.235	0.266	0.184	1.637	3.356	−0.083
D_2	0.366	0.397	0.322	0.247	0.336	0.208	1.875	3.951	−0.201
D_3	0.269	0.366	0.209	0.202	0.271	0.181	1.497	2.967	0.028
D_4	0.263	0.286	0.199	0.167	0.225	0.204	1.344	2.605	0.082
D_5	0.303	0.391	0.276	0.227	0.266	0.210	1.673	3.252	0.094
D_6	0.223	0.248	0.197	0.184	0.215	0.158	1.225	2.369	0.080
s	1.719	2.076	1.470	1.262	1.579	1.145			

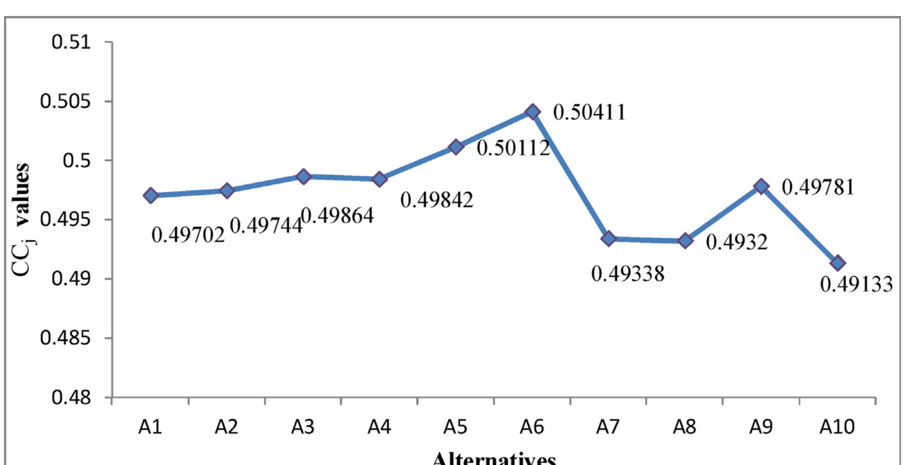

Fig. 5. Relative position of the alternative suppliers with CC_j values.

Table 4
Ranking obtained from DANP-FTOPSIS-based MSGP and DANP-FVIKOR models.

Suppliers	Z value	X-values	DANP-FTOPSIS-based MSGP ranking	DANP-FVIKOR ranking (v = 0.5)
A_1	$z_1 = 3.95002$	$X_1 = 1, X_i = 0$; where i = 2–10	7	6
A2	$Z_2 = 2.799$	$X_2 = 1, X_i = 0$; where i = 1–10, $i \neq 2$	6	10
A3	$Z_3 = 0.79944$	$X_3 = 1, X_i = 0$; where i = 1–10, $i \neq 3$	3	3
A4	$Z_4 = 0.89976$	$X_4 = 1, X_i = 0$; where i = 1–10, $i \neq 4$	4	4
A5	$Z_5 = 0.798444$	$X_5 = 1, X_i = 0$; where i = 1–10, $i \neq 5$	2	2
A6	$Z_6 = 0.79724$	$X_6 = 1, X_i = 0$; where i = 1–10, $i \neq 6$	1	**1**
A7	$Z_7 = 4.160326$	$X_7 = 1, X_i = 0$; where i = 1–10, $i \neq 7$	8	7
A8	$Z_8 = 4.16033$	$X_8 = 1, X_i = 0$; where i = 1–10, $i \neq 8$	9	8
A9	$Z_9 = 1.53183$	$X_9 = 1, X_i = 0$; where i = 1–10, $i \neq 9$	5	5
A10	$Z_{10} = 4.63373$	$X_{10} = 1, X_i = 0$; where i = 1–10, $i \neq 10$	10	9

(0.49744) > A_1 (0.49702) > A_7 (0.49338) > A_8 (0.49320) > A_{10} (0.49133). From Fig. 5 and Table 4, it is evident that A_6 and A_{10} suppliers are the best and worst, respectively, among all ten suppliers.

(iii) According to the sensitivity analysis, the weights of all criteria are mutually interchanged to see the effects on result of ranking of the alternatives. It is found out that all the outcomes are the same except one case, where A_8 and A_7 are interchanged, i.e., $A_6 > A_5 > A_3 > A_6 > A_5 > A_3 > A_4 > A_9 > A_2 > A_1 > \mathbf{A_8} > \mathbf{A_7} > A_{10}$. This result indicates that this model is robust with interchanging the weights of the criteria. In Fig. A1 (see Appendix A), the relative rankings of all the alternatives are displayed for eleven cases.

(iv) In this stage, quantitative constraints related to the cost and benefit criteria are used into the MSGP model to find out the optimal supplier. From the weights (i.e., CC_j) of each supplier, normalized weights can be computed and these can be used as priority value to build the MSGP achievement model to find out the ranking of the suppliers. Additionally, the co-efficient of variables in supplier selection profile denoting the data set and the ranges for each of the suppliers are shown in Table 1. According to the business strategy of the company, the management has set the objective to determine the best supplier with the quantitative criteria like selection of the highest weighted supplier (G_1), delivery time (G_2), average purchase cost (G_3), and number of environment friendly items used (G_4). Four goal functions$f(x)$have been used. According to the management decision, the first goal is to select the best supplier with the highest weightage value of 1, i.e.,$G_1 : f_1(x) = 1$; the second goal is set to minimize the delivery time to as high as 2,$G_2 : f_2(x) \leq 2$; the third goal is to minimize the average purchase cost, which is set as high as Rs. 1,40,000, $G_3 : f_3(x) \leq 140000$; and finally, the fourth goal aims to maximize the number of environmental friendly items used, i.e., $G_4 : f_4(x) \geq 4$. The above goals have been set through the discussion with the higher management. Based on the requirements, the MSGP model can be formulated, as shown in Eqs. (28)-(44), whose detailed explanation is given in Appendix B.

MSGP model:

$$Min\ Z = d_1^+ + d_1^- + d_2^+ + d_2^- + d_3^+ + d_3^- + d_4^+ + d_4^- +$$
$$e_1^+ + e_1^- + e_2^+ + e_2^- + e_3^+ + e_3^- + e_4^+ + e_4^- + e_5^+ +$$
$$e_5^- + e_6^+ + e_6^- + e_7^+ + e_7^- + e_8^+ + e_8^- + e_9^+ + e_9^-$$

$Min\ Z = d_1^+ + d_1^- + d_2^+ + d_2^- + d_3^+ + d_3^- + d_4^+ + d_4^- +$ $e_1^+ + e_1^- + e_2^+ + e_2^- + e_3^+ + e_3^- + e_4^+ + e_4^- + e_5^+ +$ $e_5^- + e_6^+ + e_6^- + e_7^+ + e_7^- + e_8^+ + e_8^- + e_9^+ + e_9^-$	Objective function satisfying all goals	(28)
$.099x_1 + 0$ $0.1x_2 + 0.1x_3 + 0.1x_4 + 0.1x_5 + 0.101x_6 + 0.099x_7 + 0.099x_8 + 0.1x_9 + 0.0988x_{10} - d_1^+ + d_1^- = 1$	For weighted of green supplier goal	(29)
$4x_1 + 2x_2 + [4b_1 + 1(1\text{-}b_1)]\, x_3 + [4b_2 + 2(1\text{-}b_2)]\, x_4 + [3b_3 + 1(1\text{-}b_3)]\, x_5 + [2b_4 + (1\text{-}b_4)]\, x_6 + 5x_7 + 5x_8 + [4b_5 + 2(1\text{-}b_5)]\, x_9 + 6x_{10} - d_2^+ + d_2^- \leq 2$	Minimization of delivery time	(30)
$(1/3)[4b_1 + (1\text{-}b_1)] - e_1^+ + e_1^- = 1.33$	Minimization of delivery time for A3	(31)
$(1/2)[4b_2 + 2(1\text{-}b_2)] - e_2^+ + e_2^- = 2$	Minimization of delivery time for A4	(32)
$(1/2)[3b_3 + (1\text{-}b_3)] - e_3^+ + e_3^- = 1.5$	Minimization of delivery time for A5	(33)
$(1)[2b_4 + (1\text{-}b_4)] - e_4^+ + e_4^- = 2$	Minimization of delivery time for A6	(34)
$(1/2)[4b_5 + 2(1\text{-}b_5)] - e_5^+ + e_5^- = 2$	Minimization of delivery time for A9	(35)
$15000x_1 + [15000b_6 + 14500(1\text{-}b_6)]\, x_2 + 13500x_3 + [15250b_7 + 13750(1\text{-}b_7)]\, x_4 + [14000b_8 + 13500(1\text{-}b_8)]\, x_5 + [13500b_9 + 12500(1\text{-}b_9)]\, x_6 + 13475\, x_7 + 14500x_8 + 14500x_9 + 13500x_{10} - d_3^+ + d_3^- \leq 140000$	Minimization of purchase cost	(36)
$(1/500)[15000b_6 + 14500(1\text{-}b_6)] - e_6^+ + e_6^- = 30$	Minimization of purchase cost for A2	(37)
$(1/1500)[15250b_7 + 13750(1\text{-}b_7)] - e_7^+ + e_7^- = 10.167$	Minimization of purchase cost for A4	(38)
$(1/500)[14000b_8 + 13500(1\text{-}b_8)] - e_8^+ + e_8^- = 28$	Minimization of purchase cost for A5	(39)
$(1/1000)[13500b_9 + 12500(1\text{-}b_9)] - e_9^+ + e_9^- = 12.5$	Minimization of purchase cost for A6	(40)
$2x_1 + 2x_2 + 3x_3 + 4x_4 + 4x_5 + 5x_6 + 2x_7 + 2x_8 + 3x_9 + x_{10} - d_4^+ + d_4^- \geq 4$	Maximization of environmental items	(41)
$b_i \in \{0, 1\}$	Represents the binary number	(42)
$d_i^+, d_i^- \geq 0,\ i = 1,\ldots,4.$	Represents the deviations from targets	(43)
$e_i^+, e_i^- \geq 0,\ i = 1,\ldots,9.$	Represents the deviations from targets	(44)

LINGO software has been used to solve the MSGP model using Pentium 4 CPU 2.00 GHz computer. A_6 is declared as the best supplier, as the minimum Zvalue (i.e., Z_{min}) is obtained as 0.79724, when$x_6 = 1, x_1 = x_2 = x_3 = x_4 = x_5 = x_7 = x_8 = x_9 = x_{10} = 0$. The Z values for all the suppliers are shown in Table 4. Based on the increasing order of the Z value, the final ranking of the suppliers is derived as:$A_6 > A_5 > A_3 > A_4 > A_9 > A_2 > A_1 > A_7 > A_8 > A_{10}$.

(v) From FVIKOR method, it is observed that the final ranking of the alternative suppliers is $A_6 > A_5 > A_3 > A_4 > A_9 > A_1 > A_7 > A_8 > A_{10} > A_2$ (at weight$v = 0.5$) (refer to Table 4). From the

Table 5
Comparison of the results of ranking of suppliers using two different methods.

Methods	Ranking of the suppliers
DANP + FTOPSIS + MSGP	$A_6 > A_5 > A_3 > A_4 > A_9 > A_2 > A_1 > A_7 > A_8 > A_{10}$
DANP + FVIKOR	$A_6 > A_5 > A_3 > A_4 > A_9 > A_1 > A_7 > A_8 > A_{10} > A_2$

results of Table 4, it is evident that supplier A_6 is the best among all the suppliers, and it is further supported by the results of sensitivity analysis of FVIKOR with different weight values ($\nu = 0.0,\ 0.3,\ 0.5,\ 0.7,\ and\ 1.0$) (results are not shown in this study). These results could help the decision makers to easily select the best supplier, i.e., A_6.

Table 5 presents a comparison of the results of the two methods, namely, DANP-FTOPSIS-based MSGP, and DANP-based FVIKOR. Based on these results, it can be interpreted that our proposed model (i.e., DANP-FTOPSIS-based MSGP) developed by considering both the qualitative and quantitative factors of the company provides the same result for identifying the best supplier as DANP-based FVIKOR method, which do not consider the quantitative aspects at all. Therefore, the proposed methodology has the potential to solve the supplier selection problem while dealing with both the qualitative and quantitative aspects.

6. Conclusion

This paper proposes a hybrid technique considering both qualitative and quantitative criteria at a time in a fuzzy environment by using MCDA and MP model. MCDA model includes DEMATEL-based ANP (i.e., DANP) technique that evaluates the weights of the criteria. Based on the weights, FTOPSIS-based MSGP approach has been implemented to find out the ranking of the suppliers. DEMATEL technique has been used to find out the interrelationship among the criteria. Results show that supplier A_6 is the best one among all and the ranking obtained from the proposed method (DANP-FTOPSIS-based MSGP) is almost similar to that of DANP-based FVIKOR, which has been used to validate the result of our proposed method. In addition, sensitivity analysis of FTOPSIS and FVIKOR also supports the findings of the best supplier. From the application of the DEMATEL approach, *delivery schedule* and *environmental collaboration* are found out to be the most and least important dimensions, respectively. *Service level* has the greatest impact on other dimensions. In addition, *cost* of recycled materials has been identified to be the least important criterion maintained by the company. Using the information obtained from the analysis, management should take the decision to improve the weakest criterion, i.e., *environmental collaboration* by using environmental-friendly product and simultaneously maintaining the level of quality for the strongest criterion, i.e., *delivery schedule*.

However, like other studies, this study also doesn't get rid of limitations. One of the main limitations is that the survey conducted is only an expert evaluation exercise rather than a complete industrial survey. Responses have been collected from five experts only for the qualitative data analysis. Due to unavailability of the more number of experts, responses from a large number of people could not be obtained. However, it is strongly recommended that the scale of the surveyed sample should be large enough. In addition to this present problem addressed, resources like documents are either limited in most of the cases or not easily available. The sensitivity analysis of FTOPSIS could be done more deeply, that is, the interchange of weights of all criteria should be performed to understand the relative positions of the alternatives. Another limitation is the vagueness or impreciseness of the goals. Some other parameters and constraints may exist in the supplier selection problem, which make the decision-making task more complex.

As future study, our proposed model along with other MCDA approaches like dominance-based rough set approach or multi-objective optimization on the basis of ratio analysis (MOORA) or multi-objective optimization on the basis of simple ratio analysis (MOOSRA) or ELimination Et Choix Traduisant la REalité (ELECTRE), COmplex PRoportional ASsessment (COPRAS), fuzzy additive ratio assessment (ARAS-F), or others can be used to decide the best ranking of suppliers in more complex problems involving a large number of criteria or dimensions and suppliers. Moreover, the feedback can be collected from a more number of experts in future for the purpose of said analysis. A dedicated decision support system can also be developed in future to help the industries for selecting the best supplier.

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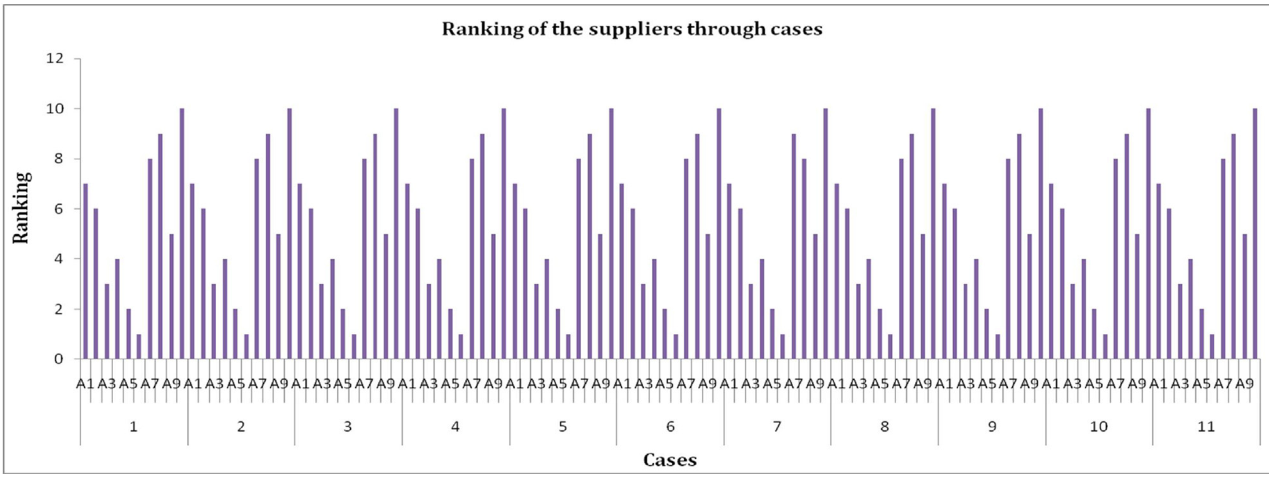
Appendix A.



Note: Rankings of the suppliers for 11 cases:

Case 1: $A_6 > A_5 > A_3 > A_4 > A_9 > A_2 > A_1 > A_7 > A_8 > A_{10}$

Case 2: $A_6 > A_5 > A_3 > A_4 > A_9 > A_2 > A_1 > A_7 > A_8 > A_{10}$

Case 3: $A_6 > A_5 > A_3 > A_4 > A_9 > A_2 > A_1 > A_7 > A_8 > A_{10}$

Case 4: $A_6 > A_5 > A_3 > A_4 > A_9 > A_2 > A_1 > A_7 > A_8 > A_{10}$

Case 5: $A_6 > A_5 > A_3 > A_4 > A_9 > A_2 > A_1 > A_7 > A_8 > A_{10}$

Case 6: $A_6 > A_5 > A_3 > A_4 > A_9 > A_2 > A_1 > A_7 > A_8 > A_{10}$

Case 7: $A_6 > A_5 > A_3 > A_4 > A_9 > A_2 > A_1 > A_8 > A_7 > A_{10}$

Case 8: $A_6 > A_5 > A_3 > A_4 > A_9 > A_2 > A_1 > A_7 > A_8 > A_{10}$

Case 9: $A_6 > A_5 > A_3 > A_4 > A_9 > A_2 > A_1 > A_7 > A_8 > A_{10}$

Case 10: $A_6 > A_5 > A_3 > A_4 > A_9 > A_2 > A_1 > A_7 > A_8 > A_{10}$

Case 11: $A_6 > A_5 > A_3 > A_4 > A_9 > A_2 > A_1 > A_7 > A_8 > A_{10}$

Fig. A1. Relative rankings of the alternatives based on 11 cases.

Appendix B. Formulation of the objective and the constraints expressed as Eqs. (29), (30), (36), and (41)

1. *Formulation of objective function of MSGP model*

For better understanding of the model, we will have to revisit the input tables once again, which are shown below.

(i) *Input 1* for MSGP model, that is, Table 1 of the manuscript, which is the data set provided by the company.
(ii) *Input 2* for MSGP model, that is, Table B1 (given below), which shows normalized weight values of the suppliers.
(iii) *Input 3* for MSGP model, that is, Table B2 (given below) for the targets or goals set by the company.

Table B1
Normalized weight values of the suppliers.

Suppliers	w_i	(w_i)Normalized
A_1	0.4970	0.099
A_2	0.4974	0.100
A_3	0.4986	0.100
A_4	0.4984	0.100
A_5	0.5011	0.100
A_6	0.5041	0.101
A_7	0.4933	0.099
A_8	0.4932	0.099
A_9	0.4978	0.100
A_{10}	0.4913	0.0988

Table B2
Goals set by the company.

Goal	Targets/goals
$G_1 : f_1(x) = 1$	For best supplier
$G_2 : f_2(x) \leq 2$	For delivery time
$G_3 : f_3(x) \leq 140000$	For average purchase cost
$G_4 : f_4(x) \geq 4$	For environmental items

Objective function in MSGP model is shown in Eq. (28). The objective of the model is to minimize the deviation of the achievements of the goals from their corresponding aspiration levels. As we have four goals, we have to consider four pairs of achievements (both over and under), i.e., (d_1^+, d_1^-), (d_2^+, d_2^-), $(d_3^+, d_3^-)$and (d_4^+, d_4^-). In addition, for the existence of each of the interval values corresponding to the supplier's criteria (average delivery time and average purchase cost), different pairs of achievement ((e_3^+, e_3^-), (e_4^+, e_4^-), (e_5^+, e_5^-), (e_6^+, e_6^-), (e_7^+, e_7^-), (e_8^+, e_8^-), and (e_9^+, e_9^-)) should be considered. Here, in this study, for average delivery time, interval values for A_3, A_4, A_5, A_6 and A_9 are (1–4), (2–4), (1–3), (1–2), and (2–4), respectively. Therefore, for each of them, over and under achievement pair is to be considered, i.e., (e_3^+, e_3^-), (e_4^+, e_4^-), (e_5^+, e_5^-), (e_6^+, e_6^-), (e_7^+, e_7^-), (e_8^+, e_8^-), and (e_9^+, e_9^-). Overall, considering the achievement pair for both point and interval criteria, net objective function will be formed and can be expressed as Eq. (28). Therefore, the objective function will be as follows:

$$Min\ Z = d_1^+ + d_1^- + d_2^+ + d_2^- + d_3^+ + d_3^- + d_4^+ + d_4^- +$$
$$e_1^+ + e_1^- + e_2^+ + e_2^- + e_3^+ + e_3^- + e_4^+ + e_4^- + e_5^+ +$$
$$e_5^- + e_6^+ + e_6^- + e_7^+ + e_7^- + e_8^+ + e_8^- + e_9^+ + e_9^-$$

2. ***Formulation of constraint*** *Eq. (29)*

Once the CC_jvalues for the suppliers are obtained, they are normalized. The normalized CC_jvalues are considered as weights of suppliers in MSGP model. Each weight corresponding to the particular supplier is used as decision variable coefficient, which represents the multi-segment aspiration levels of$j - th$segment of $i - th$goal. Here,$x$value can hold either 1 or 0. The MSGP model would search for lower value of$Z$. After stopping the MSGP algorithm, it is left with a set of Zvalues, each corresponding to a set of ten$x$values. In the set of ten $x$values, there is only one $x$having 1 representing the best supplier for the associated$Z$, whereas each of the others has zero value. For understanding of the functionality of the model in more detail, one may refer to [75]. Therefore, the first constraint will be as follows:

$$0.099x_1+00.1x_2+0.1x_3+0.1x_4+0.1x_5+0.101x_6+0.099x_7 +0.099x_8+0.1x_9+0.0988x_{10}-d_1{}^{+}+d_1{}^{-}=1$$

3. ***Formulation of constraint*** *Eq. (30)*

By following the Eq. (27), that is, $\sum_{j=1}^{m'} S_{ij}B_{ij}(b)\bullet x_i+d_i^{+}-d_i^{-}=g_i$, we can formulate Eq. (30) for the delivery time like the following after taking the numerical values of second column of Table 1.

$$4x_{1+2}x_{2+}[4b_1+1(1\text{-}b_1)]x_3+[4b_2+2(1\text{-}b_2)]x_{4+}[3b_3+1(1\text{-}b_3)]x_5 +[2b_4+(1\text{-}b_4)]x_6+5x_7+5x_8+[4b_5+2(1\text{-}b_5)]x_{9+}6x_{10}-d_2{}^{+} +d_2{}^{-}\leq 2$$

4. ***Formulation of constraint*** *Eqs. (36) and (41)*

Similarly, by using the Eq. (27), that is, $\sum_{j=1}^{m'} S_{ij}B_{ij}(b)\bullet x_i+d_i^{+}-d_i^{-}=g_i$, Eq. (36) can be formulated for the average purchase cost (refer to third column of Table 1), as given below.

$$15000x_1+[15000b_6+14500(1\text{-}b_6)]x_2+13500x_3 +[15250b_7+13750(1\text{-}b_7)]x_4+[14000b_8+13500(1\text{-}b_8)]x_5 +[13500b_9+12500(1\text{-}b_9)]x_6+13475x_7+14500x_8+14500x_9 +13500x_{10}-d_3{}^{+}+d_3{}^{-}\leq 140000$$

By following the similar procedure, Eq. (41) can be written considering fourth column of Table 1, as follows:

$$2x_1+2x_2+3x_3+4x_4+4x_5+5x_6+2x_7+2x_8+3x_9+ x_{10}-d_4{}^{+}+d_4{}^{-}\geq 4$$

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