Environmental performance evaluation of suppliers: A hybrid fuzzy multi-criteria decision approach

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ABSTRACT: Increasing environmental problems enforce companies to be more environmental responsible. A company's environmental performance is not only related to the company's inner environmental efforts, but also it is affected by the suppliers' environmental performance and image. As a stakeholder of the company, a supplier with bad environmental image affects badly the company's environmental image. Also, raw materials and semi-finished products supplied from out of the company recourses- suppliers- affects the products environmental features such as life cycle, re-usability, re-manufacturability, hazardous substances, etc. Considering these direct and indirect effects, managers should also consider environmental performances of their suppliers in their supplier evaluation process. In this paper, a methodology for the evaluation of suppliers' environmental performances is proposed. In this methodology, a hybrid Fuzzy-Analytic Network Process and Fuzzy-Preference Ranking Organization METHod for Enrichment Evaluations approach is utilized. Additionally, a numerical example is given to foster the better understanding of the methodology and the obtained results are analyzed with sensitivity analyses.

Keywords: *Decision-making; Environmental criteria; Fuzzy sets; Green supply chain*

INTRODUCTION

Supply chain management (SCM) is the integration and management of supply chain organizations and activities through cooperative organizational relationships, effective business processes and high levels of information sharing to create high-performing value systems that provide member organizations a sustainable competitive advantage (Handfield and Nichols, 2004). Many academicians and practitioners are utilized from operations management techniques to deal with optimizing internal processes of firms. These optimization efforts are both applied for a particular process or the entire set of processes that provide value to the end customer. The entire set of processes includes those that are both internal and external to the firm. This perspective is often referred to as supply chain management and is a potentially powerful way for companies to ensure that customers are receiving the most value for their money.

Arranging all activities associated with moving goods from the raw material stage to the end user constitutes the whole supply chain management

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concept. These stages include systems management, sourcing and procurement, production scheduling, order processing, inventory management, warehousing and customer service. For achieving sustainable competitive advantage beside a successful supply chain management, these activities have to be coordinated and integrated. All these stages have to be considered one by one in the optimization efforts. Besides coordinating interior stages and factors together, companies nowadays have to consider other issues that become important for the sustainability of business and management. One of these issues is environmental factors. Legitimate and social responsibilities bring pressure on the attainment of good environmental practices. One of the important topics that are considered under environmental issues is pollution. Manufacturers and firms are paying attention to the environmental benign efforts in their products/services with less packaging materials and more sensitive to the other pollution factors. The most effective way to reach this objective is constitute environmental policy in each step of the supply chain management stages. The most important stage that

environmental factors could be handled as activities related to the purchasing function. This calls the attention to the role of the environmental dimension in suppliers and buyers relationships in supply chain. Noci (1997) has defined the benefits of this cooperation in four items as; reducing the quantity of supplied components with low environmental performance, effective cost controlling of "green" products of suppliers, reducing the company's response time to the expectations of green market and avoiding problems associated with the company's "green" image. Combining environmental issues with supply chain management necessitates integrating environmental management issues such as life cycle analysis, waste management, etc. with supply chain management practices such as vendor assessment, total quality management, lean supply and collaborative practices (Lamming and Hampson, 1996).

This integration brings green supply chain management or environmentally conscious supply chain management. In literature, several studies have realized in this area such as Handfield *et al.* (2002); Humphreys *et al.* (2003); Nakashima *et al.* (2006); Ofori (2000); Sarkis (1998).

Green supply chain management is a structure that requires successful coordination, integration and management across members (enterprises) in the supply chain that includes raw material suppliers, manufacturers, distributors, users and recyclers. These efforts for collaborative relationships are necessary for environmental betterment. For this reason, a variety of approaches have developed for evaluating the companies' relationships with their suppliers to improve the environmental performance of the final products. These approaches have used methods such as the categorical method, the weighted-point method, the matrix approach, Vendor Profile Analysis (VPA), and the Analytic Hierarchy Process (AHP). These methods have assisted managers to constitute systematic analyses on the basis of criteria such as quality, cost issues, delivery and flexibility.

Based on the reasons described above, this study has three main objectives. Firstly, to identify the environmental criteria which influence a company's purchasing decisions. Secondly, to develop a framework of the supplier selection process which incorporates environmental performance and finally use the framework to develop an environmental decision support system to illustrate that how proposed model

can assist in the evaluation of suppliers environmental performance. It is emphasized that the findings should help firms enhance their competitive position in the market and in the presence of community by considering environmental factors in the evaluation phase of their suppliers. To this end, an integrated Fuzzy-Analytic Network Process (ANP) and Fuzzy-Preference Ranking Organization METHod for Enrichment Evaluations (PROMETHEE) methodology is proposed. ANP method was proposed by Saaty and Takiawz (1986) and it is an extension of AHP. In reality, the elements within the hierarchy of various criteria are often interdependent, but low-level elements may dominate high-level ones. A feedback relationship also exists in the process, thus, this structure resembles a network system (Lin, 2009). In order to solve this kind of imprecise and to cope with the complex network type of criteria relations in a multi-criteria decision-making (MCDM) problem, fuzzy ANP (F-ANP) method can be utilized.

Unlike other ranking methods in the literature, different preference functions can be defined for criteria in PROMETHEE method (Dagdeviren, 2008). It is a ranking method quite simple in conception and application compared to other methods for MCDM. It is well adapted to problems where a finite number of alternative actions are to be ranked considering several, sometimes conflicting criteria (Bilsel *et al.*, 2006). According to Ulengin *et al.* (2001), some of the advantages of PROMETHEE are: (i) PROMETHEE is a user friendly outranking method, (ii) it has been successfully applied to real life planning problems and (iii) PROMETHEE I and PROMETHEE II allow both partial and total ranking of the alternatives while still satisfying simplicity. In this paper, for treating the imprecision which is constituted by vague situations the "extension of the PROMETHEE method in a fuzzy environment" (F-PROMETHEE) is integrated with F-ANP. The research work explained in the paper has been done in Istanbul, Turkey, during January-March 2009.

MATERIALS AND METHODS
Mathematical background
Fuzzy sets

Some definitions of fuzzy sets related to this study are given as follows:

Definition 1. A fuzzy set $\tilde{A}$ in a universe of discourse X is characterized by membership function $\mu_{\tilde{A}}(X)$, which associates with each element x in X, a real number in

the interval [0, 1]. The function $\mu_{\tilde{A}}(X)$ is termed the grade of membership of x in $\tilde{A}$ (Chen, 2001).

Definition 2. A triangular fuzzy number can be defined as *a* triplet (a^l, a^m, a^u); the membership function of the fuzzy number $\tilde{A}$ is defined as below (Wang and Chang, 2007):

$$f_{\tilde{A}}(x) = \begin{cases} 0, & x < a^l, \\ (x-a^l)/(a^m-a^l), & a^l \le x \le a^m, \\ (a^u-x)/(a^u-a^m), & a^m \le x \le a^u, \\ 0, & x > a^u. \end{cases} \quad (1)$$

Let $\tilde{A}$ and $\tilde{B}$ be two triangular fuzzy numbers parameterized by the triplets (a^l, a^m, a^u) and (b^l, b^m, b^u), respectively; then the operational laws of these two triangular fuzzy numbers are as follows (Wang and Chang, 2007):

$$\tilde{A}(+)\tilde{B} = (a^l, a^m, a^u) \oplus (b^l, b^m, b^u) \quad (2)$$
$$= (a^l + b^l, a^m + b^m, a^u + b^u)$$

$$\tilde{A}(-)\tilde{B} = (a^l, a^m, a^u) - (b^l, b^m, b^u) \quad (3)$$
$$= (a^l - b^u, a^m - b^m, a^u - b^l)$$

$$\tilde{A}(x)\tilde{B} \cong (a^l, a^m, a^u) \otimes (b^l, b^m, b^u) \quad (4)$$
$$= (a^l b^l, a^m b^m, a^u b^u)$$

$$\tilde{A}(\div)\tilde{B} \cong (a^l, a^m, a^u) \div (b^l, b^m, b^u)$$
$$= (\frac{a^l}{b^l}, \frac{a^m}{b^m}, \frac{a^u}{b^u}) \quad (5)$$

$$k\tilde{A} = (ka^l, ka^m, ka^u) \quad (6)$$

$$(\tilde{A})^{-1} = (\frac{1}{a^u}, \frac{1}{a^m}, \frac{1}{a^l}) \quad (7)$$

Definition 3. A linguistic variable is a variable whose values are linguistic terms (Chen, 2001).

The concept of linguistic variable is very useful in dealing with situations which are too complex or too ill-defined to be reasonably described in conventional quantitative expressions. These linguistic variables can also be represented by fuzzy numbers (Chen, 2001).

ANP and F-ANP

ANP is a comprehensive decision-making technique that has the capability to include all the relevant criteria which have some bearing on arriving at a decision. Analytic hierarchy process serves as the starting point of ANP (Jharkharia and Shankar, 2007). The ANP provides a general framework to deal with decisions without making assumptions about the interdependence of the elements within a level. In fact, ANP uses a network without needing to specify levels as in a hierarchy. Influence is a central concept in the ANP. The ANP is a useful tool for prediction and for representing a variety of competitors with their surmised interactions and their relative strengths to wield influence in making a decision. The ANP is a coupling of two parts; the first consists of control hierarchy or a network of criteria and sub-criteria that controls the interactions, while the second is a network of influences among the elements and clusters (Saaty, 1999; Tuzkaya *et al.*, 2008; Tuzkaya and Gulsun, 2008). In some cases, if there is vagueness for the decision problem, utilizing fuzzy sets is a useful way. For this reason, in this study, the usage of the fuzzy version of ANP is preferred. In the literature, Ayag and Ozdemir (2006), Büyükozkan *et al.* (2004), Promentilla *et al.* (2008), Tuzkaya and Onut (2008) are the examples of the works which are utilized from the F-ANP approach. In the F-ANP, to evaluate the decision makers preferences, pair-wise comparisons are structured using triangular fuzzy numbers (a^l, a^m, a^u). The *mxn* fuzzy matrix can be given as in Eq. 8. The element a_{mn} represents the comparison of the component *m* (row element) with component *n* (column element). If $\tilde{A}$ is a pairwise comparison matrix (Eq. 8), it is assumed that the reciprocal and the reciprocal value, i.e. $1/a_{mn}$, is assigned to the element a_{mn} (Tuzkaya and Onut, 2008):

$$\tilde{A} = \begin{pmatrix} (1,1,1) & \left(a_{12}^l, a_{12}^m, a_{12}^u\right) & \cdots & \left(a_{1n}^l, a_{1n}^m, a_{1n}^u\right) \\ \left(\frac{1}{a_{11}^u}, \frac{1}{a_{11}^m}, \frac{1}{a_{11}^l}\right) & (1,1,1) & \cdots & \left(a_{2n}^l, a_{2n}^m, a_{2n}^u\right) \\ \cdot & \cdot & \cdot & \\ \cdot & \cdot & \cdot & \\ \cdot & \cdot & \cdot & \\ \left(\frac{1}{a_{1n}^u}, \frac{1}{a_{1n}^m}, \frac{1}{a_{1n}^l}\right) & \left(\frac{1}{a_{2n}^u}, \frac{1}{a_{2n}^m}, \frac{1}{a_{2n}^l}\right) & \cdots & (1,1,1) \end{pmatrix} \quad (8)$$

$\tilde{A}$ is also a triangular, fuzzy, pairwise comparison matrix. There are several methods for getting estimates for the fuzzy priorities, $\tilde{w}_i$, where and $i=1,2,\ldots,n$, from the judgment matrix, $\tilde{A}$, which approximates the fuzzy ratios $\tilde{a}_{ij}$, so that $\tilde{a}_{ij} \approx \tilde{w}_i / \tilde{w}_j$. One of these methods, the logarithmic least-squares method, is used in this study since it is a most-used and effective method. The triangular fuzzy weights representing the relative importance of the criteria, the feedback of the criteria and the alternatives according to individual criteria is calculated by this method. The logarithmic least-squares method for calculating triangular fuzzy weights can be given as follows (Tuzkaya and Onut, 2008):

$$\tilde{w}_i = (w_i^l, w_i^m, w_i^u), k=1,2,\ldots,n \quad (9)$$

Where,

$$w_i^s = \frac{\left(\Pi_{j=1}^n a_{ij}^s\right)^{1/n}}{\Sigma_{k=1}^n \left(\Pi_{j=1}^n a_{kj}^m\right)^{1/n}}, \quad s \in \{l,m,u\} \quad (10)$$

The alternatives are evaluated as previously expressed. Following this step, for converting the weights of the alternatives to crisp numbers, three approaches are utilized: Chang's extent analysis (1996) method, Center of Area (COA) method (Sugeno, 1985) and Yager Index (Yager, 1981) are utilized. The steps of Chang's extent analysis approach, by integrating the improvements of Zhu *et al.* (1999) are as follows: Let $X = \{x_1, x_2, \ldots, x_n\}$ be an object set and $U = \{u_1, u_2, \ldots, u_m\}$ be a goal set. Each object is taken and extent analysis for each goal, g_i, is performed, respectively. Therefore, m extent analysis values for each object can be obtained, with the following signs (Büyükozkan *et al.*, 2004):

$$M_{g_i}^1, M_{g_i}^2, \ldots, M_{g_i}^m \quad i=1,2,\ldots,n \quad (11)$$

Where all the $M_{g_i}^j$ $(j=1,2,\ldots,m)$ are triangular fuzzy numbers (TFNs).

The steps of Chang's extent analysis can be given as follows:

Step 1. The value of fuzzy synthetic extent with respect to the ith object is defined as

$$S_i = \sum_{j=1}^m M_{g_i}^j \otimes \left[\sum_{i=1}^n \sum_{j=1}^m M_{g_i}^j\right]^{-1} \quad (12)$$

To obtain $\sum_{j=1}^m M_{g_i}^j$, perform the fuzzy addition operation of m extent analysis value for a particular matrix such that:

$$\sum_{j=1}^m M_{g_i}^j = \left(\sum_{j=1}^m l_j, \sum_{j=1}^m m_j, \sum_{j=1}^m u_j\right) \quad (13)$$

And to obtain $\left[\sum_{i=1}^n \sum_{j=1}^m M_{g_i}^j\right]^{-1}$, perform the fuzzy edition operation of $M_{g_i}^j$ $(j=1,2,\ldots,m)$ values such that

$$\sum_{i=1}^n \sum_{j=1}^m M_{g_i}^j = \left(\sum_{i=1}^n l_i, \sum_{i=1}^n m_i, \sum_{i=1}^n u_i\right) \quad (14)$$

And then compute the inverse of the vector in Eq. 14 such that:

$$\left[\sum_{i=1}^n \sum_{j=1}^m M_{g_i}^j\right]^{-1} = \left(\frac{1}{\Sigma_{i=1}^n u_i}, \frac{1}{\Sigma_{i=1}^n m_i}, \frac{1}{\Sigma_{i=1}^n l_i}\right) \quad (15)$$

Step 2. The degree of possibility of $M_2 = (l_2, m_2, u_2) \geq M_1 = (l_1, m_1, u_1)$ is defined as

$$V(M_2 \geq M_1) = \sup_{y \geq x}\left[\min\left(\mu_{M_1}(x), \mu_{M_2}(y)\right)\right] \quad (16)$$

And can be equivalently expressed as follows:

$$V(M_2 \geq M_1) = hgt(M_1 \cap M_2) = \mu_{M_2}(d) =$$

$$\begin{cases} 1, & \text{if } m_2 \geq m_1, \\ 0, & \text{if } l_1 \geq u_2, \\ \dfrac{l_1 - u_2}{(m_2 - u_2) - (m_1 - l_1)} & \text{otherwise}, \end{cases} \quad (17)$$

Where *d* is the ordinate of the highest intersection point *D* between, μ_{M_1} and μ_{M_2} to compare M_1 and M_2, both the values of $V(M_1 \geq M_2)$ and $V(M_2 \geq M_1)$. are needed.

Step 3. The degree possibility for a convex fuzzy number to be greater than *k* convex fuzzy numbers $M_i (i=1, 2, ..., k)$ can be defined by

$$V(M \geq M_1, M_2..., M_k) = V \begin{bmatrix} \left[(M \geq M_1) and (M \geq M_2)\right] \\ and ...and (M \geq M_k) \end{bmatrix} \quad (18)$$

$$= \min V(M \geq M_i), \ i=1,2,3,...,k.$$

Assume that:

$$d'(A_i) = \min V(S_i \geq S_k) \quad (19)$$

For; *k = 1, 2, ..., n* and *k ≠ i*. Then the weight vector is given by:

$$W' = (d'(A_1), d'(A_2), ..., d'(A_n))^T, \quad (20)$$

Where $A_i (i=1,2,...,n)$ are *n* elements.

Step 4. Via normalization, the normalized weight vectors are

$$W = (d(A_1), d(A_2), ..., d(A_n))^T, \quad (21)$$

Where *W* is a nonfuzzy number.

The normalized weight vector can also be obtained by some other methods in the literature. One of these is Center of Area (COA) method. This technique was developed by Sugeno in 1985 (Sugeno, 1985). This is also one of the most commonly used techniques. COA technique can be expressed as:

$$x^* = \frac{\int \mu_i(x) x \, dx}{\int \mu_i(x) \, dx} \quad (22)$$

Where, x^* is the defuzzified output, $\mu_i(x)$ is the aggregated membership function and *x* is the output variable. The only disadvantage of this method is that it is computationally difficult for complex membership functions.

Another defuzzification method is Yager index (Yager, 1981) and it is simply calculated by Eq. 23:

$$\widetilde{F} = (n - a, n, n + b) = (3n - a + b)/3 \quad (23)$$

PROMETHEE and F-PROMETHEE

PROMETHEE (Preference Ranking Organization METHod for Enrichment Evaluations) is an outranking method which initial references are prepared by Brans and Vincle (1985) and Brans *et al.* (1986). It is a quite simple ranking method in conception and application compared with other methods used for multi-criteria analysis. It is well adapted to the problems where a finite set of alternatives are to be ranked according to several, sometimes conflicting criteria (Albadvi *et al.*, 2007; Dagdeviren, 2008). The evaluation is the starting point of PROMETHEE method. In this phase, alternatives are evaluated with respect to different criteria. These evaluations involve essentially numerical data. The implementation of PROMETHEE requires two additional types of information, namely (Macharis *et al.*, 2004):

• Information on the relative importance (i.e. the weights) of the criteria considered,

• Information on the decision-makers' preference function, which he/she uses when comparing the contribution of the alternatives in terms of each separate criterion.

The basic steps of the PROMETHEE algorithm can be outlined as follows (Brans *et al.*, 1986; Geldermann *et al.*, 2000):

Step 1. Specify a generalized preference function $p_j(d)$ for each criterion *j*. (Fig. 1).

Step 2. Define a vector containing the weights, which are a measure for the relative importance of each criterion, $w^T = [w_1, ..., w_k]$. If all the criteria are of the same importance in the opinion of the decision maker, all weights can be taken as being equal. The normalization of the weights, $\sum_{k=1}^{K} w_k = 1$, is not necessarily required.

Step 3. Define for all the alternatives a_t, $a_{t'} \in A$ the outranking relation π:

$$\pi : \begin{cases} AxA \rightarrow [0,1] \\ \pi(a_t, a_{t'}) = \sum_{k=1}^{K} w_k.(p_k(f_k(a_t) - f_k(a_{t'})) \end{cases} \quad (24)$$

The preference index $\pi(a_t, a_{t'})$ is a measure for the intensity of preference of the decision maker for an alternative a_t in comparison with an alternative $a_{t'}$ for the simultaneous consideration of all criteria. It is basically a weighted average of the preference functions $p_k(d)$ and can be represented as a valued outranking graph.

Step 4. As a measure for the strength of alternatives $a_t \in A$, the leaving flow is calculated:

$$\Phi^+(at) = \frac{1}{T-1} \cdot \sum_{\substack{t'=1 \\ t' \neq t}}^{n} \pi(at, at') \qquad (25)$$

The leaving flow is the sum of the values of the arcs which leave node a_t and therefore yields a measure of the "outranking character" of a_t.

Step 5. As a measure for the weakness of the alternatives $a_t \in A$, the entering flow is calculated, measuring the "outranked character" of a_t (analogously to the leaving flow):

$$\Phi^-(at) = \frac{1}{T-1} \cdot \sum_{\substack{t'=1 \\ t' \neq t}}^{n} \pi(at', at)) \qquad (26)$$

Step 6. A graphical evaluation of the outranking relation is derived: Basically, the higher the leaving flow and the lower the entering flow, the better the action. This result is graphically represented by a partial preorder (PROMETHEE I) or a complete preorder (PROMETHEE II).

In PROMETHEE I, alternative a_t is preferred to alternative $a_{t'} (a_t P a_{t'})$ at least one of the elements of Eq. 26 is satisfied (Dagdeviren, 2008):

$$at\,P\,at'\,if: \Phi^+(at) > \Phi^+(at')\;and\;\;\Phi^-(at) < \Phi^-(at')\;\;or$$
$$\Phi^+(at) > \Phi^+(at')\;and\;\;\Phi^-(at) = \Phi^-(at')\;\;or$$
$$\Phi^+(at) = \Phi^+(at')\;and\;\;\Phi^-(at) < \Phi^-(at')$$
$$\qquad (27)$$

PROMETHEE I evaluation allows indifference and incomparability situations. Therefore, sometimes partial rankings can be obtained. In the indifference situation $(a_t I a_{t'})$, two alternatives a_t and $a_{t'}$ have the same leaving and entering flows (Dagdeviren, 2008; Tuzkaya, 2009):

$$at\,I\,at'\,if: \Phi^+(at) = \Phi^+(at')\;and\;\;\Phi^-(at) = \Phi^-(at') \quad (28)$$

Two alternatives are considered incomparable, $a_t R a_{t'}$, if alternative a_t is better than alternative $a_{t'}$ in terms of leaving flow, while the entering flows indicate the reverse (Dagdeviren, 2008):

$$at\,R\,at'\,if: \Phi^+(at) > \Phi^+(at')\;and\;\;\Phi^-(at) > \Phi^-(at')\;or$$
$$\Phi^+(at) < \Phi^+(at')\;and\;\;\Phi^-(at) < \Phi^-(at') \qquad (29)$$

Via PROMETHE II, the complete ranking can be obtained. For the complete ranking calculations, net flow values of alternatives can be calculated as Eq. 30. Here, if alternative a_t's net flow is bigger than alternative $a_{t'}$'s net flow, this indicates that, alternative a_t outranks alternative $a_{t'}$.

$$\Phi^{net}(at) = \Phi^+(at) - \Phi^-(at) \qquad (30)$$

In this study, the F-PROMETHEE technique is preferred because of the fuzzy nature of the decision problem. In the literature, there are a few studies using F-PROMETHEE approach. Bilsel *et al.* (2006), Chou *et al.* (2007), Geldermann *et al.* (2000) and Goumas and Lygerou (2000) have used F-PROMETHEE previously.

In the F-PROMETHEE, the main problem arises in comparing two fuzzy numbers and the index, which corresponds to a weighted average of the fuzzy numbers, proposed from Yager (1981) is found a useful way to compare fuzzy numbers. It is determined by the center of weight of the surface representing its membership function (Bilsel *et al.*, 2006; Goumas and Lygerou, 2000). Based on the Yager's index (Yager, 1981), a triangular fuzzy number's magnitude is the value corresponding to the center of the triangle and can be expressed as in Eq. (23). The representation of a TFN here, $\tilde{F} = (n, a, b)$, is a different version of the representation used in *Fuzzy Sets*, *ANP* and *F-ANP* sections. This is equivalent to the previous representation by $\tilde{F} = (n-a, n, n+b)$. The following fuzzy PROMETHEE formulas are based on the representation of TFN as *(n, a, b)*.

In this study, PROMETHEE's linear preference function with indifference and strict preference is preferred for each criterion by DMT (Decision Making Team). In this preference function, two thresholds, *q* and *p* are needed to be determined (Fig. 1). When using the fuzzy numbers in PROMETHEE, the evaluation function explained in Fig. 1, can be converted to Eq. (31).

$$P_j(at, at') = \begin{cases} 0, if\ n-a \leq q(indifference) & (31) \\ \dfrac{(n,a,b) - q}{p - q}, \ if \ q \leq (n-a)\ and\ (n+b) \leq p \\ 1,\ if\ n+b > p(strict\ preference) \end{cases}$$

In Eq. 31, *q* and *p* values are crisp numbers and the membership functions of the fuzzy number, $C(a_t, a_{t'}) = (n, a, b)$, is adjusted accordingly so that $n-a \geq 0$ and $n+b \leq 1$. In the if-statement in Eq. 31, the controls are the TFNs which represents the differences between a_t, $a_{t'}$. Similarly to the PROMETHEE approach, the

Type 1: Usual criterion

Type 2: Quasi-criterian (U-Shape)

$$P_j(a_t, a_{t'}) = \begin{cases} 0 & if \ d_{a_t,a_{t'}} \le 0 \ (indifference) \\ 1 & if \ d_{a_t,a_{t'}} > 0 \ (strict \ preference) \end{cases}$$

$$P_j(a_t, a_{t'}) = \begin{cases} 0 & if \ d_{a_t,a_{t'}} \le q \ (indifference) \\ 1 & if \ d_{a_t,a_{t'}} > q \ (strict \ preference) \end{cases}$$

Type 3: Criterion with linear preference (V-Shape)

Type 4: Level criterion

$$P_j(a_t, a_{t'}) = \begin{cases} \dfrac{d_{a_t,a_{t'}}}{p}, if \ 0 < d_{a_t,a_{t'}} \le p \ (indifference) \\ 1, \ if \ d_{a_t,a_{t'}} > p \ (strict \ preference) \end{cases}$$

$$P_j(a_t, a_{t'}) = \begin{cases} 0 & if \ 0 < d_{a_t,a_{t'}} \le q \ (indifference) \\ 0.5, & if \ q < d_{a_t,a_{t'}} \le p \\ 1, & if \ d_{a_t,a_{t'}} > p \ (strict \ preference) \end{cases}$$

Type 5: Criterion with linear preference and indifference area

Type 6: Gaussian criterion

$$P_j(a_t, a_{t'}) = \begin{cases} 0, if \ d_{a_t,a_{t'}} \le q (indifference) \\ \dfrac{d_{a_t,a_{t'}} - q}{p - q}, \ if \ q < d_{a_t,a_{t'}} \le p \\ 1, if \ d_{a_t,a_{t'}} > p (strict \ preference) \end{cases}$$
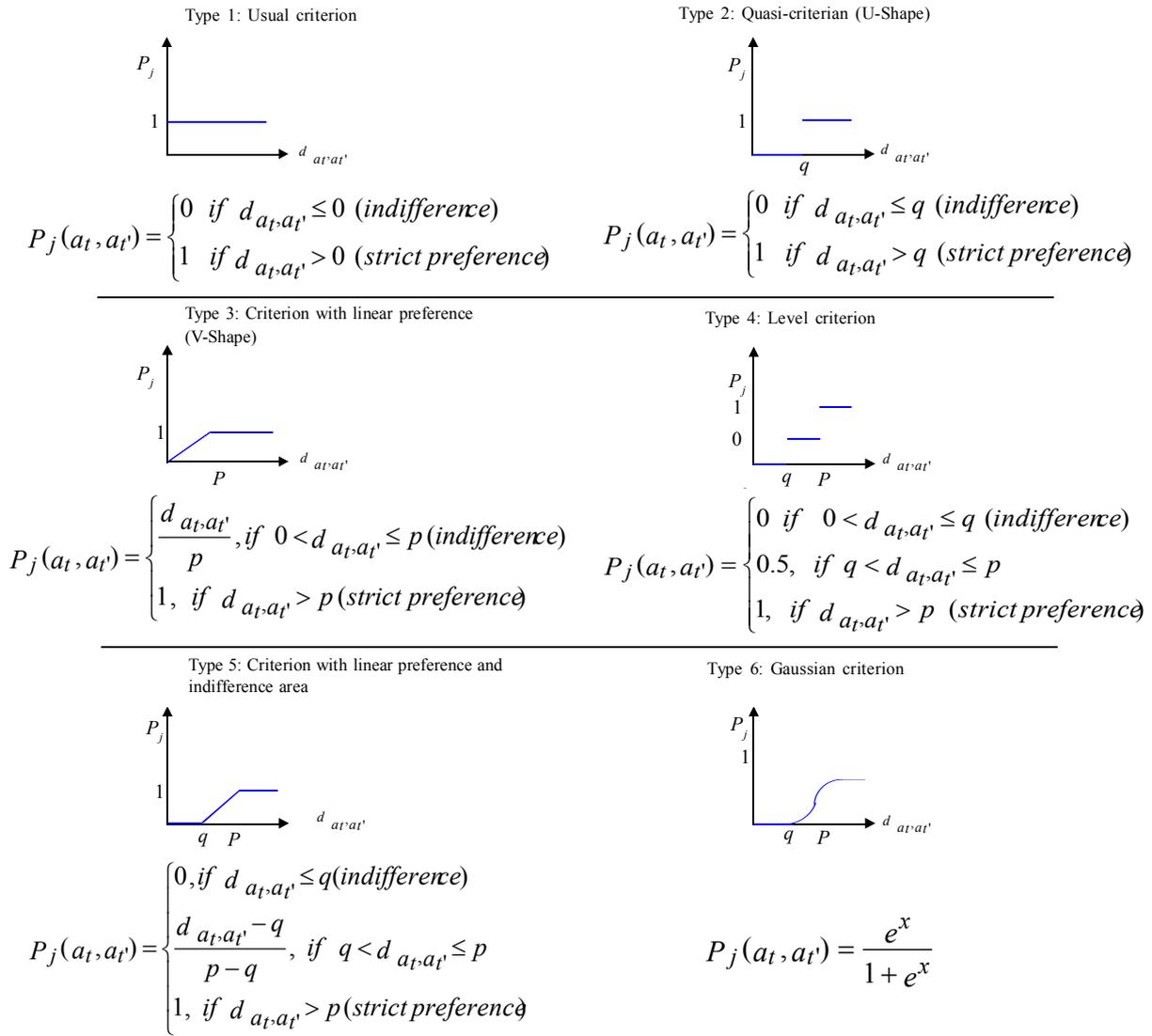
$$P_j(a_t, a_{t'}) = \dfrac{e^x}{1 + e^x}$$

Fig. 1: PROMETHEE generalized preference functions (Brans, 1986; Tuzkaya, 2009;Vego *et al.*, 2008)

leaving flow, the entering flow and the net flow notions are valid in the case of F-PROMETHEE (Bilsel *et al.*, 2006). Outside of the abovementioned differences, F-PROMETHEE utilizes from the PROMETHEE's application steps. In these steps, for the operations with fuzzy numbers, the basic operators given in the "*Fuzzy sets*" section can also be used.

A hybrid fuzzy multi-criteria decision methodology for evaluation of suppliers with the environmental criteria

In this study, a novel methodology that integrates F-ANP and F-PROMETHEE approaches is

proposed. F-ANP is utilized for the evaluation of decision criteria. The usage of ANP integrates the interdependence between criteria into the decision-making process. On the other hand, the vagueness in the decision process is reflected via the usage of fuzzy sets. Because the steps of ANP are time consuming and complicated, F-ANP is utilized only in the decision criteria evaluation phase and the rest of the calculations are completed via F-PROMETHEE approach. Fig. 2 shows the details of the proposed methodology. In the F-ANP, the decision-making team (DMT) are asked to compare the criteria considering the effects on achieving
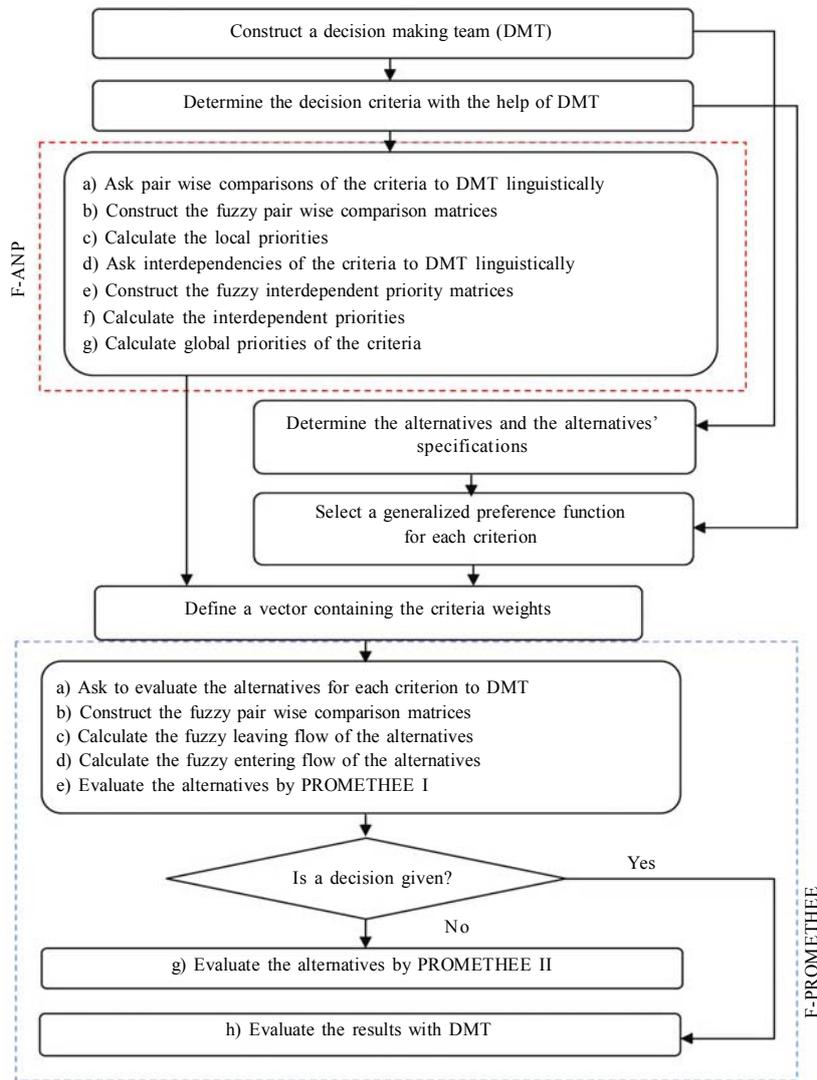
Fig. 2: The integrated F-ANP and F-PROMETHEE methodology

Table 1: Linguistic scale for importance used for ANP comparisons (Kahraman *et al.,* 2006)

Linguistic scale for importance	Triangular fuzzy scale
Just equal	(1,1,1)
Equally important (EI)	(0.5, 1, 1.5)
Weakly more important (WMI)	(1, 1.5, 2)
Strongly more important (SMI)	(1.5, 2, 2.5)
Very strongly more important (VSMI)	(2, 2.5, 3)
Absolutely more important (AMI)	(2.5, 3, 3.5)

Table 2: Linguistic scale for importance used for PROMETHEE evaluations (Bilsel *et al.*, 2006)

Linguistic scale for evaluation	Triangular fuzzy scale
Strongly disagree (SDA)	(0, 0, 0.15)
Disagree (DA)	(0, 0.15, 0.30)
Little disagree (LDA)	(0.15, 0.30, 0.50)
No comment (NC)	(0.30, 0.50, 0.65)
Little agree (LA)	(0.50, 0.65, 0.80)
Agree (A)	(0.65, 0.80, 1)
Strongly agree (SA)	(0.80, 1, 1)

main goal and asked to compare criteria considering the effects on the other criteria. In this process, the used linguistic scale for relative importance (RI) is given in Table 1.

In the F-PROMETHEE phase, the DMT is asked to evaluate alternatives considering each criterion. For this evaluation stage, the used linguistic scale for relative importance is given in Table 2.

RESULTS AND DISCUSSION

Application of proposed approach: A Case study for environmental performance evaluation of a white goods manufacturer's suppliers

To foster the better understanding and the validation of the proposed methodology, a real life case study from a white goods manufacturer of Turkey is presented. This firm has selected because of its field of activity. White goods sector is one of the important industrialized sectors in Turkey which consists of ten major and about a hundred SMEs as producers and twenty importer firms. It has enormous production capacity with a significant acceleration (Eroglu and Özdamar, 2006). Adaptation of the sector to the EU regulations has increased the international competence. However, during the adaptation continuum, environmental regulations related to the sector bring difficulties in the application. For elimination of these difficulties, there is a need for determining shortages and setting measurements for tracking improvements. To this end, first of all environmental measurements for the evaluation and monitoring of supply chains processes environmental performance should be structured. Considering this situation, in this study, the proposed approach is applied in a systematic way to a firm from Turkish White Goods Industry and interviews are realized from experts of this sector in each phase.

As a first step of the application, a decision-making team (DMT) is constructed for the decision process. The DMT is constituted from three academicians, Manager of purchasing department and his team consisted of eight purchasing specialist. After completing this phase, criteria are determined by interview sessions done with DMT and considering the related literature conducted before (especially it has been referred to the studies prepared by Lee *et al.* (2009), Lu *et al.* (2007), Nakashima *et al.* (2006), Tsoulfas and Pappis (2006), Tsoulfas and Pappis (2008)). For elimination of criteria the decision making team had a final meeting with the participation of sales manager, public relationships manager and franchising network responsible.

The main criteria could be summarized as; Green Process Management (GPM), Green Product (GP), Green Image (GI), Environment and Legislative Management (ELM), Pollution Control (PC), Environmental Costs (EC).

GPM criteria cluster contains the processes, related to the production, from R&D efforts, product design, technology, planning and monitoring and distribution phases of production and issues related to environmental and pollution performances of first and second tier of suppliers. *GP* main criteria cluster gathers issues related with the product characteristics that provides opportunity to recyclability, reusability, and re-manufacturability etc activities. Here, the ability of the contribution of the suppliers' to the green features of the product arise from components and materials supplied is examined. *GI* main criteria cluster is related with the environmental image of the suppliers and contains issues such as social responsibility efforts, activities to motivate customer for consuming green products, training and programs for employees for green consciousness, voluntarily involvement to the legislative regulations of government by firm. *ELM* main criteria cluster is related with the legislative and managerial activities of the suppliers. These activities may contain environment-related certificates (ISO 14000, WEEE etc.) and reverse logistics (RL) management programs. *PC* main criteria cluster is related with the pollution factors constituted from the supplier production and service processes and product components. These factors are related with the air emissions, wastewater, solid wastes, energy consumption, use of harmful materials and hazardous wastes. *EC* main criteria cluster contains cost factors related with the environmental and green production, logistics and other activities.

Interdependencies between main criteria clusters are given in Fig. 3. These relations can be summarized as follows: GPM cluster has influence on the GPM, GP, ELM, PC, EC and GI criteria clusters. As an example, R&D projects for green production sub-criterion of GPM has influence on design for the environment, green production technology, green distribution, second tier supplier environmental evaluation and secondary market for waste generated sub-criterion of same cluster, GPM. Same sub-criterion also has influence on all sub-criteria of the GP, ELM and PC criteria clusters. But, it influences only cost of producing green products and cost of RL about green products sub-criteria of EC criteria cluster. The reason that all the sub-criteria in the main criteria clusters do not influence each other could be explained as follows. For example, R&D projects for the green production sub-criterion could decrease cost of producing green
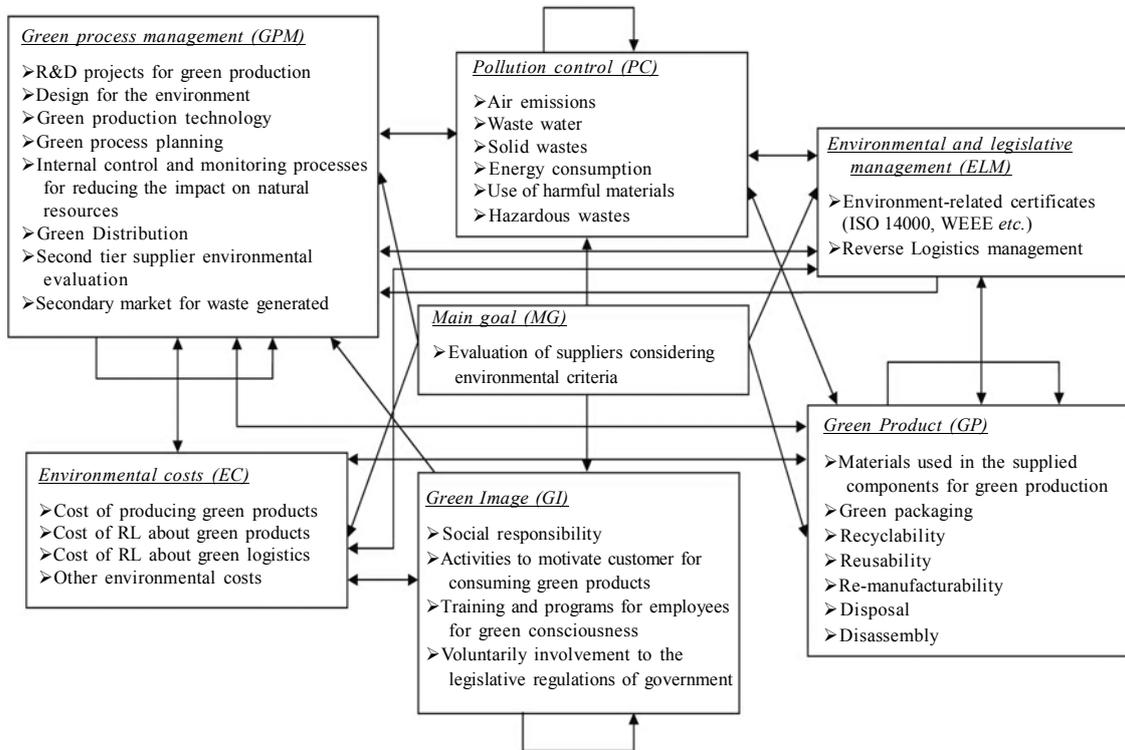
Fig. 3: Suppliers' environmental evaluation criteria and the criteria influences

Table 3: Linguistic criteria comparisons considering the impact of the main goal (MG)

MG	GPM	GP	GI	ELM	PC	EC
GPM	JE	WMI	SMI	WMI	SLI	WMI
GP	WLI	JE	SMI	WMI	EI	WMI
GI	SLI	SLI	JE	SLI	WLI	ALI
ELM	WLI	WLI	SMI	JE	SLI	WLI
PC	SMI	EI	WMI	SMI	JE	WMI
EC	WLI	WLI	AMI	WMI	WLI	JE

Table 4: Alternatives linguistic evaluations by DMT

	GPM	GP	GI	ELM	PC	EC
A_1	A	LA	LA	NC	LA	LDA
A_2	SDA	DA	SDA	SDA	SDA	A
A_3	NC	NC	LA	NC	LDA	A
A_4	LA	A	LA	NC	NC	A
A_5	LA	LA	A	LDA	LDA	LA

products and cost of RL about green products sub-criteria of EC. Because with an effective R&D performance, the right ways of producing green product with low or optimum cost could be explored. Also the green distribution sub-criterion of GPM has a direct effect on air emission sub-criterion of PC, because more environmental friendly distribution alternatives may decrease the harmful emissions to the atmosphere. All other interdependencies could be seen in Fig. 3.

In the first step of the fuzzy-ANP approach, the DMT is asked to compare the decision criteria linguistically according to their affect on the realization of the main goal (*MG*). Here, it is assumed that there are no interdependencies between criteria and the scale in

Table 1 is utilized. Table 3 shows the DMT pair-wise comparisons.

Then, the linguistic preferences of the DMT are converted to triangular fuzzy numbers utilizing from Table 1. At the next step, using logarithmic least-square technique (Eq. 9) and normalization, criteria weights are calculated with the assumption of there is no interdependence between them as (0.15, 0.19, 0.25), (0.14,0.19,0.25), (0.07, 0.09, 0.11), (0.10, 0.13, 0.17), (0.16, 0.23, 0.29) and (0.13, 0.17,0.22) for GPM, GP, GI, ELM, PC and EC, respectively.

Then the affects of each criterion on the other criteria are analyzed using same steps with the comparison of the decision criteria linguistically according to their affects on the realization of the main goal. For this stage,
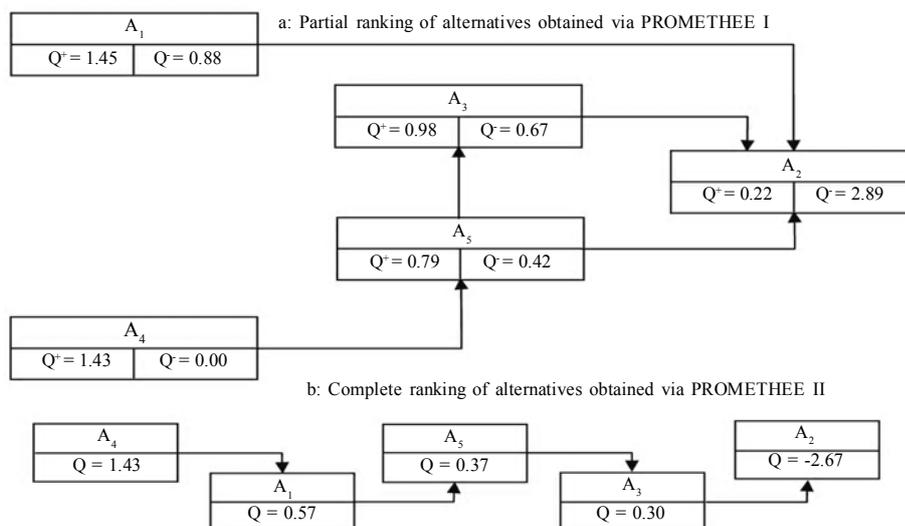
Fig. 4: Ranking results via PROMETHEE I and PROMETHEE II

the DMT is asked to "compare the effects of C_x and C_y on C_z" for each criteria pair".

At the last step of F-ANP, using l1.

logarithmic least-square technique (Eq. 9) and Chang's extent analysis, the weights of the criteria is calculated. According to the results, the weights of the *GPM, GP, GI, ELM, EC* and *PC* are 0.25, 0.21, 0.03, 0.07, 0.21 and 0.22, respectively. The weight vector is also calculated using COA method and Yager index. With these methods, very similar results are obtained. Following the F-ANP calculations, using the criteria weights, F-PROMETHEE calculations are realized. As a first step of F-PROMETHEE, the DMT is asked to determine the generalized criterion type of each criterion and *q, p* values. Generalized criterion type is selected as level criterion type for each and *q, p* values are determined as "0 and 0.6", respectively. Following this step, the DMT is asked to evaluate the alternatives linguistically (Table 4) and then the linguistic evaluations are converted to triangular fuzzy numbers utilizing from Table 2. At the next step, the differences between each alternative pair for each criterion are calculated. Using these differences, Yager index values (Eq. 23) and criteria weights, alternatives' leaving, entering and net flows are calculated (Table 5) utilizing from Eq. (24-31). Then, partial ranking of alternatives are found via PROMETHEE I (Fig. 4a). Based on this partial ranking, A_1 and A_4 alternatives outrank all the other alternatives and A2 is outranked by all the other alternatives. However, A_1 and A_4 cannot be compared with each other, since, A_1's ϕ^+ is bigger than A_4, but, A_1's ϕ^- is bigger than A_4, too. This situation causes a need to

Table 5: Alternatives' leaving, entering and net flows

	A_1	A_2	A_3	A_4	A_5	Φ^+	Φ^{net}
A_1	0,00	0,78	0,46	0,00	0,21	1,45	0,57
A_2	0,22	0,00	0,00	0,00	0,00	0,22	-2,67
A_3	0,22	0,76	0,00	0,00	0,00	0,98	0,30
A_4	0,22	0,78	0,21	0,00	0,21	1,43	1,43
A_5	0,22	0,57	0,00	0,00	0,00	0,79	0,37
Φ^-	0,88	2,89	0,67	0,00	0,42		

utilize from PROMETHEE-II technique for a complete ranking of alternatives. At the last step of calculations, the complete ranking of alternatives is determined (Fig. 4b). Based on the PROMETHEE II calculations, A_4 is the best, A_2 is the worst alternative. While in PROMETHEE I, A_1 and A_4 cannot be compared, according to PROMETHEE II, it can be seen that A_4 is better than A_1.

Analyzing the results and sensitivity analyses

As can be seen and explained from the previous section, A_4 is superior to the other alternatives. A_4's superiority comes from some reasons, such as: A_4 is at least equal to the other alternatives for the criteria *GP, ELM, PC* and *EC*. Within these criteria, *GP, EC* and *PC* have relatively high weighting values. Altough, A_4 is not superior to all the others in terms of the most important criteria, GPM, it's superiority is for the closer weighted criteria to the *GPM* (*GP, EC* and *PC*) can tolerate this situation. The least preferred alternative, A_2, is the worst alternative for all criteria except *EC* criterion.

According the results that obtained with PROMETHEE I, A_1 and A_4 cannot be compared. The reason of this situation is that, A_1 is superior to A_4 in the leaving flow

a. Changes on the alternatives' leaving flows as the change on the *GPM*'s weight

b. Changes on the alternatives' entering flows as the change on the *GPM*'s weight

c. Changes on the alternatives' net flows as the change on the *GPM*'s weight
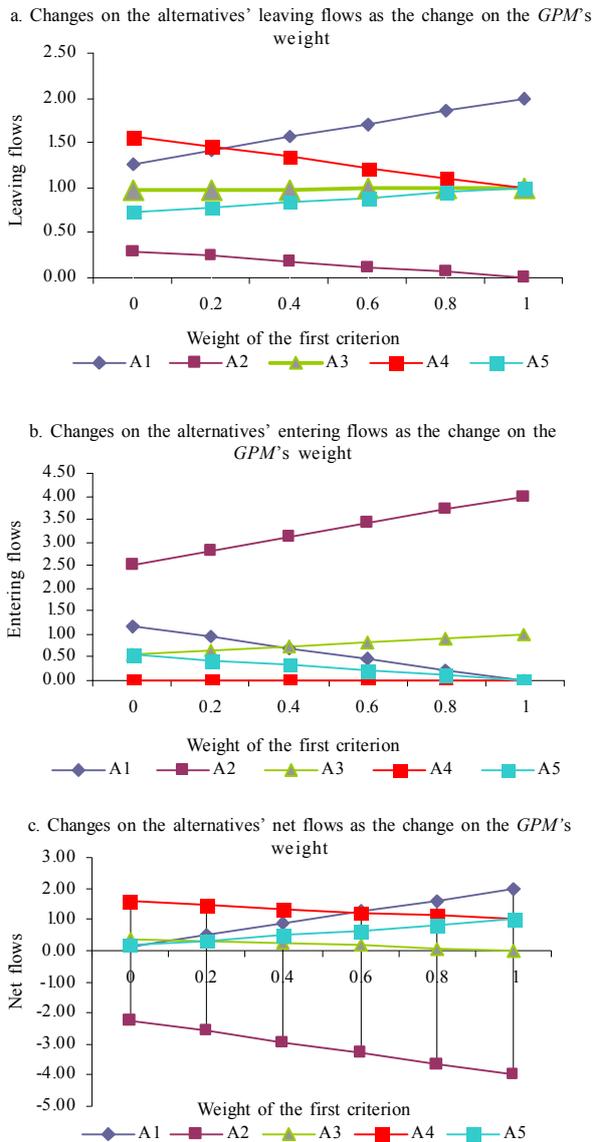

Fig. 5: Sensitivity analyses

comparison, but, A_4 is superior to A_1 in the entering flow comparison. To compare these two alternatives, the net flow should be calculated in PROMETHEE II and with PROMETHEE II complete ranking comparisons, it can be concluded that A_4 is superior to A_1.

As mentioned before, the weights of the decision criteria are determined via F-ANP. In this stage, the sensitivity of the results to the changes in the criteria weights is analyzed. As an example for all other sensitivity analysis of criteria weights, here, only the results sensitivity to *GPM* weights is presented

(Fig. 5). From Fig. 5a, changes on the alternatives' leaving flows as the change on the *GPM* weight can be seen. With the increase in the weight of the *GPM* from zero to one, the leaving flow values of A_2 and A_4 are getting worse. The reason of A_2 is getting worse is that this alternative has not a good evaluation for the criterion *GPM*. On the other hand, A_4's evaluation for this criterion is not a worse evaluation. The reason of the decrease in the A_4's situation is that this alternative is better for the other criteria, but, with the increase of weight of *GPM*, the relative importance of the others decreases. A_1 has the best evaluation for the criterion *GPM's* and this results with a significant increase of the leaving flow of it with the increase of the *GPM's* weight. Fig. 5b shows the changes on the alternatives entering flows as the change on the *GPM* weight. Alternative A_2 and A_3's entering flows are getting worse with the increase of the *GPM* weight. This is because, these two alternatives have worse linguistic evaluations (A_2 and A_3's evaluations are SDA and NC, respectively) for the criterion *GPM*. When considering the net flows (Fig. 5c), with the increase of the *GPM's* weight, the net flows of A_1 and A_5 are getting better and the situations of the others are getting worse. Since, net flow is the difference between leaving and entering flow, similar interpretations can be made for the Fig. 5c. With the increase of *GPM's* weight and decrease of the others relative weights, the situation of A_1 and A_5 are getting better, because, A_1 takes the best evaluation value for this criterion and A_5 takes its best evaluation value between higher weighted criteria. In spite of the fact that A_5 is a good linguistic evaluation for the criterion *GI* (A), the decrease of this criterion weight does not affect the situation because of its lower weight.

As a final stage, these results are proposed to the DMT. According to their investigations on the results, the environmental evaluations of the suppliers are found to be realistic and applicable as a part of their supplier evaluation procedure. This situation increases the reliability of the proposed approach. Also, when considering the application phase, proposed approach proves its effectiveness and easiness to apply. Expert opinions are reflected to the procedure in a user friendly way and also results are sensitive to the change in the parameters which is an indicator that proposed methodology may be a generally accepted methodology for the other sector applications.

CONCLUSION

In this study, an integrated fuzzy multi-criteria decision-making methodology is utilized. This is a novel methodology both for the multi-criteria decision-making literature and the suppliers' evaluation literature. Also, there is not too much study for the supplier environmental evaluation literature. This study is unique between these limited number of the study with the evaluation process, especially with the consideration of criteria influences and the vagueness of the decision process. Also, this is the first study that integrates the fuzzy-ANP and fuzzy-PROMETHEE approaches.

The proposed methodology has some advantages comparing the previously proposed methodologies which are proved with a real life case study from Turkish White Goods Industry. First of all, the vagueness embedded in this decision-making area may easily incorporated into the decision-making process with this methodology. Also, the DMT is not asked to give accurate values for the evaluations. Contrarily, both the criteria evaluations and the alternative evaluations are started with the linguistic preferences. This situation increases the usefulness and easiness of the methodology. Another advantage of the proposed methodology comes from a property of ANP. This property is the ANP's superiority that reflects the interdependencies into the decision-making process. Thanks to this property, the interdependencies among the evaluation criteria could be inserted the decision making process. Besides, PROMETHEE's easiness in calculation and application phases is a major advantage of the proposed methodology. For the future studies, the usage of this approach in different application areas may be considered, especially in the application areas that the vagueness is a specification of them.

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