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Performance evaluation of green supply chain management using integrated fuzzy multi-criteria decision making techniques

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ABSTRACT

Green Supply Chain Management (GSCM) predicates minimizing or preferably eliminating negative effects of supply chain operations on the environment. Companies have to enhance their capability on GSCM activities based on not only emerging environmental regulations but also enthusiastic politics of the companies about environmental practices. GSCM requires multi-dimensional approaches, thus multi-criteria decision making (MCDM) techniques should be implemented while evaluating GSCM performance of companies. Moreover, fuzzy group decision making methods should be implemented in order to seek solutions for vague and complex multi-attribute problems in fuzzy environment. In this study, a model based on integrated fuzzy MCDM methods is proposed for evaluating GSCM performance of companies in terms of green design, green purchasing, green transformation, green logistics and reverse logistics. The cause and effect interrelationship amongst GSCM dimensions is figured out using fuzzy DEMATEL method. Then, based on this interrelationship, fuzzy ANP method is implemented for calculating the weights of the related criteria. Finally, fuzzy TOPSIS method is applied by using the weights obtained from fuzzy ANP method, for evaluating and ranking the GSCM performance of alternative companies.

1. Introduction

Green Supply Chain Management (GSCM) has been defined as "integrating environmental thinking into supply-chain management, including product design, material sourcing and selection, manufacturing processes, delivery of the final product to the consumers as well as end-of-life management of the product after its useful life" (Srivastava, 2007). In the literature there are many other definitions for GSCM. Ahi and Searcy (2013) have identified 22 definitions in their comparative literature analysis.

Companies need to evaluate effectiveness of their GSCM implementations to improve green performance of the supply chain. United States Environmental Protection Agency (US EPA, 2000) published a practical guide namely "Lean and Green Supply Chain" which concerns reducing costs and improving environmental performance for Materials and Supply Chain Managers. This guidebook gives the best practices of leading US companies who have saved while reducing or eliminating significant environmental impacts. On the other hand, Fahimnia, Sarkis, and Eshragh (2015) also presented tactical supply chain planning model for investigating trade-offs between cost and environmental degradation. They found that (1) not all lean interventions at the tactical supply chain planning level result in green benefits, and (2) a flexible supply chain is the greenest and most efficient alternative when compared to strictly lean and centralized situations.

Companies require to evaluate the effectiveness of their GSCM implementations which enables them to improve their green skills. Although there are studies in the literature on green supplier selection process (Büyüközkan & Cifci, 2012; Tseng & Chiu, 2013), there is a need for developing models for evaluating overall GSCM performance of any company. Since GSCM requires multi-dimensional approaches, multi-criteria decision making (MCDM) techniques should be implemented while evaluating GSCM performance of companies. Moreover, fuzzy group decision making methods should be implemented in order to seek solutions for vague and complex multi-attribute problems in fuzzy environment.

In this study such a model is proposed based on integrated fuzzy DEMATEL, fuzzy ANP and fuzzy TOPSIS methods which is novel on assessing overall GSCM performance of companies. First of all, dimensions and involved criteria that effect GSCM performance are determined investigating the literature and by consulting both academic and industrial experts. Then, fuzzy DEMATEL

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method is used to obtain interrelationship amongst the dimensions, which is required during ANP method. Fuzzy DEMATEL method is a useful tool to gather group ideas and analyze the cause and effect relationship of complex problems in fuzzy environments (Lin & Wu, 2004, 2008). Based on this interrelationship network, fuzzy ANP method is conducted in order to calculate the weights of criteria associated with the dimensions. ANP method is preferred to overcome the problem of interrelation among criteria or factors. And finally, fuzzy TOPSIS method is implemented for evaluating and ranking alternative companies in respect with their ability on GSCM activities. TOPSIS has a systematic procedure with simple computation process, and represents a reasonable outcome.

During the fuzzy DEMATEL and fuzzy ANP implementation four academic and four industrial experts are consulted in order to figure out interrelationship amongst the GSCM dimensions and then calculating the weights of associated criteria. Four alternative companies are investigated by two academic experts for evaluating GSCM activities of the companies in respect of predefined criteria. The companies are small and medium sized enterprises in the sector of machine manufacturing which are located in Sakarya city of Turkey.

2. Green supply chain management

GSCM implies minimizing and preferably eliminating the negative effects of the supply chain on the environment (Andic, Yurt, & Baltacıoglu, 2012). Kainuma and Tawara (2006) proposed the multiple attribute utility theory method and evaluated the performance of a supply chain in both managerial and environmental viewpoints. GSCM practices are in relation with technological innovation too. GSCM practices enhance firms' technological innovation whilst green activities improve the environment and produce a positive effect on the manufacturing establishment (Lee, Ooi, Chong, & Seow, 2014).

Multi-criteria decision making methods offer suitable implementation tools for GSCM domain. Sarkis (2003) presented a strategic decision framework by using the analytical network process (ANP) which focused on the components and elements of GSCM. Chen, Shih, Shyur, and Wu (2012) used ANP for solving complex strategy selection problems of GSCM and evaluating the most important activities of business functions. Diabat and Govindan (2011) developed a model of the drivers which affects the implementation of GSCM using an Interpretive Structural Modeling (ISM) framework. Shang, Lu, and Li (2010) investigated crucial GSCM capability dimensions and firm performance on the basis of a factor analysis and identified six dimensions namely green manufacturing and packaging, green marketing, environmental participation, green suppliers, green stock, and green ecodesign. On the other hand, Mathiyazhagan, Govindan, NoorulHaq, and Geng (2013) analyzed the barriers for the implementation of GSCM concept and identified twenty-six barriers.

One of the most important issues in GSCM is evaluation and selection process of green suppliers. Shen, Olfat, Govindan, Khodaverdi, and Diabat (2013) proposed a fuzzy TOPSIS approach for green suppliers' evaluation by examining GSCM. Büyüközkan and Cifci (2012) developed an integrated methodology and applied in a real case study in fuzzy environment by using DEMATEL, ANP and TOPSIS methods for green supplier evaluation. Tseng and Chiu (2013) used grey relational analysis for ranking alternative suppliers by identifying and evaluating the appropriate environmental and non-environmental GSCM criteria for a case firm.

Lin (2013) claimed that economic and environmental performance of proactive firms would be improved as they adopt GSCM. He examined the influential factors among eight criteria using the fuzzy set theory and DEMATEL method. Mathiyazhagan, Diabat, Al-Refaie, and Xu (2015) aimed to investigate the pressures for GSCM adoption and to rank the pressures based on experts' opinion through AHP technique in the mining and mineral industry context.

Barari, Agarwal, Zhang, Mahanty, and Tiwari (2012) aimed to provide integrated and holistic conceptual framework by using evolutionary game approach with the objective of profit maximization of the entities of the supply chain. Jamshidi, Fatemi Ghomi, and Karimi (2012) utilized a memetic algorithm in combination with the Taguchi method to solve a multi-objective optimization problem for green supply chain considering cost and environmental effects. Wang, Lai, and Shi (2011) interested in decisions during design phase for environmental investments and proposed a multi-objective optimization model which represents the tradeoff between the total cost and the environment influence.

The approach proposed by Yuce and Mastrocinque (2015) which combines the Fuzzy Analytic Hierarchy Process (AHP) and the Bees Algorithm in order to solve the supplier selection problem could be adopted for green suppliers by amending the criteria convenient with GSCM. Mastrocinque, Yuce, Lambiase, and Packianather (2013) and Yuce, Mastrocinque, Lambiase, Packianather, and Pham (2014) proposed the Bees Algorithm for multi-objective supply chain optimization which also be considered for applying in GSCM domain.

Our study contributes to the literature by providing GSCM dimensions and related criteria in a new perspective by proposing a model based on integrated fuzzy DEMATEL, fuzzy ANP and fuzzy TOPSIS methods which is novel on assessing overall GSCM performance of companies.

3. Proposed approach

The main steps of GSCM evaluation approach are illustrated in Fig. 1. The initial step of the methodology is identifying the evaluation dimensions and related criteria of GSCM. Then Fuzzy DEMATEL method is used for revealing interactions among the dimensions. On the basis of the main interactions, Fuzzy ANP method is implemented in order to calculate the local weights of each criterion. At the following step, the case firms are investigated in terms of the predefined GSCM criteria for obtaining evaluation inputs for the Fuzzy TOPSIS method. This final method gives the ranking of the case firms regarding their GSCM activities.

3.1. Main drivers of GSCM

According to the literature survey of GSCM and the experts' opinions, five main dimensions are identified namely Green Design, Green Purchasing, Green Transformation, Green Logistics and Reverse Logistics. Each dimension has its own criteria which are used while evaluating the firms in more detail. All the dimensions and their corresponding criteria are shown in Fig. 2.

Green Design is considering the environmental issues during the design phase, such as product features, material selection, manufacturing operations, and energy usage. The consideration also involves life-cycle design, eco-design, and design-for-environment (Chen et al., 2012). *Green Purchasing* is procurement of recycled, reusable or recyclable materials (Min & Galle, 2001). *Green Transformation consists of green manufacturing* (Shang et al., 2010), *green packaging* (Shang et al., 2010) *and green stock politics* (Shang et al., 2010) implementations while transforming raw-materials into final products. *Green Logistics* (Chen et al., 2012) is minimizing the routes, using less polluting vehicles, etc. *Reverse Logistics* (Ahi & Searcy, 2013) consists of the stages after a product has been used. It is about the activities performed in terms of reusing the materials of the products.

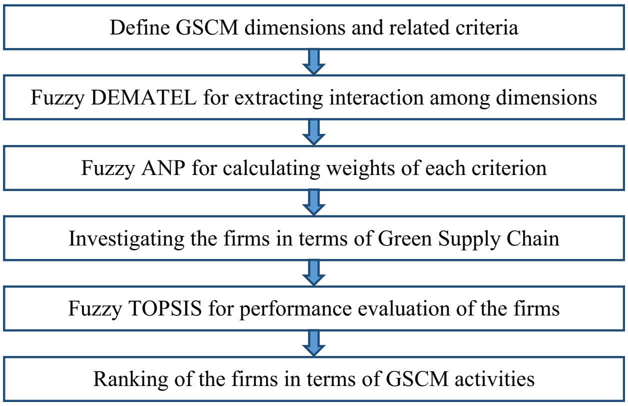

Fig. 1. GSCM evaluation approach.

3.2. Fuzzy DEMATEL method

The Battelle Geneva Institute developed DEMATEL method in order to solve difficult problems that mainly involve interactive man model techniques as well as to measure qualitative and factor linked aspects of societal problems (Gabus & Fontela, 1972). It analyzes the influential status and strength between the factors and convert them into an explicit structural mode of a system (Lin & Wu, 2008). The DEMATEL method has been developed initially to study the structural relations in a complex system. Then it is adapted in many academic fields, such as industrial strategy analysis, competence evaluation, solution analysis, and selection. Lin and Wu (2004, 2008) developed a fuzzy DEMATEL method to gather group ideas and analyze the cause and effect relationship of complex problems in fuzzy environments. The procedure of the fuzzy DEMATEL method implemented in this study is explained below:

Step 1: Develop the evaluation criteria and design the fuzzy linguistic scale. For evaluation of GSCM, sets of dimensions and related criteria are established. Since evaluation criteria have the nature of causal relationship and usually comprise several complicated aspects, and to deal with the ambiguities of human assessments, the fuzzy linguistic scale is used in the group decision making. The different degrees of influence are expressed with five linguistic terms as {No, Low, Medium, High, Very high}

Table 1
The correspondence of linguistic terms and linguistic values.

Linguistic terms	Linguistic values
No influence (N)	(0,0,0.25)
Low influence (L)	(0,0.25,0.50)
Medium influence (M)	(0.25,0.50,0.75)
High influence (H)	(0.50,0.75,1.00)
Very high influence (VH)	(0.75,1.00,1.00)

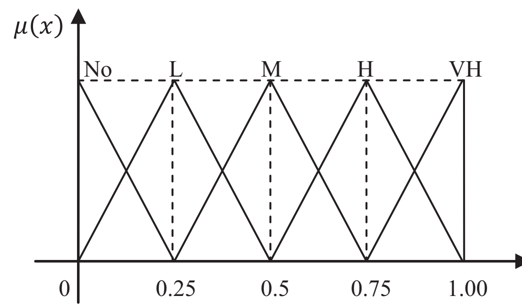

Fig. 3. Triangular fuzzy numbers for linguistic variables.

and their corresponding positive triangular fuzzy numbers are shown in Table 1 and see Fig. 3.

Step 2: Acquire and average the assessments of decision makers. In this step, a group of p expert is asked to acquire sets of pair-wise comparisons of the dimensions $D = \{D_i | i = 1, 2, \ldots, n\}$ by linguistic terms in order to measure the relationship between the dimensions. So, p fuzzy matrices $\tilde{Z}^1, \tilde{Z}^2, \ldots, \tilde{Z}^p$ were obtained, each corresponding to an expert. Then, the average fuzzy matrix $\tilde{Z}$ is calculated as below and is called the initial direct-relation fuzzy matrix.

$$\tilde{Z} = \frac{\tilde{Z}^1 \oplus \tilde{Z}^2 \oplus \cdots \oplus \tilde{Z}^p}{p} \quad (1)$$

The initial direct-relation fuzzy matrix $\tilde{Z}$ is shown as following

$$\tilde{Z} = \begin{bmatrix} 0 & \tilde{z}_{12} & \cdots & \tilde{z}_{1n} \\ \tilde{z}_{21} & 0 & \cdots & \tilde{z}_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ \tilde{z}_{n1} & \tilde{z}_{n2} & \cdots & 0 \end{bmatrix}$$

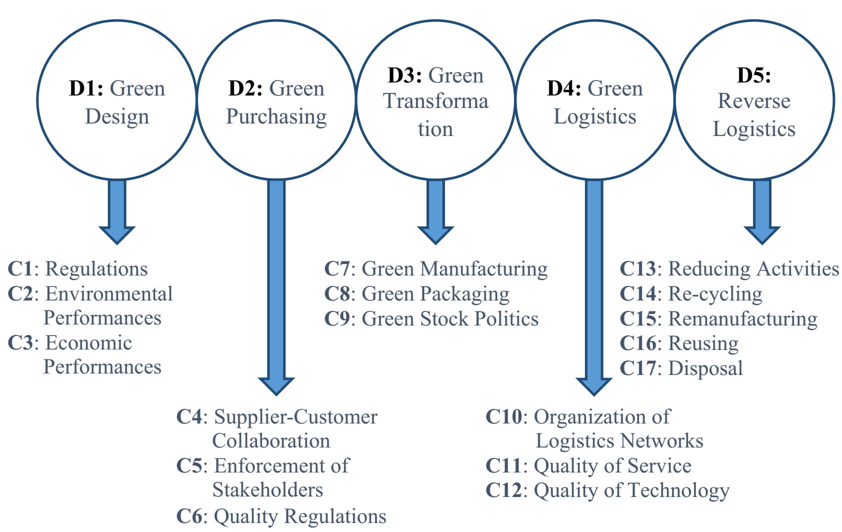

Fig. 2. Dimensions and related criteria of green supply chain management.

where $\tilde{z}_{ij} = (\ell_{ij}, m_{ij}, u_{ij})$ are triangular fuzzy numbers. $\tilde{z}_{ii}\ (i = 1, 2, \ldots, n)$ is shown as zero but whenever is necessary it will be regarded as triangular fuzzy number (0,0,0).

Step 3: Acquire the normalized direct-relation fuzzy matrix. By normalizing the initial direct-relation fuzzy matrix, normalized direct-relation fuzzy matrix $\tilde{X}$ is obtained by using

$$\tilde{X} = \begin{bmatrix} \tilde{x}_{11} & \tilde{x}_{12} & \cdots & \tilde{x}_{1n} \\ \tilde{x}_{21} & \tilde{x}_{22} & \cdots & \tilde{x}_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ \tilde{x}_{n1} & \tilde{x}_{n2} & \cdots & \tilde{x}_{nn} \end{bmatrix}$$

where

$$\tilde{x}_{ij} = \frac{\tilde{z}_{ij}}{r} = \left(\frac{\ell_{ij}}{r}, \frac{m_{ij}}{r}, \frac{u_{ij}}{r}\right) \tag{2}$$

and

$$r = \max_{1 \leqslant i \leqslant n}\left(\sum_{j=1}^{n} u_{ij}\right) \tag{3}$$

It is assumed at least one i such that $\sum_{j=1}^{n} u_{ij} < r$ and this assumption is well satisfied in practical cases.

Step 4: Acquire the total-relation fuzzy matrix. Let $\tilde{x}_{ij} = (\ell'_{ij}, m'_{ij}, u'_{ij})$ and define three crisp matrices, whose elements are extracted from $\tilde{X}$, as follows:

$$X_\ell = \begin{bmatrix} 0 & \ell'_{12} & \cdots & \ell'_{1n} \\ \ell'_{21} & 0 & \cdots & \ell'_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ \ell'_{n1} & \ell'_{n2} & \cdots & 0 \end{bmatrix} \quad X_m = \begin{bmatrix} 0 & m'_{12} & \cdots & m'_{1n} \\ m'_{21} & 0 & \cdots & m'_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ m'_{n1} & m'_{n2} & \cdots & 0 \end{bmatrix}$$

$$X_u = \begin{bmatrix} 0 & u'_{12} & \cdots & u'_{1n} \\ u'_{21} & 0 & \cdots & u'_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ u'_{n1} & u'_{n2} & \cdots & 0 \end{bmatrix}$$

As in the crisp DEMATEL, total-relation fuzzy matrix $\tilde{T}$ is defined as $\tilde{T} = \lim_{k\to\infty}(\tilde{X} + \tilde{X}^2 + \cdots + \tilde{X}^k)$ and is shown as:

$$\tilde{T} = \begin{bmatrix} \tilde{t}_{11} & \tilde{t}_{12} & \cdots & \tilde{t}_{1n} \\ \tilde{t}_{21} & \tilde{t}_{22} & \cdots & \tilde{t}_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ \tilde{t}_{n1} & \tilde{t}_{n2} & \cdots & \tilde{t}_{nn} \end{bmatrix} \quad \text{where } \tilde{t}_{ij} = (\ell''_{ij}, m''_{ij}, u''_{ij}) \quad \text{and}$$

$$[\ell''_{ij}] = X_\ell \times (I - X_\ell)^{-1} \tag{4}$$

$$[m''_{ij}] = X_m \times (I - X_m)^{-1} \tag{5}$$

$$[u''_{ij}] = X_u \times (I - X_u)^{-1} \tag{6}$$

Step 5: Obtaining $(\widetilde{D}_i + \tilde{R}_i)^{def}$ and $(\widetilde{D}_i - \tilde{R}_i)^{def}$ values. Each $\tilde{t}_{ij} = (\ell''_{ij}, m''_{ij}, u''_{ij})$ triangular fuzzy numbers of total-relation fuzzy matrix $\tilde{T}$ is defuzzified and $\tilde{T}^{def}$ matrix is obtained as defined below:

$$\tilde{T}^{def} = \begin{bmatrix} \tilde{t}^{def}_{11} & \tilde{t}^{def}_{12} & \cdots & \tilde{t}^{def}_{1n} \\ \tilde{t}^{def}_{21} & \tilde{t}^{def}_{22} & \cdots & \tilde{t}^{def}_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ \tilde{t}^{def}_{n1} & \tilde{t}^{def}_{n2} & \cdots & \tilde{t}^{def}_{nn} \end{bmatrix} \quad \text{where } \tilde{t}^{def}_{ij} = (\ell''_{ij}, m''_{ij}, u''_{ij})^{def}$$

Then, $\widetilde{D}^{def}_i$, $\tilde{R}^{def}_i$, $(\widetilde{D}^{def}_i + \tilde{R}^{def}_i)$ and $(\widetilde{D}^{def}_i - \tilde{R}^{def}_i)$ values are calculated as in crisp DEMATEL method where $\widetilde{D}^{def}_i$ and $\tilde{R}^{def}_i$ are the sum of rows and columns of matrix $\tilde{T}^{def}$, respectively.

In this study CFSC (Converting Fuzzy data into Crisp Scores) defuzzification method proposed by Opricovic and Tzeng (2003) is used for calculating defuzzified total-relation matrix $\tilde{T}^{def}$.

3.3. CFCS defuzzification method

There are several defuzzification methods. The most commonly used defuzzification method is the Centroid (Center of gravity) method (Yager & Filev, 1994), but this does not distinguish between two fuzzy numbers which have the same crisp value in spite of different shapes. Therefore CFCS defuzzification method is used since it can give a better crisp value than the Centroid method.

CFCS method is generated by Opricovic and Tzeng (2003) for multi-criteria decision making which can distinguish two symmetrical triangular fuzzy numbers with the same mean, whereas the Centroid method does not distinguish between two such fuzzy numbers. CFCS method can also be applied when some values are crisp, $\ell = m = u$.

Let $\tilde{f}_{ij} = (\ell_{ij}, m_{ij}, u_{ij})$, $j = 1, 2, \ldots, J$ be triangular fuzzy numbers, where J is the number of alternatives. The crisp value of ith criterion could be determined by the following four step CFCS algorithm:

1. *Normalization:*

$R = \max_j u_{ij},\ L = \min_j \ell_{ij}$ and $\Delta = R - L$

Compute for each alternatives

$$x_{\ell j} = (\ell_{ij} - L)/\Delta, x_{mj} = (m_{ij} - L)/\Delta, x_{uj} = (u_{ij} - L)/\Delta \tag{7}$$

2. *Compute left score (ls) and right score (rs) normalized values:*

$$x^{ls}_j = x_{mj}/(1 + x_{mj} - x_{\ell j}) \quad \text{and} \quad x^{rs}_j = x_{uj}/(1 + x_{uj} - x_{mj}) \tag{8}$$

3. *Compute total normalized crisp value:*

$$x^{crisp}_j = \left[x^{ls}_j \times (1 - x^{ls}_j) + x^{rs}_j \times x^{rs}_j\right] \Big/ \left[1 - x^{ls}_j + x^{rs}_j\right] \tag{9}$$

4. *Compute crisp values for $\tilde{f}_{ij}$:*

$$\tilde{f}^{crisp}_{ij} = L + x^{crisp}_j \times \Delta \tag{10}$$

3.4. Fuzzy ANP method

Analytic network process (ANP) is the general form of analytic hierarchy process (AHP) and was proposed by Saaty (1996) to overcome the problem of interrelation among criteria or factors. It provides measurements to acquire ratio scale priorities for the distribution of influence between factors and groups of factors in the decision (Saaty, 2001). Many decision problems cannot be hierarchically constructed as they comprise the interaction and dependence of higher level elements in a hierarchy on lower level elements. Thus, rather than a hierarchy, ANP is represented by a network (Saaty, 2005).

The ANP synthesizes the result of dependence and feedback amongst clusters of elements through a supermatrix whose entries are themselves matrices of column priorities (Yang & Chang, 2012). The supermatrix structure of a hierarchy is given as in Fig. 4.

Then the initial supermatrix is converted to a matrix in which each of its columns sums to unity. That is why, this matrix need to be normalized by the cluster's weight to get the column sums to 1. After this process, obtained matrix is called the weighted supermatrix (Saaty & Vargas, 1998). The procedure is followed by

$$
\begin{array}{cc|cccccccccc}
 & & & C_1 & & & C_2 & & \cdots & & C_m & \\
 & & e_{11} & \cdots & e_{1n_1} & e_{21} & \cdots & e_{2n_2} & \cdots & e_{m1} & \cdots & e_{mn_m} \\
\hline
C_1 & \begin{matrix} e_{11} \\ \vdots \\ e_{1n_1} \end{matrix} & & W_{11} & & & W_{12} & & \cdots & & W_{1m} & \\
C_2 & \begin{matrix} e_{21} \\ \vdots \\ e_{2n_2} \end{matrix} & & W_{21} & & & W_{22} & & \cdots & & W_{2m} & \\
\vdots & \vdots & & \vdots & & & \vdots & & \ddots & & \vdots & \\
C_m & \begin{matrix} e_{m1} \\ \vdots \\ e_{mn_m} \end{matrix} & & W_{m1} & & & W_{m2} & & \cdots & & W_{mm} &
\end{array}
$$

$$W = \begin{pmatrix} W_{11} & W_{12} & \cdots & W_{1m} \\ W_{21} & W_{22} & \cdots & W_{2m} \\ \vdots & \vdots & \ddots & \vdots \\ W_{m1} & W_{m2} & \cdots & W_{mm} \end{pmatrix}$$

Fig. 4. The supermatrix representation.

raising the weighted supermatrix to the power large enough until the weights have been converged and remain stable. This new matrix is called the limit supermatrix.

ANP equipped with fuzzy set theory helps in overcoming the impreciseness or vagueness in the preferences. Fuzzy set theory is more advantages than traditional set theory when describing set concepts in human language. The fuzzy ANP method can easily accommodate the interrelationships existing among the functional activities (Mohanty, Agarwal, Choudhury, & Tiwari, 2005). Table 2 gives the fuzzy linguistic terms and corresponding triangular fuzzy numbers (TFNs) which are used for pairwise comparisons. The pairwise comparisons are implemented according to fuzzy ANP method within each cluster or main criteria, and according to dependency relationships which are obtained from fuzzy DEMATEL in order to generate relative importance weights.

There are many fuzzy AHP methods for calculating weights to be used in supermatrix of ANP. These methods were proposed by various authors in the literature (Buckley, 1985; Chang, 1992, 1996, 1997; Deng, 1999; Leung & Cao, 2000; Mikhailov, 2004; Van Laarhoven & Pedrycz, 1983). These methods are systematic approaches to the alternative selection and justification problem by using the concepts of fuzzy set theory and hierarchical structure analysis (Yüksel & Dağdeviren, 2010). In this study, Chang's (1996) extent analysis method is employed. The extent analysis method is described below.

Let $X = \{x_1, x_2, \ldots, x_n\}$ be an object set, and $G = \{g_1, g_2, \ldots, g_m\}$ be a goal set. According to the method, 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:

$$M^1_{g_i}, M^2_{g_i}, \ldots, M^m_{g_i}, \quad i = 1, 2, \ldots, n$$

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

The steps of the extent analysis method are given below:

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

$$S_i = \sum_{j}^{m} M^j_{g_i} \otimes \left[\sum_{i=1}^{n} \sum_{j=1}^{m} M^j_{g_i} \right]^{-1} \tag{11}$$

To obtain $\sum_j^m M^j_{g_i}$, perform the fuzzy addition operation of m extent analysis values for a particular matrix such that

$$\sum_{j}^{m} M^j_{g_i} = \left(\sum_{j=1}^{m} l_j, \sum_{j=1}^{m} m_j, \sum_{j=1}^{m} u_j \right), \tag{12}$$

Table 2
The linguistic variables and triangular fuzzy numbers for importance.

Linguistic variables	Fuzzy number	Triangular fuzzy number	Triangular fuzzy reciprocal number
Equally Important (EI)	$\tilde{1}$	(1,1,1)	(1,1,1)
Weekly Important (WI)	$\tilde{3}$	(1,3,5)	(1/5,1/3,1)
Strongly Important (SI)	$\tilde{5}$	(3,5,7)	(1/7,1/5,1/3)
Very Important (VI)	$\tilde{7}$	(5,7,9)	(1/9,1/7,1/5)
Absolutely Important (AI)	$\tilde{9}$	(7,9,9)	(1/9,1/9,1/7)

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

$$\sum_{i=1}^{n} \sum_{j=1}^{m} M^j_{g_i} = \left(\sum_{i=1}^{n} l_i, \sum_{i=1}^{n} m_i, \sum_{i=1}^{n} u_i \right) \tag{13}$$

and then compute the inverse of the vector in Eq. (9) such that

$$\left[\sum_{i=1}^{n} \sum_{j=1}^{m} M^j_{g_i} \right]^{-1} = \left(\frac{1}{\sum_{i=1}^{n} l_i}, \frac{1}{\sum_{i=1}^{n} m_i}, \frac{1}{\sum_{i=1}^{n} u_i} \right) \tag{14}$$

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

$$V(M_2 \geqslant M_1) = \sup[\min(\mu_{M_1}(x), \mu_{M_2}(y))]$$

and can be equivalently expressed as follows:

$$V(M_2 \geqslant M_1) = hgt(M_1 \cap M_2) = \mu_{M_2}(d) = \begin{cases} 1, & \text{if } m_2 \geqslant m_1, \\ 0, & \text{if } l_1 \geqslant u_2, \\ \frac{l_1 - u_2}{(m_2 - u_2) - (m_1 - l_1)}, & \text{otherwise}, \end{cases} \tag{15}$$

where d is the ordinate of the highest intersection point d between μ_{M_1} and μ_{M_2} (see Fig. 5). Both values of $V(M_1 \geqslant M_2)$ and $V(M_2 \geqslant M_1)$ are required in order to compare M_1 and M_2.

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

$$V(M \geqslant M_1, M_2, \ldots, M_k) = V[(M \geqslant M_1) \text{ and } (M \geqslant M_2) \text{ and} \ldots \text{and } (M \geqslant M_k)] = \min V(M \geqslant M_i), \quad i = 1, 2, \ldots, k. \tag{16}$$

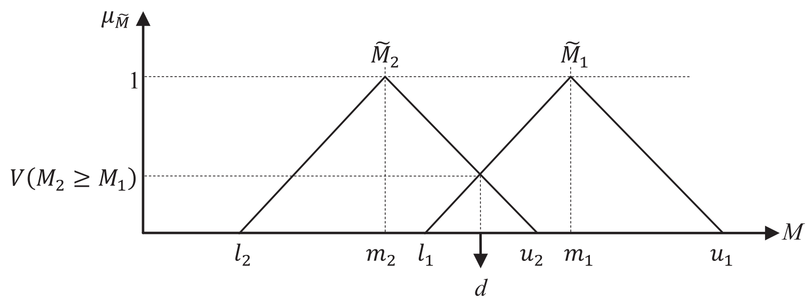

Fig. 5. The intersection between M_1 and M_2.

Assume that

$$d'(A_i) = \min V(S_i \geqslant S_k) \quad \text{for } k = 1, 2, \ldots, n; k \neq i. \tag{17}$$

Then the weight vector is given by

$$W' = \left(d'(A_1), d'(A_2), \ldots, d'(A_n)\right)^T, \tag{18}$$

where $A_i (i = 1, 2, \ldots, n)$ are n elements.

Step 4: Via the normalization, the normalized weight vectors are

$$W = (d(A_1), d(A_2), \ldots, d(A_n))^T, \tag{19}$$

where W is a nonfuzzy number.

In this case study, fuzzy ANP is based on fuzzy DEMATEL outcomes and used for calculating the weights of the criteria of each green dimension. Those weights are used as input during fuzzy TOPSIS method computations in order to rank alternative companies.

3.5. Fuzzy TOPSIS method

The technique for order preference by similarity to an ideal solution (TOPSIS) was proposed by Hwang and Yoon (1981) and expanded by Chen and Hwang (1992). The main principle in TOPSIS method is that, in a graph, any chosen alternative should have the shortest distance from the ideal solution and the farthest distance from the negative-ideal solution (Opricovic & Tzeng, 2004). The steps of the fuzzy TOPSIS method is adapted from Chen (2000) as follows.

Step 1: Construct the fuzzy decision matrix. There are m alternatives $A_i = (A_1, A_2, \ldots, A_m)$ to be evaluated in terms of n criteria $C_j = (C_1, C_2, \ldots, C_n)$ using Table 3. The fuzzy multi-criteria decision making problem can be expresses as:

$$\widetilde{D} = \begin{array}{c} \\ A_1 \\ A_2 \\ \vdots \\ A_m \end{array} \!\!\! \begin{array}{c} \begin{array}{cccc} C_1 & C_2 & \ldots & C_n \end{array} \\ \begin{bmatrix} \tilde{x}_{11} & \tilde{x}_{12} & \ldots & \tilde{x}_{1n} \\ \tilde{x}_{21} & \tilde{x}_{22} & \ldots & \tilde{x}_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ \tilde{x}_{m1} & \tilde{x}_{m2} & \ldots & \tilde{x}_{mn} \end{bmatrix} \end{array} \quad \text{and } W = [w_1, w_2, \ldots, w_n] \tag{20}$$

$\tilde{x}_{ij} = \frac{1}{K}(l_{ij}, m_{ij}, u_{ij})$ is a triangular fuzzy number indicating the evaluation rating of the ith alternative A_i with respect to jth criterion C_j where K is the number of decision makers. w_j represents the weight of the jth criterion C_j which is obtained by fuzzy ANP method.

Step 2: Normalize the fuzzy decision matrix. $\tilde{R}$ indicates the normalized fuzzy decision matrix:

$$\tilde{R} = [\tilde{r}_{ij}]_{mxn}, \quad i = 1, 2, \ldots, m \text{ and } j = 1, 2, \ldots, n$$

The normalized values for benefit related criteria (B) and cost related criteria (C) are calculated as:

Table 3
Linguistic terms and linguistic values for alternative ratings.

Linguistic terms	Linguistic values
Very Poor (VP)	(0,0,0.25)
Medium Poor (MP)	(0,0.25,0.50)
Fair (F)	(0.25,0.50,0.75)
Medium Good (MG)	(0.50,0.75,1.00)
Very Good (VG)	(0.75,1.00,1.00)

$$\tilde{r}_{ij} = \left(\frac{l_{ij}}{u_j^*}, \frac{m_{ij}}{u_j^*}, \frac{u_{ij}}{u_j^*}\right), \quad u_j^* = \max_i u_{ij}, \quad \text{if } j \in B \tag{21}$$

$$\tilde{r}_{ij} = \left(\frac{l_j^-}{u_{ij}}, \frac{l_j^-}{m_{ij}}, \frac{l_j^-}{l_{ij}}\right), \quad l_j^- = \min_i l_j^-, \quad \text{if } j \in C \tag{22}$$

Step 3: Compute the weighted normalized fuzzy decision matrix. The weighted normalized fuzzy decision matrix $\tilde{V}$ is computed as:

$$\tilde{V} = [\tilde{v}_{ij}]_{mxn}, \quad i = 1, 2, \ldots, m; \quad j = 1, 2, \ldots, n$$

$$\tilde{v}_{ij} = \tilde{r}_{ij} \times w_j \tag{23}$$

where w_j is the weight of the criterion j extracted from supermatrix of the fuzzy ANP phase.

Step 4: Compute the distances of each alternative from positive ideal solution and negative ideal solution. The fuzzy positive ideal reference point (FPIRP) denoted by A^* and the fuzzy negative ideal reference point (FNIRP) denoted by A^- can be defined as:

$$A^* = (\tilde{v}_1^*, \tilde{v}_2^*, \ldots, \tilde{v}_n^*), \quad A^- = (\tilde{v}_1^-, \tilde{v}_2^-, \ldots, \tilde{v}_n^-) \tag{24}$$

where $\tilde{v}_j^* = (1, 1, 1)$ and $\tilde{v}_j^- = (0, 0, 0)$.

The distance of each alternative from FPIRP and FNIRP can be calculated respectively as:

$$d_i^* = \sum_{j=1}^{n} d(\tilde{v}_{ij}, \tilde{v}_j^*), \quad i = 1, 2, \ldots, m \tag{25}$$

$$d_i^- = \sum_{j=1}^{n} d(\tilde{v}_{ij}, \tilde{v}_j^-), \quad i = 1, 2, \ldots, m \tag{26}$$

where $d(\tilde{a}_1, \tilde{a}_2)$ denotes the distance between two triangular fuzzy numbers and calculated as:

$$d(\tilde{a}_1, \tilde{a}_2) = \sqrt{\frac{1}{3}\left[(l_1 - l_2)^2 + (m_1 - m_2)^2 + (u_1 - u_2)^2\right]} \tag{27}$$

Step 5: Calculate the closeness coefficient and rank the alternatives. The closeness coefficient (CC_i) of each alternative is obtained as:

$$CC_i = \frac{d_i^-}{d_i^* + d_i^-}, \quad i = 1, 2, \ldots, m \tag{28}$$

Table 4
The evaluation values of one of the experts in terms of the effect between the dimensions.

	D1	D2	D3	D4	D5
D1	N	VH	M	L	VH
D2	L	N	H	VH	VH
D3	M	M	N	H	L
D4	N	VH	H	N	L
D5	VH	VH	H	N	N

If CC_i value approaches to 1 indicates that the alternative is close to the FPIRP and far from FNIRP. The alternative with the highest CC_i value is selected as the best alternative.

On the basis of the interrelationship among green dimensions obtained by fuzzy DEMATEL, the local weights of each criterion are calculated by fuzzy ANP. Then the local weights are used within the fuzzy TOPSIS method while evaluating the alternative companies in terms of their GSCM activities.

4. Case study and implementation

The proposed performance evaluation model for GSCM is validated through a case study in which four alternative companies are investigated in terms of predefined green dimensions and related criteria. Consequently, the alternative companies are evaluated and ranked by following the proposed approach using fuzzy DEMATEL, fuzzy ANP and fuzzy TOPSIS methods in an integrated manner.

First of all, for applying fuzzy DEMATEL method, experts from academic and industrial domain are asked to assess influence degree of each dimension to the others. Table 4 gives the linguistic assessment result of one of the experts. The corresponding triangular fuzzy numbers for the linguistic terms of the expert are given in Table 5. Similarly, results are obtained from the rest of the experts and then averages of related triangular fuzzy numbers are calculated using Eq. (1). The average values are given in Table 6 which is called initial direct-relation fuzzy matrix. The normalized direct-relation fuzzy matrix is obtained using Eqs. (2) and (3) and shown in Table 7. After calculating the normalized direct-relation fuzzy matrix, the total-relation fuzzy matrix is obtained using Eqs. (4)–(6). The total-relation fuzzy matrix is shown in Table 8.

Then, CFCS method is used for defuzzification of the fuzzy values in total-relation fuzzy matrix using Eqs. (7)–(10). $(\widetilde{D}_i^{def} + \tilde{R}_i^{def})$ and $(\widetilde{D}_i^{def} - \tilde{R}_i^{def})$ values are calculated and shown in Table 9. The threshold value is determined as 1.2 according to the expert opinions. The values above the threshold are represented in bold in the table which gives the cause and effect relationship amongst the GSCM dimensions.

According to the cause and effect relationship obtained by the fuzzy DEMATEL method, pairwise comparisons are constructed by following fuzzy ANP method in order to calculate the weights of the criteria. For example, since "D3: Green transformation" effects

Table 5
Corresponding triangular fuzzy number for linguistic evaluation.

	D1			D2			D3			D4			D5		
D1	0.00	0.00	0.25	0.75	1.00	1.00	0.25	0.50	0.75	0.00	0.25	0.50	0.75	1.00	1.00
D2	0.00	0.25	0.50	0.00	0.00	0.25	0.50	0.75	1.00	0.75	1.00	1.00	0.75	1.00	1.00
D3	0.25	0.50	0.75	0.25	0.50	0.75	0.00	0.00	0.25	0.50	0.75	1.00	0.00	0.25	0.50
D4	0.00	0.00	0.25	0.75	1.00	1.00	0.50	0.75	1.00	0.00	0.00	0.25	0.00	0.25	0.50
D5	0.75	1.00	1.00	0.75	1.00	1.00	0.50	0.75	1.00	0.00	0.00	0.25	0.00	0.00	0.25

Table 6
The initial direct-relation fuzzy matrix.

	D1			D2			D3			D4			D5		
D1	0.00	0.00	0.25	0.50	0.75	0.92	0.50	0.75	0.92	0.17	0.42	0.67	0.33	0.58	0.75
D2	0.17	0.42	0.67	0.00	0.00	0.25	0.33	0.58	0.83	0.58	0.83	0.92	0.33	0.58	0.75
D3	0.50	0.75	0.92	0.50	0.75	0.92	0.00	0.00	0.25	0.25	0.50	0.75	0.17	0.42	0.67
D4	0.00	0.08	0.33	0.50	0.75	0.92	0.33	0.58	0.83	0.00	0.00	0.25	0.17	0.42	0.67
D5	0.33	0.58	0.75	0.58	0.83	1.00	0.42	0.67	0.92	0.08	0.25	0.50	0.00	0.00	0.25

Table 7
The normalized direct-relation fuzzy matrix.

	D1			D2			D3			D4			D5		
D1	0.00	0.00	0.07	0.14	0.21	0.26	0.14	0.21	0.26	0.05	0.12	0.19	0.10	0.17	0.21
D2	0.05	0.12	0.19	0.00	0.00	0.07	0.10	0.17	0.24	0.17	0.24	0.26	0.10	0.17	0.21
D3	0.14	0.21	0.26	0.14	0.21	0.26	0.00	0.00	0.07	0.07	0.14	0.21	0.05	0.12	0.19
D4	0.00	0.02	0.10	0.14	0.21	0.26	0.10	0.17	0.24	0.00	0.00	0.07	0.05	0.12	0.19
D5	0.10	0.17	0.21	0.17	0.24	0.29	0.12	0.19	0.26	0.02	0.07	0.14	0.00	0.00	0.07

Table 8
The total-relation fuzzy matrix.

	D1			D2			D3			D4			D5		
D1	0.05	0.25	4.74	0.22	0.55	6.30	0.20	0.50	5.97	0.10	0.38	5.11	0.13	0.41	5.05
D2	0.09	0.33	4.71	0.08	0.36	5.96	0.15	0.45	5.79	0.20	0.45	5.02	0.13	0.39	4.91
D3	0.17	0.42	4.89	0.21	0.54	6.28	0.07	0.31	5.80	0.12	0.39	5.12	0.09	0.36	5.02
D4	0.03	0.22	4.15	0.19	0.46	5.50	0.13	0.38	5.19	0.04	0.21	4.35	0.08	0.30	4.39
D5	0.14	0.38	4.79	0.23	0.55	6.21	0.17	0.47	5.87	0.08	0.33	4.99	0.05	0.25	4.85

Table 9
Defuzzified total-relation matrix.

	D1	D2	D3	D4	D5	$\tilde{D}_i^{def}$	$\tilde{D}_i^{def}+\tilde{R}_i^{def}$	$\tilde{D}_i^{def}-\tilde{R}_i^{def}$
D1	1.03	**1.53**	**1.44**	**1.21**	**1.22**	6.42	11.81	1.03
D2	1.10	**1.32**	**1.37**	**1.26**	**1.18**	6.22	13.43	−1.00
D3	**1.20**	**1.52**	**1.25**	**1.22**	1.18	6.36	13.04	−0.31
D4	0.90	**1.33**	**1.22**	0.93	1.02	5.41	11.16	−0.35
D5	1.16	**1.52**	**1.40**	1.14	1.05	6.27	11.91	0.62
$\tilde{R}_i^{def}$	5.39	7.21	6.68	5.75	5.64			

Table 10
One of the experts' pairwise comparison matrix of D1 (C1, C2, C3) in terms of C7.

	Linguistic evaluation			Related fuzzy numbers									
	C1	C2	C3		C1			C2			C3		
C1	EI	WI	WI	C1	1	1	1	1	3	5	1	3	5
C2		EI		C2	1/5	1/3	1	1	1	1	1/7	1/5	1/3
C3		SI	EI	C3	1/5	1/3	1	3	5	7	1	1	1

Table 11
Geometric average of all of the expert evaluations, and the weights.

	C1			C2			C3			**Wi**
C1	1.00	1.00	1.00	1.00	3.00	5.00	1.00	1.73	3.87	**0.42**
C2	0.20	0.33	1.00	1.00	1.00	1.00	0.17	0.26	0.58	**0.16**
C3	0.26	0.58	1.00	1.73	3.87	5.92	1.00	1.00	1.00	**0.42**

"D1: Green design", the fuzzy evaluation of importance of criteria which are associated with D1 (C1, C2 and C3) in terms of C7 is given in Table 10. Then geometric average is taken after obtaining evaluations of the rest of the experts in order to calculate the local weights using Eqs. (11)–(19). The result is shown in Table 11.

Similarly, the rest of the weights are calculated in the same way based on the interactions derived from the fuzzy DEMATEL and put into the unweighted supermatrix (see Table 12). The weights given at Table 11 are illustrated in bold in the unweighted supermatrix. Then, this supermatrix is normalized to transform it into the weighted supermatrix in which each of its columns sums to 1. The power of the weighted supermatrix is taken until the values of each column are stabilized and equal to obtain the limit supermatrix as given in Table 13. Any column of the matrix shows the weights of corresponding criteria.

After calculating the weights of the criteria using fuzzy ANP method, alternative companies are investigated and linguistically evaluated (using Table 3) according to each criterion which is the initial step of fuzzy TOPSIS method. Table 14 gives the one of the experts' linguistic evaluation of the alternative companies with respect to the criteria, and related fuzzy numbers. Similarly the evaluations of the rest of the experts are obtained and fuzzy decision matrix is constructed (Eq. (20)). The normalized fuzzy decision matrix is calculated (Eqs. (21) and (22)) and then the weighted normalized fuzzy decision matrix is computed using Eq. (23). Finally, alternative companies are ranked in terms of closeness of each alternative to the positive ideal reference point (Eqs. (24)–(28)). Table 15 gives the ranking of the companies and implies that company B is the most successful one according to GSCM activities. The rest of the companies are ranked as A, C and D.

The proposed approach is validated through the case study and the alternative companies were evaluated in fuzzy environment considering vagueness and uncertainty of real life cases and also subjective human perceptions. There are studies which examine green supplier performance, however in this study fuzzy MCDM techniques are integrated for evaluating the overall GSCM performance of companies. The evaluation enables companies to check their own green performance comparing the other companies and to obtain useful feedback about the areas of improvement.

Table 12
The unweighted supermatrix.

	C1	C2	C3	C4	C5	C6	C7	C8	C9	...	C15	C16	C17
C1	0.00	0.00	0.00	0.00	0.00	0.00	**0.42**	0.40	0.29	...	0.00	0.00	0.00
C2	0.00	0.00	0.00	0.00	0.00	0.00	**0.16**	0.55	0.35	...	0.00	0.00	0.00
C3	0.00	0.00	0.00	0.00	0.00	0.00	**0.42**	0.05	0.37	...	0.00	0.00	0.00
C4	0.52	0.51	0.60	0.00	0.00	0.00	0.54	0.54	0.55	...	0.31	0.43	0.31
C5	0.25	0.37	0.40	0.00	0.00	0.00	0.31	0.35	0.30	...	0.31	0.35	0.33
C6	0.23	0.13	0.00	0.00	0.00	0.00	0.14	0.11	0.16	...	0.39	0.22	0.36
C7	0.43	0.49	0.42	0.51	0.47	0.43	0.00	0.00	0.00	...	0.41	0.50	0.54
C8	0.38	0.28	0.29	0.37	0.31	0.27	0.00	0.00	0.00	...	0.28	0.12	0.35
C9	0.19	0.23	0.30	0.13	0.23	0.31	0.00	0.00	0.00	...	0.32	0.38	0.11
...	...	...	...	...	...	...	...	...	...	...	...	...	...
C15	0.22	0.20	0.25	0.00	0.00	0.00	0.00	0.00	0.00	...	0.00	0.00	0.00
C16	0.20	0.26	0.27	0.00	0.00	0.00	0.00	0.00	0.00	...	0.00	0.00	0.00
C17	0.09	0.05	0.00	0.00	0.00	0.00	0.00	0.00	0.00	...	0.00	0.00	0.00

Table 13
The limit supermatrix.

	C1	C2	C3	C4	C5	C6	C7	C8	C9	...	C15	C16	C17
C1	0.042	0.042	0.042	0.042	0.042	0.042	0.042	0.042	0.042	...	0.042	0.042	0.042
C2	0.033	0.033	0.033	0.033	0.033	0.033	0.033	0.033	0.033	...	0.033	0.033	0.033
C3	0.030	0.030	0.030	0.030	0.030	0.030	0.030	0.030	0.030	...	0.030	0.030	0.030
C4	0.132	0.132	0.132	0.132	0.132	0.132	0.132	0.132	0.132	...	0.132	0.132	0.132
C5	0.098	0.098	0.098	0.098	0.098	0.098	0.098	0.098	0.098	...	0.098	0.098	0.098
C6	0.051	0.051	0.051	0.051	0.051	0.051	0.051	0.051	0.051	...	0.051	0.051	0.051
C7	0.171	0.171	0.171	0.171	0.171	0.171	0.171	0.171	0.171	...	0.171	0.171	0.171
C8	0.107	0.107	0.107	0.107	0.107	0.107	0.107	0.107	0.107	...	0.107	0.107	0.107
C9	0.038	0.038	0.038	0.038	0.038	0.038	0.038	0.038	0.038	...	0.038	0.038	0.038
...	...	...	...	...	...	...	...	...	...	...	...	...	...
C15	0.006	0.006	0.006	0.006	0.006	0.006	0.006	0.006	0.006	...	0.006	0.006	0.006
C16	0.006	0.006	0.006	0.006	0.006	0.006	0.006	0.006	0.006	...	0.006	0.006	0.006
C17	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	...	0.001	0.001	0.001

Table 14
One of the experts' evaluation of the alternative companies in terms of the criteria.

Linguistic evaluation						Related fuzzy numbers												
	A	B	C	D			A			B			C			D		
C1	VG	VG	MG	F		C1	0.75	1.00	1.00	0.75	1.00	1.00	0.50	0.75	1.00	0.25	0.50	0.75
C2	VG	VG	VG	VG		C2	0.75	1.00	1.00	0.75	1.00	1.00	0.75	1.00	1.00	0.75	1.00	1.00
C3	VG	VG	MG	MP		C3	0.75	1.00	1.00	0.75	1.00	1.00	0.50	0.75	1.00	0.00	0.25	0.50
C4	MG	MG	F	F		C4	0.50	0.75	1.00	0.50	0.75	1.00	0.25	0.50	0.75	0.25	0.50	0.75
C5	F	F	VP	MP		C5	0.25	0.50	0.75	0.00	0.25	0.50	0.00	0.00	0.25	0.00	0.25	0.50
C6	VG	VG	MG	VP		C6	0.75	1.00	1.00	0.75	1.00	1.00	0.50	0.75	1.00	0.00	0.00	0.25
C7	VP	MP	VP	VP		C7	0.00	0.00	0.25	0.00	0.25	0.50	0.00	0.00	0.25	0.00	0.00	0.25
C8	VP	MP	MP	VP		C8	0.00	0.00	0.25	0.00	0.25	0.50	0.00	0.25	0.50	0.00	0.00	0.25
C9	VG	VG	VG	MP		C9	0.75	1.00	1.00	0.75	1.00	1.00	0.75	1.00	1.00	0.00	0.25	0.50
...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
C15	VP	VP	VP	VP		C15	0.00	0.00	0.25	0.00	0.00	0.25	0.00	0.00	0.25	0.00	0.00	0.25
C16	VP	VP	VP	VP		C16	0.00	0.00	0.25	0.00	0.00	0.25	0.00	0.00	0.25	0.00	0.00	0.25
C17	MP	MP	MP	MP		C17	0.00	0.25	0.50	0.00	0.25	0.50	0.00	0.25	0.50	0.00	0.25	0.50

Table 15
Ranking of the alternative companies.

	d_i^*	d_i^-	CC_i	**Rank**
A	16.409	0.655	**0.038**	**2**
B	16.338	0.738	**0.043**	**1**
C	16.511	0.565	**0.033**	**3**
D	16.693	0.394	**0.023**	**4**

5. Conclusion

The interest of companies on GSCM activities have been increasing in recent years and this yields wide spread of studies which could be found in the literature. Hence the evaluation of GSCM performance is necessary in order to improve the effectiveness of green activities of companies. For this purpose, this study proposes a practical hybrid fuzzy multi-criteria decision making approach consisting of fuzzy DEMATEL, fuzzy ANP and fuzzy TOPSIS methods for evaluating overall green performance of companies. The proposed approach is validated through a case study in which four alternative companies are investigated in terms of predefined green supply chain management dimensions and corresponding criteria.

First of all, dimensions and relevant criteria for GSCM are decided. Then, interrelationship amongst the dimensions are extracted by using fuzzy DEMATEL technique. According to the influence of each dimension over other dimensions, the weights of the criteria are calculated by using fuzzy ANP method. Finally, alternative companies are investigated in terms of their GSCM activities and fuzzy TOPSIS method is implemented for ranking the companies according to their GSCM performance. The proposed approach evaluates the overall performance of companies regarding GSCM activities which eventually enables the companies to examine their own relative performance degree comparatively and to obtain useful feedback about the areas of improvement regarding green activities.

The proposed approach can be applied for more companies and also by differentiating GSCM criteria. The methodology can also be implemented for several evaluation and ranking domains. In the future studies some other MCDM techniques could be integrated such as VIKOR or fuzzy cognitive map. Integration of mathematical programming methods could also be considered for the future research studies.

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