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A novel hybrid MCDM approach based on fuzzy DEMATEL, fuzzy ANP and fuzzy TOPSIS to evaluate green suppliers

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ABSTRACT

It is well known that "green" principles and strategies have become vital for companies as the public awareness increased against their environmental impacts. 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. For industries, environmentally responsible manufacturing, return flows, and related processes require green supply chain (GSC) and accompanying suppliers with environmental/green competencies. During recent years, how to determine suitable and green suppliers in the supply chain has become a key strategic consideration. Therefore this paper examines GSC management (GSCM) and GSCM capability dimensions to propose an evaluation framework for green suppliers. However, the nature of supplier selection is a complex multi-criteria problem including both quantitative and qualitative factors which may be in conflict and may also be uncertain. The identified components are integrated into a novel hybrid fuzzy multiple criteria decision making (MCDM) model combines the fuzzy Decision Making Trial and Evaluation Laboratory Model (DEMATEL), the Analytical Network Process (ANP), and Technique for Order Performance by Similarity to Ideal Solution (TOPSIS) in a fuzzy context. A case study is proposed for green supplier evaluation in a specific company, namely Ford Otosan.

1. Introduction

Money, components, processes and information flows might establish a supply chain management system but simultaneously, due to government legislation and increasing awareness among the people to protect the environment; firms today cannot ignore environmental issues if they want to survive in the global market. In this sense, green supply chain management (GSCM) has emerged as a way for firms to achieve profit and market share objectives by lowering environmental impacts and increasing ecological efficiency (van Hock & Erasmus, 2000). In response to demands, companies have to find ways to incorporate environmental and social aspects into their supply chain management.

In order to reap the greatest benefits from environmental management, firms must integrate all members in the green supply chain (GSC) (Lee, Kang, Hsu, & Hung, 2009). Among these expectations, increasing attention is devoted to suppliers' social responsibility with a particular focus on fair and legal use of natural resources. Hence, strategic partnership with environmentally, socially and economically powerful suppliers should be integrated within the GSC for improving the performance in many directions including reducing costs and lead time, eliminating wastages, improving quality and flexibility to meet the needs of the customers, etc. For this reason, the aim of this study is to propose an evaluation model to judge the appropriateness of suppliers for an organization which has environmental goals and measure the validity of the model with a real case study.

There are various mathematical techniques for evaluation of suppliers, such as data envelopment analysis (DEA) (Wu, 2009), heuristics (He, Chaudhry, Lei, & Baohua, 2009; Sen, Başligil, Şen, & Baraçli, 2007), analytic hierarchy process (AHP) (Sevkli, Koh, Zaim, Demirbag, & Tatoglu, 2007), fuzzy AHP (Chan & Kumar, 2007; Lee et al., 2009; Rao & Holt, 2005), fuzzy goal programming (Kumar, Vrat, & Shankar, 2006; Tsai & Hung, 2009), fuzzy analytic network process (ANP) (Lin, 2009; Tuzkaya & Önüt, 2008) in literature. For the purpose of evaluating and selecting green suppliers, both qualitative and quantitative factors must be considered. Thus, green supplier selection is a kind of multiple criteria decision making (MCDM) problem and we need to employ MCDM methods to handle it appropriately. Here emphasis is placed on the relationships of factors which can be handled by ANP (Saaty, 1996) effectively. The ANP can deal with the dependence in feedback systematically. In this study also Decision Making Trial and Evaluation Laboratory (DEMATEL) method (Gabus & Fontela, 1972) is used to extract the mutual relationships of interdependencies within criteria and the strength of interdependence. Lastly to choose the alternative for ideal solution of this problem, Technique for Order Performance

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by Similarity to Ideal Solution (TOPSIS) is used. However it should not be ignored that the fuzzy nature of human life makes these kinds of MCDM analysis more difficult. Yet for human being's subjective judgment, a theory needed in measuring the ambiguity of these concepts. Therefore, fuzzy logic (Zadeh, 1965) is used in evaluations that allows for uncertainty among factors.

Briefly, fuzzy DEMATEL (Chen, Tseng, & Lin, 2008; Tseng, 2009a; Wu & Lee, 2007); fuzzy ANP (Liu & Lai, 2009; Tuzkaya, Ozgen, Ozgen, & Tuzkaya, 2009; Yüksel & Dağdeviren, 2010); and fuzzy TOPSIS (Salehi & Tavakkoli-Moghaddam, 2008; Yong, 2006; İç & Yurdakul, 2010) approaches used by several authors are workable. Because by applying these theories, it can be easy to discover things inside the complex problem. In the literature there are some works on these methods, but there is not any research that combines these three methods together. Thereby, this study proposes a new integrated approach that could cope with the interdependencies among various criteria in fuzzy environment. Ford Otosan is selected as a case company in this study for the evaluation of green supplier alternatives. The supplied case study provides additional insights for research and practical applications.

The organization of the paper is then as follows. The paper begins with the literature survey of GSCM. Then, after a brief review of methodologies, various main components of the GSCM are examined to structure a framework for green supplier evaluation. The next section includes the illustration of the proposed green supplier methodology through the case of Ford Otosan. The paper concludes with future directions.

2. Literature survey

Industrial production can have a great impact and damage on the sustainability of the natural environment and human life such as the impacts include depletive resource use, global environmental impacts, local environmental impacts, health impacts, and safety risks. These environmental issues have received more and more attention in recent years and supply chain operation with sustainable consideration has become an increasingly important issue. Thereby, these growing interest and importance to the supply function raise the importance of the environmental performance of suppliers (Faruk, Lamming, Cousins, & Bowen, 2002; Hall, 2000; Sarkis, 2003; Simpson & Power, 2005). The benefits to the firm arising from advanced environmental management practice can include: cost reduction (efficient use of raw materials, reduction in fines, risks or insurance costs); quality improvement; early adoption of new regulations; and better human resource management practice (Simpson & Power, 2005; Theyel, 2001).

GSCs are gaining increasing interest among researchers and practitioners. GSC is a broad concept that refers to a variety of methods by which companies work with their suppliers to improve and maintain the performance of their products or manufacturing processes of the suppliers, customers or both. The emergence of GSC is one of the most significant developments in the past decade, offering the opportunity for companies to align their supply chains in accordance with environmental and sustainability goals.

The most common GSCM practices involve organizations assessing the environmental performance of their suppliers, requiring suppliers to undertake measures that ensure environmental quality of their products, and evaluating the cost of waste in their operating systems (Handfield, Walton, Sroufe, & Melnyk, 2002). A high level of environmental performance achieved by a firm may be broken down by a poor level of environmental management by its suppliers. Therefore, green suppliers and their selection, evaluation, etc. processes are vital in a green supply chain.

The past few years have led researchers to investigate the environmental concepts in management and supply chains. Lu, Wu, and Kuo (2007) proposed environmental principles applicable to green supplier evaluation by using multi-objective decision analysis. According to current environmental regulations, companies' environmental policies, and nongovernmental organizations' environmental guidelines; the main environmental criteria were determined as materials, energy use, solid residue, liquid residue, gaseous residue. And this framework was evaluated using a fuzzy AHP methodology. Ozgen, Önüt, Gülsün, Tuzkaya, and Tuzkaya (2008) presented a two-phase possibilistic linear programming methodology for multi-objective supplier evaluation and order allocation problems. The required dimensions for evaluating suppliers were indicated as delivery reliability, flexibility and responsiveness, cost, assets and environmental responsiveness. Tuzkaya, Ozgen, Ozgen, and Tuzkaya (2009) evaluated the environmental performance of suppliers with a hybrid fuzzy multi-criteria decision approach: fuzzy ANP and Fuzzy Preference Ranking Organization Method for Enrichment Evaluations (PROMETHEE) methodology. In their study, evaluation criteria are determined as pollution control, green process management, environmental and legislative management, environmental costs, green product, and green image. Gumus (2009) introduced evaluation of hazardous waste transportation firms by using a two step fuzzy-AHP and TOPSIS methodology. The determined criteria were hygiene and safety, quality of service, complementary service, economic factors, service time, taking care of the human health and environmental protection standards, problem solving ability, and the owned vehicle fleet. Lee et al. (2009) presented a green supplier selection model for high-tech industry. The required dimensions for evaluating green suppliers were indicated as quality, technology capability, pollution control, environment management, green product, and green competencies/green image.

Recently, Bai and Sarkis (2010) proposed a study for green supplier development and performed an analytical evaluation using rough set theory. The methodology generates decision rules relating the various attributes to the performance outcomes (environmental, business, and joint performance). Kuo, Wang, and Tien (2010) integrated artificial neural network (ANN) and two multi-attribute decision analysis (MADA) methods: DEA and ANP for green supplier selection. Their green supplier selection structure contains quality, cost, delivery, service, environment, and corporate social responsibility. Punniyamoorthy, Mathiyalagan, and Parthiban (2011) introduced a strategic model using structural equation modeling and fuzzy logic in supplier selection. Their criteria of supplier selection are management and organization, quality, technical capability, production facilities and capacities, financial position, delivery, services, relationships, safety and environmental concern, and cost. Awasthi, Chauhan, and Goyal (2010) proposed a fuzzy multi-criteria approach for evaluating environmental performance of suppliers. They used fuzzy TOPSIS for evaluation and their criteria were usage of environment friendly technology, environment friendly materials, green market share, partnership with green organizations, management commitment to green practices, adherence to environmental policies, involvement in green projects, staff training, lean process planning, design for environment, environmental certification, and pollution control initiatives.

3. Proposed green supplier evaluation framework

This study proposes a novel hybrid analytic approach based on the fuzzy DEMATEL, fuzzy ANP, and fuzzy TOPSIS methodologies to assist in GSCM strategic decisions. The general view of the proposed green supplier evaluation methodology is shown in Fig. 1.

Based on these steps, we firstly mention about the proposed techniques, and then we identify the green supplier evaluation criteria and present the proposed evaluation model in the following sub sections.

3.1. Proposed methodologies for the green supplier evaluation framework

3.1.1. Fuzzy DEMATEL

The DEMATEL method, originated from the Geneva Research Centre of the Battelle Memorial Institute (Gabus & Fontela, 1973), is especially pragmatic to visualize the structure of complicated causal relationships. DEMATEL is a comprehensive method for building and analyzing a structural model involving causal relationships between complex factors. It can clearly see the cause-effect relationship of criteria when measuring a problem (Chen-Yi, Ke-Ting, & Gwo-Hshiung, 2007). It portrays a basic concept of contextual relation among the elements of the system (which is not a part of this study because of its integrated methodology), in which the numeral represents the strength of influence.

Although DEMATEL is a good technique for evaluating problems, the relationships of systems are generally given by crisp values in establishing a structural model. However, in this real world, crisp values are inadequate. Many evaluation criteria are surely imperfect and probably uncertain factors. Thus, fuzzy theory (Zadeh, 1965) is applied to the DEMATEL method for solving such a MCDM problem. Fuzzy DEMATEL method is used as many researchers in the literature (Chang, Chang, & Wu, 2011; Chen et al., 2008; Lin & Wu, 2008; Liou, Yen, & Tzeng, 2008; Tseng, 2009b; Wu & Lee, 2007), considering the fact that human judgment about preferences are often unclear and hard to estimate by exact numerical values.

3.1.2. Fuzzy ANP

ANP is a general form of the analytical hierarchy process (AHP) first introduced by Saaty (1996). While the AHP employs a

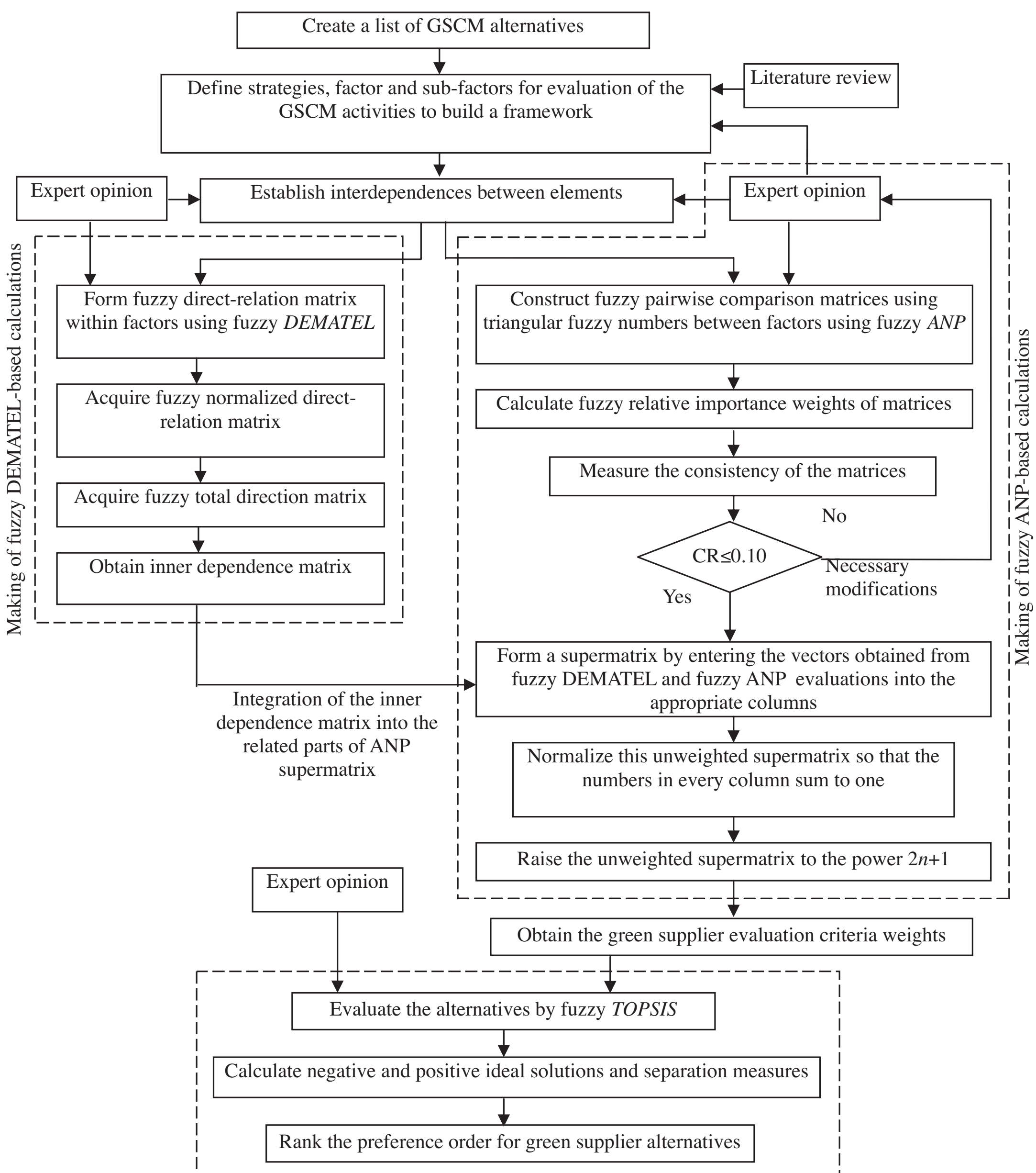

Fig. 1. Proposed green supplier evaluation methodology.

unidirectional hierarchical relationship among decision levels, the ANP enables interrelationships among the decision levels and attributes in a more general form. Instead of a hierarchy, the ANP-based system is a network that replaces single direction relationships with dependence and feedback (Saaty, 1996). The ANP uses ratio scale measurements based on pair wise comparisons; however, it does not impose a strict hierarchical structure as in AHP, and models a decision problem using a systems-with-feedback approach. The ANP refers then to the systems of which a level may both dominate and be dominated, directly or indirectly, by other decision attributes and levels. Fig. 2 depicts the structure difference of a hierarchy and a network.

The ANP approach is capable of handling interdependence among elements by obtaining the composite weights through the development of a "supermatrix". A node represents a component (or cluster) with elements inside it; a straight line/or an arc denotes the interactions between two components; and a loop indicates the inner dependence of elements within a component. For instance, when the elements of a component "Goal" depend on another component "Criteria", we represent this relation with an arrow from component "Goal" to "Criteria". The supermatrix development is defined in the next sub-section.

As indicated that human judgment about preferences are often unclear and hard to estimate by exact numerical values, again fuzzy logic is necessary for handling problems characterized by vagueness and imprecision. Therefore human judgments, which are unclear, simultaneously address the issue of combining both fuzzy set theory and ANP for green supplier assessment. In the literature many researchers such as Tuzkaya and Önüt (2008), Mohanty, Agarwal, Choudhury, and Tiwari (2005), Liu and Lai (2009), Dağdeviren and Yüksel (2010), Luo, Zhou, Zheng, Mo, and He (2010), Liu and Wang (2010), Vinodh, Ramiya, and Gautham (2011) applied fuzzy ANP to several research fields.

3.1.3. Fuzzy TOPSIS

TOPSIS is a multiple criteria method to identify solutions from a finite set of alternatives and initially proposed by Chen and Hwang (1992). The underlying logic of TOPSIS proposed by Hwang and Yoon (1981) is to define the ideal solution and negative ideal solution. The optimal solution should have the shortest distance from the positive ideal solution and the farthest from the negative ideal solution. If to remind, human judgments are usually rely on imprecision, subjectivity and vagueness; so they address fuzzy logic. Here evaluations expressed by linguistic terms and then set into fuzzy numbers.

Fuzzy TOPSIS methodology requires preliminarily information about the relative importance of the criteria. This importance is expressed by attributing a weight to each considered criterion w_j. The weight of each criterion is evaluated by fuzzy DEMATEL and fuzzy ANP steps as mentioned. There are various fuzzy TOPSIS studies in various areas as clean agent selection (Aiello, 2009), firms' competence evaluation (Amiri, Zandieh, Soltani, & Vahdani, 2009), assessing thermal-energy storage in concentrated solar power (CSP) systems (Cavallaro, 2010), development of a quick credibility scoring decision support system (Iç & Yurdakul, 2010), personnel selection (Kelemenis & Askounis, 2010), supplier selection (Roghanian, Rahimi, & Ansari, 2010), assessment of traffic police centers performance (Sadi-Nezhad & Damghani, 2010), evaluating the competitive advantages of shopping websites (Sun and Lin; 2009), virtual enterprise partner selection (Ye, 2010), etc.

In the literature, there are some realized studies that combine ANP, TOPSIS and DEMATEL methodologies. Chen and Chen (2010) presented an innovation support system for Taiwanese higher education using a novel conjunctive MCDM approach based on DEMATEL, fuzzy ANP, and TOPSIS. Lin, Hsieh, and Tzeng (2010) evaluated vehicle telematics system by using DEMATEL, ANP, and TOPSIS techniques with dependence and feedback. However, although these kinds of combined works have increased in the recent years, there is not any study combines DEMATEL, ANP, and TOPSIS in fuzzy environment.

3.2. Criteria of green supplier evaluation framework

A detailed literature search with the concepts related to GSC is realized. We can find some concepts and elements which can be served as the foundation for a decision framework for prioritizing or selecting systems by the organization that would aid in selecting green suppliers. These are summarized as follows:

Green logistics dimension: A more tactical set of organizational elements that will influence how the supply chain is to be managed, either internally or externally, can be described by green logistics dimension of an organization. Major elements of the green logistics dimension will typically include procurement, production, distribution, reverse logistics and packaging (Awasthi et al., 2010; Lee et al., 2009; Punniyamoorthy et al., 2011; Rao & Holt, 2005; Sarkis, 2003; Sarkis, Meade, & Talluri, 2004; Tuzkaya et al., 2009; Zhu, Sarkis, & Lai, 2007; Zhu, Sarkis, & Lai, 2008). It is estimated that 80% of all product related environmental impacts are determined in the design phase, so integrating environmental considerations early in the product design development cycle is the most effective way of reducing their impact and the major elements of the design stage are the selection of the materials and production design (Goosey, 2004). In an environmental friendly chain the first step is procurement and vendor selection. Production influences the green supply chain with the design and the production process. Within this function, environmental issues such as closed-loop manufacturing, total quality environmental management, de-manufacturing and source reduction make some form of value-adding contribution, even

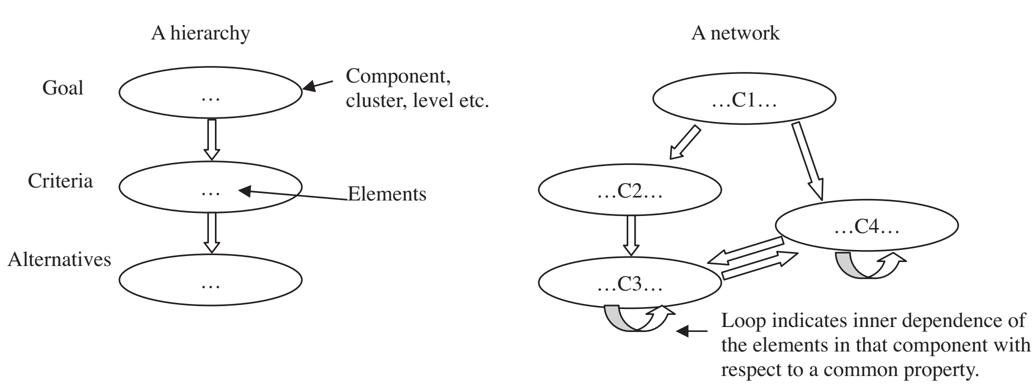

Fig. 2. Structure of a hierarchy and a network.

though some of them also influence other functional areas (Sarkis et al., 2004). For instance a well designed product should avoid the need for using hazardous or restricted materials during the manufacturing process and should minimize waste during the manufacturing process (Jabbour & Jabbour, 2009; Kubokawa & Saito, 2000; Kurk & Eagan, 2008). Distribution is another operation that effect green supply chain. The carrier, the capacity of the carrier, the type of fuel that the carrier uses, the frequency of transportation and the distance to the customers are some items that affect the performance of the green distribution. A significant trend in GSCM has been the recognition of the strategic importance of reverse logistics. The definition of reverse logistics from an environmental perspective focuses primarily on the return of recyclable or reusable products and materials into the forward supply chain. Designing effective and efficient RL networks is a key driver for providing the economic benefits necessary to initiate and sustain GSCM initiatives on a large scale (Srivastava, 2007). Packaging characteristics such as size, shape and materials have an impact on distribution due to their affect on the transport characteristics of the products. Better packaging, along with rearranged loading patterns can reduce material usage, increase space utilization in warehouses and in trucks, and reduce the amount of handling. Systems that encourage and adopt returnable packaging will require a strong customer-supplier relationship and an effective reverse logistics channel.

Green organizational activities dimension: The major five green organization activities dimensions are reduce, reuse, remanufacture, recycle and disposal (Awasthi et al., 2010; Humphreys, Wong, & Chan, 2003; Lee et al., 2009; Meade & Sarkis, 2002; Rao & Holt, 2005; Sarkis, 2003; Simpson & Power, 2005; Tuzkaya et al., 2009). Reduction is viewed as an in-process, relatively proactive, measure that can be taken by organizations. The waste management hierarchy can typically be depicted by an inverted triangle with reuse at the top which has maximum width, signifying maximum preference to this management option. Reuse is 'the use of a product or component part in its same form for the same use without remanufacturing. The reuse of product may be the reuse of the entire product, for example the selling of second hand cars or computers, or it may be the reuse of components of a product, for spares for example. Remanufacturing product involves bringing used products up to quality standards which are as rigorous as those for new products. Recycling is the process by which products otherwise destined for disposal are processed to recover base materials, for example, precious metals from computer chips. For minimization of environmental impact the ideal scenario would be maximum possible reuse and disposal in a landfill only when it cannot be reused or recycled. As recycling is preferred over disposal in a landfill for the objectives of minimization of environmental impact and perceived risk, recycling of the waste would be preferred even after it is no longer economically attractive than disposal. This would mean a delay in shift from recycling stage of hierarchy to disposal, as compared to the scenario of priority to minimization of cost. However, when the objective shifts to minimization of cost, reuse will be preferred only if it is economically more attractive than recycle and recycling would be continued only if it is economically more attractive than disposal in a landfill.

Organizational performance dimension: There are four widely accepted manufacturing performance indicators: cost, quality, delivery and flexibility (Jabbour & Jabbour, 2009; Kuo et al., 2010; Lee et al., 2009; Tuzkaya et al., 2009; Punniyamoorthy et al. (2011). These generic strategic performance requirements, which may not be environmentally based, are necessary to help identify how well various alternatives can perform on these factors. They are necessary because the alternative that is selected should not only best support the green supply chain, but also makes sense from a business perspective. The use of these organizational performance measures have been supported by a number of strategic thinkers (Handfield & Nichols, 2002; Ketchen & Hult, 2007; Vachon & Klassen, 2006). One characteristic of these performance measures is that they are not static. They tend to change over time and will be greatly influenced by the product life cycle. That is, in the introduction phases, flexibility and time may be more important than cost. Whereas cost efficiencies tend to gain importance in more mature environments. These dynamical characteristics are incorporated into the decision framework.

Green supplier evaluation criteria: The major five evaluation criteria for green suppliers are organization, financial performance, service quality, technology, and green competencies (Awasthi et al., 2010; Bai & Sarkis, 2010; Humphreys et al., 2003; Kou et al., 2010; Lee et al., 2009; Punniyamoorthy et al., 2011; Rao & Holt, 2005; Vachon & Klassen, 2006; Walker, Sisto, & McBain, 2008). Organization factor shows the supplier's degree of compatibility to the GSC. Here business structure, degree of cooperation relationship closeness and attitudes are the critical factors for the supplier to be appropriate to GSC. The compatible organization cultures and degree of fitness are some of the desired attributes. Financial performance shows the performance and control of the supplier economically. Financial position, economical stability and price/cost can take part in financial performance. There is no doubt that financial position of the supplier and the stability of the finance is fundamental for the continuity of the supplier firms. Service quality contains the factors that can improve the quality of suppliers so GSC. The quality certificates that the supplier has as ISO 9000, etc., information quality, capability of on time delivery and on time response to request are the important factors for qualified suppliers. With these factors, they can improve their quality, responsiveness and efficiency which are essential for a supplier's continuity. Technology is the factor that can facilitate innovations and flexibility to the supplier and SSC. Capacity, R&D capability, and capability to manage environmental technologies, reverse flows, etc. are the contents of the technology factor. By this way, suppliers can be more innovative, flexible and environmentally friendly. Lastly, green competencies show the competencies of supplier in improving GSC management. It contains social responsibility, cleaner/environmental production and technologies environmental management system. The supplier organization should also be capable of environmental management competencies and environmental image.

Green supplier alternatives: Some green supplier alternatives are identified for improving the environmental performance of the supply chains of the organizations. Fig. 3 presents the network structure of this evaluation framework.

4. Case Study

4.1. Application of the evaluation framework in Ford Otosan

Ford Motor Company is a multinational corporation and the world's third largest automaker based on worldwide vehicle sales. In 2006, Ford was the second-ranked automaker in the US with a

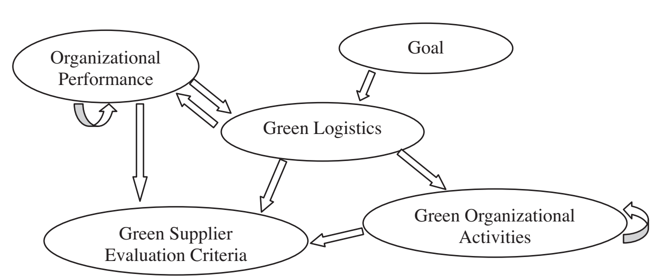

Fig. 3. Network structure of the evaluation framework.

17.5% market share, behind General Motors (24.6%) but ahead of Toyota (15.4%) and Daimler Chrysler (14.4%). In the 2007 Fortune 500 list, Ford was the seventh-ranked American-based company according to global revenues ($160.1 Billion). In 2006, Ford produced approximately 6.6 million automobiles, and employed about 280,000 employees at 100 plants and facilities worldwide (http://www.ford.com).

Otosan started production in 1965 and since then has occupied a major role in the development of Turkish automotive industry. In 1997, Ford Motor Company and Koç Holding signed an agreement and created Ford Otosan as a joint venture. Each company holds 41% share in the venture. Today, Ford Otosan's capital is 500 Million TL. Ford Otosan has three facilities in Turkey and is employing 8008 people. In 2006, Ford Otosan sold 113.857 vehicles just in Turkey and has been the market leader last 5 years. In 2006, Ford Otosan was the market leader with a 17.1% market share (http://www.ford.com.tr). Ford Otosan's plant, located in Kocaeli, is named as "Best Plant in the World" having the best scores in 2002, 2003, 2004 and 2005 among European Ford Plants.

Today, Ford Otosan is one of the biggest and most technologically advanced automotive plants in the world and green practices are implemented at all stages of the manufacturing process. For these reasons Ford Otosan is selected as a case company in this study to evaluate green supply chain management initiatives. Decision makers were Vedat Okyar (Senior Purchasing Manager-Trim Parts in Gölcük Plant) and Serdar Aydın (New Project Chief in Gölcük Plant). There were five possible green suppliers that are thought they have specific green competencies.

4.2. The computational steps of the proposed integrated framework

Step 1: Determination of the evaluation model. After setting the decision goal, construct a committee of experts with E members and determine the alternatives and sets of criteria for evaluation. The evaluation criteria have already been discussed in Section 3.2 and the evaluation model can be seen in Fig. 4.

Step 2: Design fuzzy linguistic scale for evaluations. In this step, development of relationships within and among the attributes using experts' opinion through paired comparison analysis is needed. Firstly, for the purpose of measuring the relationships, it is required to design the comparison scale as shown in Table 1. The different degrees of influence are expressed with eleven linguistic terms and the equivalent fuzzy membership functions for linguistic values are shown in Fig. 5. Consensus of opinions exists among experts in the evaluation process.

Step 2: Establish casual relations using the fuzzy DEMATEL.

Step 2.1: Acquire fuzzy direct-relation matrix. Experts make sets of the pairwise comparisons in terms of influence and direction within necessary criteria that is a $n \times n$ matrix $\widetilde{A}$, in which $\tilde{a}_{ij} = (l_{ij}, m_{ij}, u_{ij})$ is denoted as the degree to which the criterion i affects the criterion j for experts. Table 2 gives an example of fuzzy direct-relation matrix for organization performance dimension.

Step 2.2: Acquire normalized fuzzy direct-relation matrix. After producing the direct-relation matrix as the first step, we can continue with normalizing the direct-direction matrix as in DEMATEL method. On the base of the direct-relation matrix $\widetilde{A}$, the normalized direct-relation matrix $\widetilde{X}$ can be obtained through Eq. (1). In Table 3, normalized direct-relation matrix can be seen

Let $\tilde{a}_{ij} = (l_{ij}, m_{ij}, u_{ij})$ and $s = 1/\max_{1 \le i \le n} \sum_{j=1}^{n} u_{ij}$, then

$$\widetilde{X} = s \times \widetilde{A}. \tag{1}$$

Step 2.3: Acquire fuzzy total-relation matrix. As soon as the normalized direct-relation matrix $\widetilde{X}$ is obtained, the total-relation matrix $\widetilde{T}$,can be acquired by using the following formulas, in which the I is denoted as the identity matrix.

Let $\tilde{x}_{ij} = (l_{ij}, m_{ij}, u_{ij})$ and define three crisp matrices, whose elements are extracted from $\widetilde{X}$ as follows [35].

$$X_1 = \begin{bmatrix} 0 & l_{12} & \dots & l_{1n} \\ l_{21} & 0 & \dots & l_{2n} \\ \cdot & & & \cdot \\ \cdot & & & \cdot \\ \cdot & & & \cdot \\ l_{n1} & l_{n2} & \dots & 0 \end{bmatrix}, \quad X_2 = \begin{bmatrix} 0 & m_{12} & \dots & m_{1n} \\ m_{21} & 0 & \dots & m_{2n} \\ \cdot & & & \cdot \\ \cdot & & & \cdot \\ \cdot & & & \cdot \\ m_{n1} & m_{n2} & \dots & 0 \end{bmatrix},$$

$$X_3 = \begin{bmatrix} 0 & u_{12} & \dots & u_{1n} \\ u_{21} & 0 & \dots & u_{2n} \\ \cdot & & & \cdot \\ \cdot & & & \cdot \\ \cdot & & & \cdot \\ u_{n1} & u_{n2} & \dots & 0 \end{bmatrix}.$$

According to the crisp case, we define the total-relation fuzzy matrix $\widetilde{T}$ through (2):

$$\widetilde{T} = \widetilde{X}(I - \widetilde{X})^{-1}. \tag{2}$$

$$\text{Let } \widetilde{T} = \begin{bmatrix} \tilde{t}_{11} & \tilde{t}_{12} & \dots & \tilde{t}_{1n} \\ \tilde{t}_{21} & \tilde{t}_{22} & \dots & \tilde{t}_{2n} \\ \cdot & & & \cdot \\ \cdot & & & \cdot \\ \cdot & & & \cdot \\ \tilde{t}_{n1} & \tilde{t}_{n2} & \dots & \tilde{t}_{nn} \end{bmatrix},$$

where $\tilde{t}_{ij} = (l'_{ij}, m'_{ij}, u'_{ij})$ then

$$Matrix\left[l'_{ij}\right] = X_l(I - X_l)^{-1}, \tag{3}$$

$$Matrix\left[m'_{ij}\right] = X_m(I - X_m)^{-1}, \tag{4}$$

$$Matrix\left[u'_{ij}\right] = X_u(I - X_u)^{-1}. \tag{5}$$

By applying these formulas, the total-relation matrix acquired is given in Table 4.

Step 2.4: Obtain the inner dependence matrix. In this step, after defuzzification of the total-relation matrix $\widetilde{T}$ by using Eq. (6), the sum of each column in total-relation matrix became equal to 1 by the normalization method.

$$\mathrm{F}(\tilde{t}_{ij}) = 1/2 \int_0^1 \left(\inf_{x \in \Re} \tilde{t}_{ij}^{\alpha} + \sup_{x \in \Re} \tilde{t}_{ij}^{\alpha} \right) d\alpha. \tag{6}$$

Then the inner dependence matrix can be acquired to put in the unweighted supermatrix of ANP later. Table 5 shows the inner dependence matrix of organizational performance dimension and can be seen in Fig. 6 as matrix B of the supermatrix.

Step 3: Establish remaining relations using the fuzzy ANP. In ANP, like AHP, pair wise comparisons of the elements in each level are conducted with respect to their relative importance towards their control criterion. By using triangular fuzzy numbers again, the relative strength of each pair of elements and the preferences of the decision maker in the same hierarchy are indicated. Via pair-wise comparison, the fuzzy judgment matrix $\widetilde{A}'$ is constructed as:

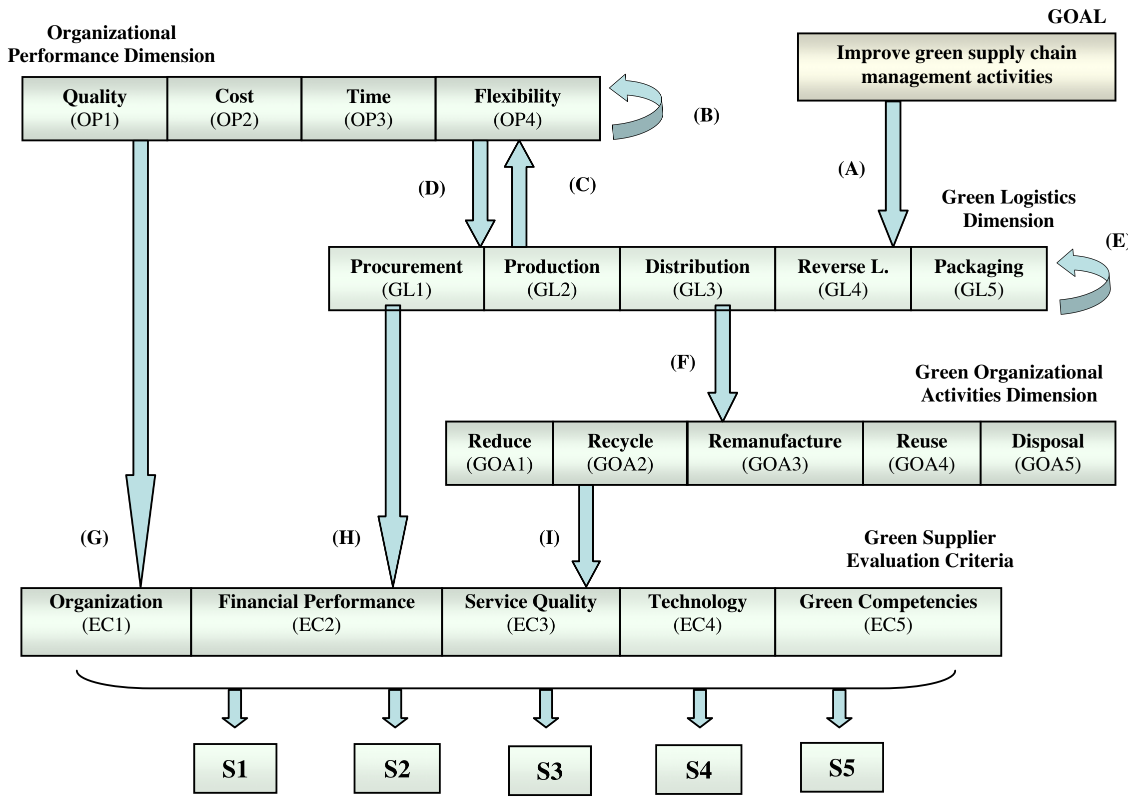

Fig. 4. Detailed evaluation model.

Table 1
Corresponding linguistic terms for evaluation.

Linguistic term	Abbrev.	Fuzzy scales
None	N	(0,0,1)
Very Low	VL	(0,0.1,0.2)
Low	L	(0.1,0.2,0.3)
Fairly Low	FL	(0.2,0.3,0.4)
More or less Low	ML	(0.3,0.4,0.5)
Medium	M	(0.4,0.5,0.6)
More or less Good	MG	(0.5,0.6,0.7)
Fairly Good	FG	(0.6,0.7,0.8)
Good	G	(0.7,0.8,0.9)
Very Good	VG	(0.8,0.9,1)
Excellent	E	(0.9,1,1)

$$\widetilde{A}' = \begin{bmatrix} \tilde{a}'_{11} & \tilde{a}'_{12} & \dots & \tilde{a}'_{1n} \\ \tilde{a}'_{21} & \tilde{a}'_{22} & \dots & \tilde{a}'_{2n} \\ . & & & . \\ . & & & . \\ . & & & . \\ \tilde{a}'_{n1} & \tilde{a}'_{n2} & \dots & \tilde{a}'_{nn} \end{bmatrix}, \tag{7}$$

where $\tilde{a}'_{ij} = \left(l'_{ij}, m'_{ij}, u'_{ij}\right)$ indicates the importance among the compared criteria (importance of i over j) where $i = j = 1,2,\ldots,n$. Table 6 gives examples of linguistic and fuzzy evaluations between green logistics dimensions and goal. This evaluation can be seen in Fig. 6 as matrix A of supermatrix. Other evaluations are populated in the same way.

Step 3.1: Calculate the relative importance weights. The priority vectors for each pairwise comparison matrix will be needed to complete the various supermatrix submatrices. Estimate triangular fuzzy priorities $\tilde{w}_k$ where $k = 1, 2\ldots,n$ from the judgment matrix. The logarithmic least-squares method can be used for calculating

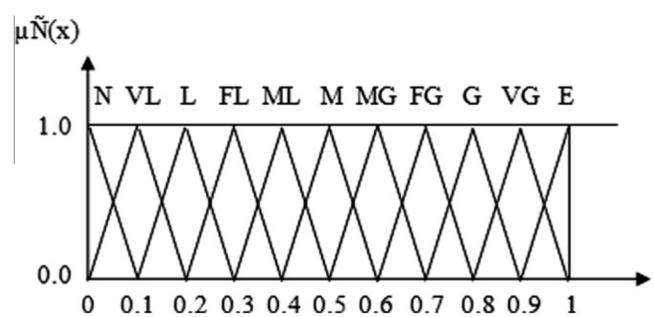

Fig. 5. Fuzzy membership functions for linguistic values.

these weights (Onüt, Kara, & Işik, 2009; Ramik, 2007; Tuzkaya et al., 2009; Tuzkaya & Önüt, 2008):

$$\tilde{w}_k = (w_l k, w_k^m, w_k^u) \quad k = 1, 2, \ldots, n \quad \text{where},$$

$$w_k^s = \frac{\left(\prod_{i=1}^{n} a_{kj}^s\right)^{1/n}}{\sum_{i=1}^{n}\left(\prod_{i=1}^{n} a_{ij}^m\right)^{1/n}}, s \in \{l, m, u\} \tag{8}$$

for $0 < \alpha \leqslant 1$ and all i, j, where $i = 1, 2,\ldots,n$, $j = 1, 2\ldots,n$. In order to control the result of the method, the consistency ratio for each of the matrices and the overall inconsistency for the hierarchy are calculated. The Consistency Ratio (CR) is used to directly estimate the consistency of the pair-wise comparisons and should be less than 0.10. Then it can be said the comparisons are acceptable, otherwise they are not acceptable. In this study, the inconsistency ratios for all the comparison matrices were calculated for the mean values of the fuzzy numbers. Because the lower and upper values provide flexibility for human judgments, they are not expected to have rigid consistency.

Table 2
Fuzzy direct relation matrix of organizational performance dimension.

	Quality (OP1)	Cost (OP2)	Time (OP3)	Flexibility (OP4)
Quality (OP1)	*	(0.8,0.9,1)	(0.4,0.5,0.6)	(0,0.1,0.2)
Cost (OP2)	(0.5,0.6,0.7)	*	(0.4,0.5,0.6)	(0,0,0.1)
Time (OP3)	(0.4,0.5,0.6)	(0.6,0.7,0.8)	*	(0,0.1,0.2)
Flexibility (OP4)	(0.3,0.4,0.5)	(0.8,0.9,1)	(0.5,0.6,0.7)	*

Step 3.2: Defuzzify the weights obtained from fuzzy matrices. In this step, defuzzification of the weights is done in the same way as Eq. (6).

Such an example, priority calculation of the *production* – one of the green logistics dimensions – with respect to goal (from Table 6) is as follows. By applying Eq. (8), the fuzzy weight is obtained as,

$$w_k^l = \frac{(0.2\times 0.1\times 0.6\times 1/1\times 1)^{1/5}}{(1\times 0.9\times 1/0.4\times 1/0.3\times 1/0.3)^{1/5} + (1/0.9\times 1\times 1/0.4\times 1/0.2\times 1/0.2)^{1/5} + (0.4\times 0.4\times 1\times 1/0.7\times 1/0.7)^{1/5} + (0.3\times 0.2\times 0.7\times 1\times 1)^{1/5} + (0.3\times 0.2\times 0.7\times 1/1\times 1)^{1/5}} = 0.3048.$$

$$w_k^m = \frac{(0.3\times 0.2\times 0.7\times 1/1\times 1)^{1/5}}{(1\times 0.9\times 1/0.4\times 1/0.3\times 1/0.3)^{1/5} + (1/0.9\times 1\times 1/0.4\times 1/0.2\times 1/0.2)^{1/5} + (0.4\times 0.4\times 1\times 1/0.7\times 1/0.7)^{1/5} + (0.3\times 0.2\times 0.7\times 1\times 1)^{1/5} + (0.3\times 0.2\times 0.7\times 1/1\times 1)^{1/5}} = 0.3828.$$

$$w_k^u = \frac{(0.4\times 0.3\times 0.8\times 1/0.9\times 1)^{1/5}}{(1\times 0.9\times 1/0.4\times 1/0.3\times 1/0.3)^{1/5} + (1/0.9\times 1\times 1/0.4\times 1/0.2\times 1/0.2)^{1/5} + (0.4\times 0.4\times 1\times 1/0.7\times 1/0.7)^{1/5} + (0.3\times 0.2\times 0.7\times 1\times 1)^{1/5} + (0.3\times 0.2\times 0.7\times 1/1\times 1)^{1/5}} = 0.5478.$$

Then using this fuzzy vector and applying Eq. (6), defuzzified weight 0.4046 is obtained.

Step 4: Form a supermatrix. ANP uses the formation of a supermatrix to allow for the resolution of the effects of the interdependence that exists between the clusters within the decision network hierarchy. The supermatrix is a partitioned matrix, where each submatrix is composed of a set of relationships between two clusters in the graphical model. A generic supermatrix is shown in Fig. 6, with the notation representing the various relationships from Fig. 4; for instance, "A" is the submatrix representing the influence relationship between green logistics dimension elements' and control factor of the goal of selecting a green supplier.

By entering the priorities found by fuzzy DEMATEL and fuzzy ANP into the appropriate columns, initial supermatrix can be constructed. Table 7 presents the initial supermatrix of the study.

Table 3
Fuzzy normalized direct relation matrix of organizational performance dimension.

	(OP1)	(OP2)	(OP3)	(OP4)
(OP1)	*	(0.36,0.40,45)	(0.18,0.22,0.27)	(0,0.04,0.09)
(OP2)	(0.22,0.27,0.31)	*	(0.18,0.22,0.27)	(0,0,0.04)
(OP3)	(0.18,0.22,0.27)	(0.27,0.31,0.36)	*	(0,0.04,0.09)
(OP4)	(0.13,0.18,0.22)	(0.36,0.40,0.45)	(0.22,0.27,0.31)	*

Table 4
Fuzzy total direct relation matrix of organizational performance dimension.

	(OP1)	(OP2)	(OP3)	(OP4)
(OP1)	(0.17,0.33,0.70)	(0.51,0.73,1.23)	(0.31,0.49,0.89)	(0,0.08,0.29)
(OP2)	(0.32,0.47,0.82)	(0.19,0.34,0.76)	(0.28,0.42,0.78)	(0,0.04,0.23)
(OP3)	(0.30,0.48,0.86)	(0.42,0.63,1.10)	(0.13,0.27,0.62)	(0,0.08,0.28)
(OP4)	(0.34,0.56,1.03)	(0.60,0.86,1.43)	(0.40,0.61,1.07)	(0,0.05,0.26)

4.1: Solve the supermatrix. To complete this task, firstly each of the columns may either be normalized by dividing each weight in the column by the sum of that column. Then, the final step in the process is to obtain a priority ranking for each of the alternatives. To derive the overall priorities of elements, the normalized supermatrix is raised to limiting powers to calculate the overall priorities, and thus the cumulative influence of each element on every other element with which it interacts is obtained. In this case, the supermatrix is raised to the power 25. This weighted supermatrix is shown in Table 8.

According to this weighted supermatrix, weights of the criteria on the objective of green supplier selection are shown in the "Goal" column to use in fuzzy TOPSIS steps later.

Step 5: Evaluate the alternatives by using fuzzy TOPSIS steps. The technique is adapted from Chen (2000) and the steps of the methodology are as follows.

Step 5.1: Establish fuzzy decision matrix for evaluation of the green supplier alternatives. With *m* alternatives and *n* criteria, fuzzy MCDM problem can be expressed as:

Table 5
Inner dependence matrix of organizational performance dimension.

	(OP1)	(OP2)	(OP3)	(OP4)
(OP1)	0.19	0.28	0.27	0.29
(OP2)	0.25	0.14	0.24	0.20
(OP3)	0.26	0.25	0.16	0.28
(OP4)	0.30	0.33	0.33	0.23

	Goal	GL	OP	GOA	EC
Goal	0	0	0	0	0
Green Logistics Dimensions (GL)	**A**	**E**	**D**	0	0
Organizational Performance (OP)	0	**C**	**B**	0	0
Green Organizational Activities (GOA)	0	**F**	0	0	0
Green Supplier Evaluation Criteria (EC)	0	**H**	**G**	**I**	*I*

Fig. 6. General submatrix notation for supermatrix. Note: *I* is the identity matrix.

Table 6
Linguistic and fuzzy evaluation matrices of green logistics with respect to goal.

Linguistic terms					Fuzzy terms				
GL1	GL2	GL3	GL4	GL5	GL1	GL2	GL3	GL4	GL5
1	VG				1	(0.8, 0.9, 1)	(1/0.5, 1/0.4, 1/0, 3)	(1/0.4, 1/0.3, 1/0, 2)	(1/0.4, 1/0.3, 1/0, 2)
	1				(1/1, 1/0.9, 1/0, 8)	1	(1/0.5, 1/0.4, 1/0, 3)	(1/0.3, 1/0.2, 1/0, 1)	(1/0.3, 1/0.2, 1/0, 1)
ML	ML	1			(0.3, 0.4, 0.5)	(0.3, 0.4, 0.5)	1	(1/0.8, 1/0.7, 1/0, 6)	(1/0.8, 1/0.7, 1/0, 6)
FL	L	FG	1	E	(0.2, 0.3, 0.4)	(0.1, 0.2, 0.3)	(0.6, 0.7, 0.8)	1	(0.9, 1, 1)
FL	L	FG		1	(0.2, 0.3, 0.4)	(0.1, 0.2, 0.3)	(0.6, 0.7, 0.8)	(1/1, 1/1, 1/0, 9)	1

Table 7
Initial supermatrix of green supplier selection for the improvement of GSC.

	Goal	GL1	GL2	GL3	GL4	GL5	OP1	OP2	OP3	OP4	GOA1	GOA2	GOA3	GOA4	GOA5	C1	C2	C3	C4	C5
Goal	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
GL1	0.32	0.18	0.30	0.22	0.25	0.29	0.43	0.44	0.08	0.06	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
GL2	0.40	0.34	0.21	0.26	0.30	0.28	0.29	0.20	0.34	0.16	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
GL3	0.13	0.13	0.10	0.09	0.14	0.16	0.14	0.20	0.34	0.44	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
GL4	0.08	0.15	0.21	0.17	0.11	0.13	0.06	0.07	0.17	0.26	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
GL5	0.09	0.20	0.18	0.26	0.19	0.14	0.07	0.07	0.09	0.08	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
OP1	0.00	0.61	0.12	0.24	0.13	0.52	0.19	0.28	0.27	0.29	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
OP2	0.00	0.26	0.06	0.09	0.59	0.26	0.25	0.14	0.24	0.20	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
OP3	0.00	0.08	0.25	0.53	0.23	0.16	0.26	0.25	0.16	0.28	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
OP4	0.00	0.06	0.57	0.14	0.06	0.06	0.30	0.33	0.33	0.23	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
GOA1	0.00	0.46	0.46	0.46	0.46	0.46	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
GOA2	0.00	0.10	0.10	0.10	0.10	0.10	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
GOA3	0.00	0.15	0.15	0.15	0.15	0.15	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
GOA4	0.00	0.26	0.26	0.26	0.26	0.26	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
GOA5	0.00	0.05	0.05	0.05	0.05	0.05	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
C1	0.00	0.20	0.15	0.20	0.25	0.10	0.19	0.11	0.20	0.25	0.10	0.10	0.10	0.15	0.20	1.00	0.00	0.00	0.00	0.00
C2	0.00	0.25	0.25	0.25	0.10	0.20	0.20	0.30	0.25	0.25	0.15	0.10	0.15	0.15	0.20	0.00	1.00	0.00	0.00	0.00
C3	0.00	0.25	0.25	0.15	0.20	0.20	0.30	0.19	0.15	0.19	0.15	0.10	0.15	0.15	0.10	0.00	0.00	1.00	0.00	0.00
C4	0.00	0.20	0.25	0.30	0.15	0.20	0.20	0.20	0.30	0.26	0.24	0.35	0.24	0.20	0.20	0.00	0.00	0.00	1.00	0.00
C5	0.00	0.10	0.10	0.10	0.30	0.30	0.11	0.20	0.10	0.05	0.36	0.35	0.36	0.35	0.30	0.00	0.00	0.00	0.00	1.00

Table 8
Weighted supermatrix of green supplier selection for the improvement of GSC.

	GOAL	GL1	GL2	GL3	GL4	GL5	OP1	OP2	OP3	OP4	GOA1	GOA2	GOA3	GOA4	GOA5
C1	0.16	0.16	0.16	0.16	0.17	0.14	0.18	0.15	0.18	0.20	0.11	0.10	0.11	0.15	0.20
C2	0.20	0.20	0.20	0.20	0.17	0.19	0.21	0.24	0.22	0.22	0.15	0.10	0.15	0.15	0.20
C3	0.19	0.20	0.19	0.17	0.18	0.18	0.23	0.19	0.18	0.19	0.15	0.10	0.15	0.15	0.10
C4	0.23	0.22	0.24	0.25	0.21	0.23	0.22	0.22	0.26	0.25	0.24	0.35	0.24	0.20	0.20
C5	0.22	0.22	0.21	0.22	0.27	0.26	0.16	0.20	0.16	0.14	0.35	0.35	0.35	0.35	0.30

Table 9
Linguistic and fuzzy decision matrix for green supplier alternative evaluation.

	Linguistic terms					Fuzzy terms				
	C1	C2	C3	C4	C5	C1	C2	C3	C4	C5
S1	FG	G	FG	MG	ML	(0.6, 0.7, 0.8)	(0.7, 0.8, 0.9)	(0.6, 0.7, 0.8)	(0.5, 0.6, 0.7)	(0.3, 0.4, 0.5)
S2	VG	G	G	VG	VG	(0.8, 0.9, 1)	(0.7, 0.8, 0.9)	(0.7, 0.8, 0.9)	(0.8, 0.9, 1)	(0.8, 0.9, 1)
S3	VG	E	E	G	G	(0.8, 0.9, 1)	(0.9, 1, 1)	(0.9, 1, 1)	(0.7, 0.8, 0.9)	(0.7, 0.8, 0.9)
S4	MG	VG	G	VG	MG	(0.5, 0.6, 0.7)	(0.8, 0.9, 1)	(0.7, 0.8, 0.9)	(0.8, 0.9, 1)	(0.5, 0.6, 0.7)
S5	M	MG	FG	G	G	(0.4, 0.5, 0.6)	(0.5, 0.6, 0.7)	(0.6, 0.7, 0.8)	(0.7, 0.8, 0.9)	(0.7, 0.8, 0.9)

Table 10
Weighted decision matrix for green supplier alternative evaluation.

	C1	C2	C3	C4	C5
S1	(0.10, 0.11, 0.13)	(0.14, 0.16, 0.18)	(0.11, 0.13, 0.15)	(0.12, 0.14, 0.16)	(0.07, 0.09, 0.11)
S2	(0.13, 0.14, 0.16)	(0.14, 0.16, 0.18)	(0.13, 0.15, 0.17)	(0.18, 0.21, 0.23)	(0.18, 0.20, 0.22)
S3	(0.13, 0.14, 0.16)	(0.18, 0.20, 0.20)	(0.17, 0.19, 0.19)	(0.16, 0.18, 0.21)	(0.15, 0.18, 0.20)
S4	(0.08, 0.10, 0.11)	(0.16, 0.18, 0.20)	(0.13, 0.15, 0.17)	(0.18, 0.21, 0.23)	(0.11, 0.13, 0.15)
S5	(0.06, 0.08, 0.10)	(0.10, 0.12, 0.14)	(0.11, 0.13, 0.15)	(0.16, 0.18, 0.21)	(0.15, 0.18, 0.20)

Table 11
Positive–negative distances and final performance indices of green supplier alternatives.

	Positive						Negative					
	d1	d2	d3	d4	d5	d_{TOT}	d1	d2	d3	d4	d5	d_{TOT}
S1	0.89	0.84	0.87	0.86	0.91	4.37	0.11	0.16	0.13	0.14	0.09	0.64
S2	0.86	0.84	0.85	0.79	0.80	4.14	0.14	0.16	0.15	0.21	0.20	0.86
S3	0.86	0.81	0.82	0.82	0.82	4.12	0.14	0.19	0.18	0.18	0.18	0.88
S4	0.90	0.82	0.85	0.79	0.87	4.23	0.10	0.18	0.15	0.21	0.13	0.77
S5	0.48	0.88	0.87	0.82	0.82	3.87	0.08	0.12	0.13	0.18	0.18	0.70

Table 12
Final performance indices of green supplier alternatives.

Performance index	
S1	0.1272
S2	0.1728
S3	0.1767
S4	0.1541
S5	0.1528

$$\widetilde{D} = \begin{array}{c} \\ A_1 \\ A_2 \\ A_3 \\ A_4 \end{array} \begin{array}{c} \begin{array}{cccc} C_1 & C_2 & \dots & C_n \end{array} \\ \begin{bmatrix} \tilde{x}_{11} & \tilde{x}_{12} & \dots & \tilde{x}_{1n} \\ \vdots & \ddots & & \\ \vdots & & \ddots & \\ \tilde{x}_{m1} & \tilde{x}_{m2} & \dots & \tilde{x}_{mn} \end{bmatrix} \end{array}$$

$\widetilde{D}$ represents the fuzzy decision matrix with alternatives A and criteria C, and can be seen with linguistic and fuzzy terms in Table 9.

Step 5.2: Normalize the decision matrix. Normalized fuzzy decision matrix $\widetilde{R}$ is calculated as:

$$\widetilde{R} = [\tilde{r}_{ij}]_{m^*n}, \quad i = 1,2\dots,m; \quad j = 1,2\dots n,$$

$$\tilde{r}_{ij} = \left(\frac{a_{ij}}{C_j^+}, \frac{b_{ij}}{C_j^+}, \frac{c_{ij}}{C_j^+}\right), \tag{9}$$

where $C_j^+ = \max_i C_{ij}$.To avoid the complicated normalization formula used in the classical TOPSIS, the linear scale transformation is used to transform the various criteria scales into a comparable scale (Chen, 2000). Linear scale transformation for normalization is also employed by Kuo et al. (2007) and Celik et al. (2009). Here normalized decision matrix remains the same because max C_{ij} = 1.

Step 5.3: Compute weighted decision matrix. Weighted normalized fuzzy decision matrix that is shown in Table 10 is computed by using Eq. (11), where w_j is the weight for the criterion j obtained from supermatrix

$$\tilde{v}_{ij} = \tilde{r}_{ij} \otimes \tilde{w}_j, \tag{10}$$

where $\tilde{v} = [\tilde{v}_{ij}]_{m^*n}, i = 1,2,\dots,m;\ j = 1,2,\dots,n.$

Step 5.4: Calculate the distances from positive and negative ideal points. Since the triangular fuzzy numbers are included in [0,1] range, positive and negative ideal reference points (FPIRP, FNIRP) are as follows:

$$A^+ = \{\tilde{v}_1^+, \tilde{v}_2^+, \dots \tilde{v}_n^+\}, \quad A^- = \{\tilde{v}_1^-, \tilde{v}_2^-, \dots \tilde{v}_n^-\}, \tag{11}$$

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

The next step is to calculate the distance of alternatives from FPIRP and FNIRP.

$$d_i^+ = \sum_{j=1}^{n} d(\tilde{v}_{ij}, \tilde{v}_j^+), \quad i = 1,2,\dots,m;\ j = 1,2\dots n, \tag{12}$$

$$d_i^- = \sum_{j=1}^{n} d(\tilde{v}_{ij}, \tilde{v}_j^-), \quad i = 1,2\dots m; \quad j = 1,2,\dots,n, \tag{13}$$

$$d(\widetilde{A}, \widetilde{B}) = \sqrt{\frac{1}{3}\left[(a_1 - b_1)^2 + (a_2 - b_2)^2 + (a_3 - b_3)^2\right]}. \tag{14}$$

Positive and negative distances of the green supplier alternatives can be seen in Table 11.

Step 5.5: Rank the alternatives. The performance indices are computed to rank the alternatives. Performance indices are sorted in a decreasing order. Table 12 shows the final ranking and according to this hybrid methodology, the best possible green supplier is S3 with a score of 0.1767.

5. Conclusion

This study suggests a novel hybrid MCDM approach to evaluate green suppliers for the need of improving GSCM initiatives. Based on the literature survey and with the validation of industrial experts, possible green supplier evaluation criteria were defined and a new evaluation model was formulated. The proposed model was implemented in Ford Otosan, one of the pioneering companies about environmental subjects in Turkey.

The combined fuzzy ANP and fuzzy DEMATEL approaches used in this study offered a more precise and accurate analysis by integrating interdependent relationships within and among a set of criteria. Moreover, fuzzy TOPSIS method helped to choose the alternative for ideal solution of this problem efficiently.

While it is believed that the presented model provides value, there are also further points that can be included. To our knowledge, no previous work investigated such a problem by an integrated method with DEMATEL, ANP, and TOPSIS in fuzzy environment. As the proposed approach is novel, it might be applied to other MCDM problems.

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References

Aiello, G. (2009). Clean agent selection approached by fuzzy TOPSIS decision-making method. *Fire Technology, 45*, 405–418.

Amiri, M., Zandieh, M., Soltani, R., & Vahdani, B. (2009). A hybrid multi-criteria decision-making model for firms competence evaluation. *Expert Systems with Applications, 36*, 12314–12322.

Awasthi, A., Chauhan, S. S., & Goyal, S. K. (2010). A fuzzy multicriteria approach for evaluating environmental performance of suppliers. *International Journal of Production Economics, 126*(2), 370–378.

Bai, C., & Sarkis, J. (2010). Green supplier development: Analytical evaluation using rough set theory. *Journal of Cleaner Production, 18*(12), 1200–1210.

Cavallaro, F. (2010). Fuzzy TOPSIS approach for assessing thermal-energy storage in concentrated solar power (CSP) systems. *Applied Energy, 87*(2), 496–503.

Chan, F. T. S., & Kumar, N. (2007). Global supplier development considering risk factors using fuzzy extended AHP-based approach. *Omega, 35*, 417–431.

Chang, B., Chang, C.-W., & Wu, C.-H. (2011). Fuzzy DEMATEL method for developing supplier selection criteria. *Expert Systems with Applications, 38*(3), 1850–1858.

Chen, C.C., Tseng, M.L., & Lin, Y.H. (2008). Using fuzzy DEMATEL to develop a causal and effect model of hot spring service quality expectation. In *IEEE international conference on industrial engineering and engineering management* (pp. 1004–1008).

Chen, J.-K., & Chen, I-S. (2010). Using a novel conjunctive MCDM approach based on DEMATEL, fuzzy ANP, and TOPSIS as an innovation support system for Taiwanese higher education. *Expert Systems with Applications, 37*, 1981–1990.

Chen, S. J., & Hwang, C. L. (1992). Fuzzy multiple attribute decision-making methods and application. In *Lecture notes in economics and mathematical systems*. New York: Springer.

Chen-Yi, H., Ke-Ting, C., & Gwo-Hshiung, T. (2007). FMCDM with fuzzy DEMATEL approach for customers' choice behavior model. *International Journal of Fuzzy Systems, 9*(4), 236–246.

Dağdeviren, M., & Yüksel, İ. (2010). A fuzzy analytic network process (ANP) model for measurement of the sectoral competition level (SCL). *Expert Systems with Applications, 37*(2), 1005–1014.

Faruk, A. C., Lamming, R. C., Cousins, P. D., & Bowen, F. E. (2002). Analyzing, mapping, and managing environmental impacts along the supply chain. *Journal of Industrial Ecology, 5*(2), 13–36.

Gabus, A., & Fontela, E. (1972). *World problems, an invitation to further thought within the framework of DEMATEL*. Switzerland, Geneva: Battelle Geneva Research Centre.

Gabus, A., & Fontela, E. (1973). *Perceptions of the world problematique: Communication procedure, communicating with those bearing collective responsibility*. Switzerland Geneva: Battelle Geneva Research Centre. no. 1..

Goosey, M. (2004). End-of-life electronics legislation – An industry perspective. *Circuit World, 30*(2), 41–45.

Gumus, A. T. (2009). Evaluation of hazardous waste transportation firms by using a two step fuzzy-AHP and TOPSIS methodology. *Expert Systems with Applications, 36*, 4067–4074.

Hall, J. (2000). Environmental supply chain dynamics. *Journal of Cleaner Production, 8*(6), 206–225.

Handfield, R. B., & Nichols, E. L. (2002). *Supply chain redesign*. Upper Saddle River, NJ: Financial Times Prentice Hall..

Handfield, R., Walton, S., Sroufe, R., & Melnyk, S. (2002). Applying environmental criteria to supplier assessment: A study of the application of the analytical hierarchy process. *European Journal of Operational Research, 141*, 70–87.

He, S., Chaudhry, S. S., Lei, Z., & Baohua, W. (2009). Stochastic vendor selection problem: Chance-constrained model and genetic algorithms. *Annals of Operations Research, 168*, 169–179.

Humphreys, P. K., Wong, Y. K., & Chan, F. T. S. (2003). Integrating environmental criteria into the supplier selection process. *Journal of Materials Processing Technology, 138*, 349–356.

Hwang, C. L., & Yoon, K. (1981). *Multiple attribute decision-making: Methods and application*. New York: Springer.

Iç, Y. T., & Yurdakul, M. (2010). Development of a quick credibility scoring decision support system using fuzzy TOPSIS. *Expert Systems with Applications, 37*, 567–574.

Jabbour, A. B. L. S., & Jabbour, C. J. C. (2009). Are supplier selection criteria going green? Case studies of companies in Brazil. *Industrial Management & Data Systems, 109*, 477–495.

Kelemenis, A., & Askounis, D. (2010). A new TOPSIS-based multi-criteria approach to personnel selection. *Expert Systems with Applications, 37*(7), 4999–5008.

Ketchen, D. J., Jr., & Hult, G. T. M. (2007). Bridging organization theory and supply chain management: The case of best value supply chains. *Journal of Operations Management, 25*(2), 573–580.

Kubokawa, S., & Saito, I. (2000). Manufacturing management strategies for environmental protection: Toward the environmental upgrading of management and manufacturing systems to cope with environmental laws. *Production Planning & Control, 11*(2), 107–112.

Kumar, M., Vrat, P., & Shankar, R. (2006). A fuzzy goal programming approach for vendor selection problem in a supply chain. *International Journal of Production Economics, 101*, 273–285.

Kuo, R. J., Wang, Y. C., & Tien, F. C. (2010). Integration of artificial neural network and MADA methods for green supplier selection. *Journal of Cleaner Production, 18*(12), 1161–1170.

Kurk, F., & Eagan, P. (2008). The value of adding design-for the-environment to pollution prevention assistance options. *Journal of Cleaner Production, 16*(6), 722–726.

Lee, A. H. I., Kang, Y., Hsu, H. C-F., & Hung, H.-C. (2009). A green supplier selection model for high-tech industry. *Expert Systems with Applications, 36*, 7917–7927.

Lin, C.-L., Hsieh, M.-S., & Tzeng, G.-H. (2010). Evaluating vehicle telematics system by using a novel MCDM techniques with dependence and feedback. *Expert Systems with Applications, 37*(10), 6723–6736.

Lin, C.-J., & Wu, W.-W. (2008). A causal analytical method for group decision-making under fuzzy environment. *Expert Systems with Applications, 34*(1), 205–213.

Lin, R.-H. (2009). An integrated FANP–MOLP for supplier evaluation and order allocation. *Applied Mathematical Modelling, 33*, 2730–2736.

Liou, J. J. H., Yen, L., & Tzeng, G.-H. (2008). Building an effective safety management system for airlines. *Journal of Air Transport Management, 14*(1), 20–26.

Liu, K. F. R., & Lai, J.-H. (2009). Decision-support for environmental impact assessment: A hybrid approach using fuzzy logic and fuzzy analytic network process. *Expert Systems with Applications, 36*, 5119–5136.

Liu, H.-T., & Wang, C.-H. (2010). An advanced quality function deployment model using fuzzy analytic network process. *Applied Mathematical Modelling, 34*(11), 3333–3351.

Lu, L. Y. Y., Wu, C. H., & Kuo, T.-C. (2007). Environmental principles applicable to green supplier evaluation by using multiobjective decision analysis. *International Journal of Production Research, 45*, 4317–4331.

Luo, Z.-M., Zhou, J.-Z., Zheng, L.-P., Mo, L., & He, Y.-Y. (2010). A TFN–ANP based approach to evaluate Virtual Research Center comprehensive performance. *Expert Systems with Applications, 37*(12), 8379–8386.

Meade, L., & Sarkis, J. (2002). A conceptual model for selecting and evaluating third-party reverse logistics providers. *Supply Chain Management: An International Journal, 7*(5), 283–295.

Mohanty, R. P., Agarwal, R., Choudhury, A. K., & Tiwari, M. K. (2005). A fuzzy ANP-based approach to R&D project selection: A case study. *International Journal of Production Research, 43*, 5199–5216.

Ozgen, D., Önüt, S., Gülsün, B., Tuzkaya, U. R., & Tuzkaya, G. (2008). A two-phase possibilistic linear programming methodology for multi-objective supplier evaluation and order allocation problems. *Information Sciences, 178*, 485–500.

Onüt, S., Kara, S. S., & Işik, E. (2009). Long term supplier selection using a combined fuzzy MCDM approach: A case study for a telecommunication company. *Expert Systems with Applications, 36*, 3887–3895.

Punniyamoorthy, M., Mathiyalagan, P., & Parthiban, P. (2011). A strategic model using structural equation modeling and fuzzy logic in supplier selection. *Expert Systems with Applications, 38*(1), 458–474.

Rao, P., & Holt, D. (2005). Do green supply chains lead to competitiveness and economic performance? *International Journal of Operations & Production Management, 25*(9), 898–916.

Ramik, J. (2007). A decision system using ANP and fuzzy inputs. *International Journal of Innovative Computing, Information and Control, 3*(4), 825–837.

Roghanian, E., Rahimi, J., & Ansari, A. (2010). Comparison of first aggregation and last aggregation in fuzzy group TOPSIS. *Applied Mathematical Modelling, 34*(12), 3754–3766.

Saaty, T. L. (1996). *The analytic network process*. Pittsburgh: RWS Publications.

Sadi-Nezhad, S., & Damghani, K. K. (2010). Application of a fuzzy TOPSIS method base on modified preference ratio and fuzzy distance measurement in assessment of traffic police centers performance. *Applied Soft Computing, 10*(4), 1028–1039.

Salehi, M., & Tavakkoli-Moghaddam, R. (2008). Project selection by using a fuzzy TOPSIS technique. *World Academy of Science, Engineering and Technology, 40*, 85–90.

Sarkis, J. (2003). A strategic decision framework for green supply chain management. *Journal of Cleaner Production, 11*(4), 397–409.

Sarkis, J., Meade, L. M., & Talluri, S. (2004). E-logistics and the natural environment. *Supply Chain Management: An International Journal, 9*(4), 303–312.

Sen, S., Başligil, H., Şen, C. G., & Baraçli, H. (2007). A framework for defining both qualitative and quantitative supplier selection criteria considering the buyer-supplier integration strategies. *International Journal of Production Research, 46*(7), 1825–1845.

Sevkli, M., Koh, S. C. L., Zaim, S., Demirbag, M., & Tatoglu, E. (2007). An application of data envelopment analytic hierarchy process for supplier selection: A case study of BEKO in Turkey. *International Journal of Production Research, 45*, 1973–2003.

Simpson, D. F., & Power, D. J. (2005). Use the supply relationship to develop lean and green suppliers. *Supply Chain Management: An International Journal, 10*, 60–68.

Srivastava, S. K. (2007). Green supply chain management: A state-of-the-art literature review. *International Journal of Management Reviews, 9*(1), 53–80.

Sun, C.-C., & Lin, G. T. R. (2009). Using fuzzy TOPSIS method for evaluating the competitive advantages of shopping websites. *Expert Systems with Applications, 36*(9), 11764–11771.

Theyel, G. (2001). Customer and supplier relations for environmental performance. *Greener Management International, 35*, 61–69.

Tsai, W.-H., & Hung, S.-J. (2009). A fuzzy goal programming approach for green supply chain optimization under activity-based costing and performance evaluation with a value-chain structure. *International Journal of Production Research, 47*(18), 4991–5017.

Tseng, M.-L. (2009a). A causal and effect decision making model of service quality expectation using grey-fuzzy DEMATEL approach. *Expert Systems with Applications, 36*, 7738–7748.

Tseng, M.-L. (2009b). Using the extension of DEMATEL to integrate hotel service quality perceptions into a cause-effect model in uncertainty. *Expert Systems with Applications, 36*, 9015–9023.

Tuzkaya, U. R., & Önüt, S. (2008). A fuzzy analytic network process based approach to transportation-mode selection between Turkey and Germany: A case study. *Information Sciences, 178*, 3133–3146.
Tuzkaya, G., Ozgen, A., Ozgen, D., & Tuzkaya, U. R. (2009). Environmental performance evaluation of suppliers: A hybrid fuzzy multi-criteria decision approach. *International Journal of Environmental Science and Technology, 6*, 477–490.
Vinodh, S., Ramiya, R. A., & Gautham, S. G. (2011). Application of fuzzy analytic network process for supplier selection in a manufacturing organisation. *Expert Systems with Applications, 38*(1), 272–280.
Vachon, S., & Klassen, R. D. (2006). Green project partnership in the supply chain: The case of the package printing industry. *Journal of Cleaner Production, 14*, 661–671.
van Hock, R. I., & Erasmus (2000). From reversed logistics to green supply chains. *Logistics Solutions, 2*, 28–33.
Walker, H., Sisto, L. D., & McBain, D. (2008). Drivers and barriers to environmental supply chain management practices: Lessons from the public and private sectors. *Journal of Purchasing & Supply Management, 14*, 69–85.
Wu, D. (2009). Supplier selection: A hybrid model using DEA, decision tree and neural network. *Expert Systems with Applications, 36*, 9105–9112.
Wu, W.-W., & Lee, Y.-T. (2007). Developing global managers' competencies using the fuzzy DEMATEL method. *Expert Systems with Applications, 32*, 499–507.
Ye, F. (2010). An extended TOPSIS method with interval-valued intuitionistic fuzzy numbers for virtual enterprise partner selection. *Expert Systems with Applications, 37*(10), 7050–7055.
Yong, D. (2006). Plant location selection based on fuzzy TOPSIS. *International Journal of Advanced Manufacturing Technology, 28*, 839–844.
Yüksel, İ., & Dağdeviren, M. (2010). Using the fuzzy analytic network process (ANP) for balanced scorecard (BSC): A case study for a manufacturing firm. *Expert Systems with Applications, 37*(2), 1270–1278.
Zadeh, L. A. (1965). Fuzzy sets. *Information & Control, 8*, 338–353.
Zhu, Q., Sarkis, J., & Lai, K.-H. (2007). Green supply chain management: pressures, practices and performance within the Chinese automobile industry. *Journal of Cleaner Production, 15*(11–12), 1041–1052.
Zhu, Q., Sarkis, J., & Lai, K.-H. (2008). Green supply chain management implications for closing the loop. *Transportation Research Part E: Logistics and Transportation Review, 44*(1), 1–18.