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Integrated fuzzy multi criteria decision making method and multi-objective programming approach for supplier selection and order allocation in a green supply chain

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ABSTRACT

An organization's environmental performance is affected by its suppliers' environmental performance, and selecting green suppliers is a strategic decision in order to be more competitive in today's global market. The supplier selection problem involves several quantitative and qualitative criteria. In the supplier selection process, if suppliers have limited capacity or other constraints, it is necessary to determine the best supplier and order quantity of each supplier. In this paper, we present an integrated approach, of fuzzy multi attribute utility theory and multi-objective programming, for rating and selecting the best green suppliers according to economic and environmental criteria and then allocating the optimum order quantities among them. At first, the fuzzy analytic hierarchy process and fuzzy technique for order preference by similarity to ideal solution is applied in order to analyze the importance of multiple criteria by incorporating experts' opinion and to determine the best green suppliers. Next, multi-objective linear programming is used to consider and to formulate various constraints such as quality control, capacity, and other objectives. The objective of the mathematical model is simultaneously to maximize the total value of purchasing and to minimize the total cost of purchasing. To handle the subjectivity of decision makers' preferences, fuzzy logic has been applied. The efficiency and application of the proposed approach has been illustrated with a case study in an automobile manufacturing company. The obtained results help firms establish a systematic approach for tackling green supplier selection and order allocation problems in a realistic situation. Finally managerial implications, conclusions, and directions for additional research are introduced.

1. Introduction

In a competitive environment, the selection of suppliers represents one of the most critical issues facing manufacturing firms. The cost of raw materials in such industries comprises the major portion of a product's final cost, and the selection of appropriate suppliers significantly reduces purchasing costs (Ghodsypour and O'Brien, 1998, 2001; Demirtas and Ustun, 2008; Amid et al., 2011).

Due to governmental legislation and an increased awareness among people of protecting the environment, firms cannot ignore environmental issues if they want to maintain their competitive advantage in this globalization trend. Growing environmental concerns means it is necessary to consider environmental pollution issues that accompany industrial development in supply chain management activities, leading to the emerging concept of green supply chain management (GSCM) (Hsu and Hu, 2009; Diabat and Kannan, 2011). In recent years, companies have implemented several regulatory checks and programs to ensure that suppliers can provide materials and services both with high quality and also dedicated to environmental standards (Awasthi et al., 2010; Kuo et al., 2010). GSCM is generally recognized as monitoring suppliers based on their environmental performance and having collaboration only with green suppliers that satisfy environmental standards (Hsu and Hu, 2009).

Essentially, two types of supplier selection are prominent. In the first type (single sourcing), one supplier can satisfy the entire buyer's needs and the buyer needs to make only one decision: which supplier is the best. In the second and more common type

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(multiple sourcing), more than one supplier must be selected because no single supplier can satisfy all the buyer's orders. Hence, companies need to select both the best suppliers and how much quantity should be allocated among them for creating a constant environment of competitiveness (Alyanak and Armaneri, 2009). Accordingly, multiple sourcing provides significant assurance of timely delivery and order flexibility due to the diversity of the firm's total orders (Ghodsypour and O'Brien, 1998; Kumar et al., 2004; Aissaoui et al., 2007; Jolai et al., 2011). There are different individual and integrated approaches for supplier selection. Ho et al. (2010) reviewed various integrated approaches for multiple sourcing suppliers and concluded that the integrated AHP–GP approach is most popular. The extensive application of the analytic hierarchy process (AHP) method is due to its simplicity, ease of use, and flexibility (Kannan and Vinay, 2008; Borade et al., 2013). Goal programming (GP) is used widely for solving multi criteria decision making (MCDM) and multi-objective decision making (MODM) problems because of its simplicity and flexibility. Goal programming can handle relatively large numbers of decision variables, resource constraints, and objectives (Jolai et al., 2011; Dubey et al., 2012). Goal programming is a branch of multi-objective optimization; it extends linear programming to deal with multiple, normally conflicting objectives (Jolai et al., 2011; Chang, 2011; Lee et al., 2009b). Chai et al. (2012) provided a systematic literature review on 123 journal articles published from 2008 to 2012 on the application of decision making (DM) techniques for supplier selection and indicated that the most frequently used technique is AHP followed by linear programming (LP) and Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS). Wu and Barnes (2011) reviews the literature on supply partner decision-making published between 2001 and 2011 and concluded that the most famous combined approaches for supplier selection problem are the models that include mathematical programming, AHP/ANP, or fuzzy set approach. Hence, this paper introduces a multi-objective programming approach to solve the multiple sourcing green suppliers' problems. At first, the fuzzy analytic hierarchy process (FAHP) and TOPSIS methods are used to assign criteria weight and to rank all alternative suppliers. In the next phase, we construct a weighted max-min fuzzy multi-objective model to determine the order quantity of each green supplier based on various constraints.

Increasingly more authors have addressed supplier selection issues in green supply chain from environmental aspects (e.g. Rao, 2005; Kannan et al., 2008; Hsu and Hu, 2009; Lee et al., 2009a; Bai and Sarkis, 2010; Awasthi et al., 2010; Kuo et al., 2010; Yeh and Chuang, 2011; Hsu et al., in press; Buyukozkan and Cifci, 2011, 2012; Tseng and Chiu, 2013; Govindan et al., 2013). Also, many researchers have applied different methods of mathematical programming (MPm) and hybrid techniques for solving supplier selection and order allocation problem (e.g. Amid et al., 2006; Yigin et al., 2007; Kokangul and Susuz, 2009; Wua et al., 2010; Amin et al., 2011; Chen, 2011; Zeydan et al., 2011). As mentioned, many studies have discussed traditional supply chain management and green supplier selection, but developing practical order allocation methods to solve multiple sourcing supplier problem in green supply chains are very limited. In this paper, we make the following contributions:

1) We develop a green supplier selection and order allocation model based on various economic and environmental criteria. To our knowledge, this paper pioneers the consideration of a green supplier selection and order allocation problem in the field of green supply chains.
2) We propose a most popular integrated FAHP and multi-objective programming approach to solve the multiple sourcing suppliers' problems.

The rest of paper is organized as follows. Section 2 provides a comprehensive literature survey of supplier selection and order allocation methods and supplier selection criteria. Section 3 introduces an integrated approach for a green supplier selection and order allocation problem including fuzzy set theory, FAHP and fuzzy TOPSIS. In Sections 4 and 5 the proposed method is illustrated with a case study in an automobile manufacturing company, and a sensitivity analysis of results is presented. Finally, Sections 6 and 7 present managerial implications, concluding remarks, limitations, and future works.

2. Literature review

2.1. Supplier selection and order allocation methods

Supplier selection is a MCDM problem containing both quantitative and qualitative criteria which, together, are in conflict. Over the last few years, many researchers have worked on the supplier selection problem to develop suitable decision making methods which can deal with the problem effectively (Zeydan et al., 2011). Some recent works include Amin et al. (2011), Feng et al. (2011), and Zouggari and Benyoucef (2012).

Regarding the analytical methods employed in the supplier selection process, De Boer et al. (2001) and Ha and Krishnan (2008) performed an extensive review of decision methods for supporting supplier selection. Ho et al. (2010) reviewed the literature of the MCDM approaches for supplier evaluation and selection. In a supplier selection process, one model can be combined with other techniques in order to improve the quality of the tools (Ha and Krishnan, 2008; Chen, 2011). Chen (2011) summarized supplier selection methods into two clusters of single model and combined models as illustrated in Fig. 1. Extensive single model approaches have been proposed for supplier selection, such as the AHP (Haq and Kannan, 2006a; Marufuzzaman et al., 2009), analytic network process (ANP) (Gencer and Gurpinar, 2007), interpretive structural modeling (ISM) (Kannan and Haq, 2007; Kannan et al., 2010; Govindan et al., 2012a; Govindan et al., 2012b; Mathiyazhagan et al., 2013) case-based reasoning (CBR) (Choy et al., 2003a,b), data envelopment analysis (DEA) (Wu et al., 2007), genetic algorithm (GA) (Ding et al., 2005), neural networks (Choy et al., 2003c), Fuzzy TOPSIS (Kannan et al., 2009b), Fuzzy extent analysis (Kannan and Murugesan, 2011) and mathematical programming (MPm) and their hybrids. In multiple sourcing, many researchers have applied different methods of MP such as linear programming (LP) (Ng, 2008), mixed integer LP (Hong et al., 2005), multi-objective programming (MOP) (Rezaei and Davoodi, 2011), and goal programming (GP) (Lee et al., 2009b; Jolai et al., 2011). A MPm model formulates the decision problem in terms of a mathematical objective function that needs to be maximized or minimized by varying the values of variables in the objective function (Hong et al., 2005). In his review work, Ho et al. (2010) mentioned that there are several hybrid techniques that have been used for solving supplier selection in multiple sourcing environments and order allocation, such as AHP and LP (Ghodsypour and O'Brien, 1998), DEA and MOP (Talluri et al., 2008), AHP and GP (Kull and Talluri, 2008; Mafakheri et al., 2011), AHP, DEA, and neural networks (Ha and Krishnan, 2008), AHP and grey relational analysis (Haq and Kannan, 2006b) and ANP and GP (Demirtas and Ustun, 2009) and ISM and TOPSIS (Kannan et al., 2009a). Many authors have proposed several types of MOP approaches for the supplier selection and order allocation problem, including Ghodsypour and O'Brien (2001); Narasimhan et al. (2006); Wadhwa and Ravindran (2007); Demirtas and Ustun (2008); Kannan et al., 2009c; Amid et al. (2011); Jolai et al. (2011); Amin et al. (2011); and Liao and Kao (2011). Amin and Zhang (2012) have summarized the models

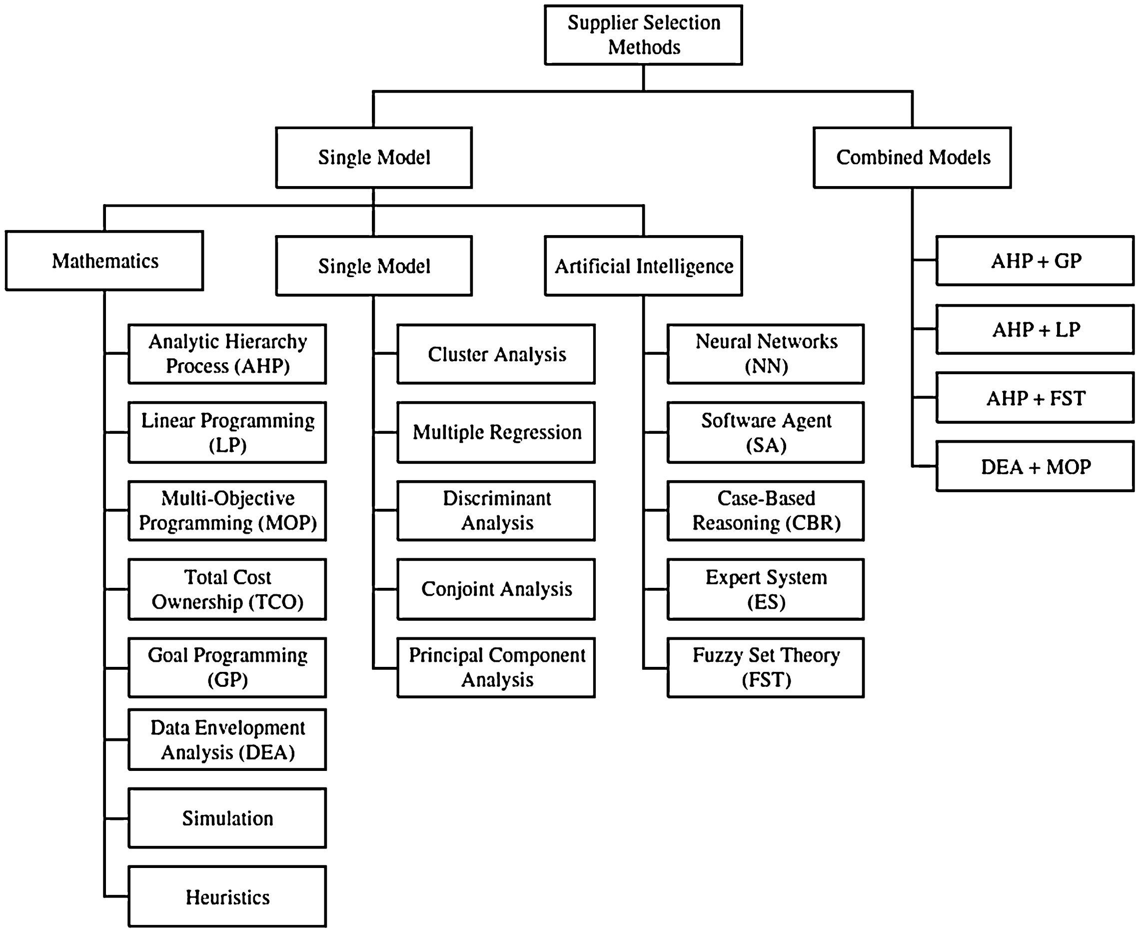

Fig. 1. Existing analytical methods for supplier selection Adopted from Chen (2011).

used for a supplier selection and order allocation problem currently available in literature.

2.2. Supplier selection criteria

2.2.1. Economic supplier selection criteria

Establishing the criteria for supplier selection and evaluation has been a popular area of research since the 1960s. If we look into the history of popular criterion identified in the literature, we can conclude three primary categories of emphasis: in the late 1970s and early 1980s, cost was the main focus; then in the early 1990s, cycle time and customer responsiveness were considered, and, finally, in the late 1990s, the focus shifted to flexibility. Now, environmental factors are a key issue which gives rise to the new paradigm of focusing on green supply chains (Huang and Keskar, 2007).

A number of literature surveys have been made to summarize the criteria and decision methods involved in papers starting from the mid-1960s (e.g. Weber et al., 1991, 1993; Ghodsypour and O'Brien, 1998; De Boer et al., 2001; Aissaoui et al., 2007; Wu and Olson, 2008; Lee, 2009; Ho et al., 2010; Liao and Kao, 2011; Chen, 2011). Various researchers have done thorough studies to identify important criteria for the vendor selection problem, and their findings are summarized here. According to Dickson (1966), the important criteria are quality, delivery, and performance history; Weber et al. (1991, 1993) identified the most important criteria as price, delivery, quality, facilities and capacity, geographic location, and technology capability; and, based on the literature review conducted by Ho et al. (2010), the most popular criterion is quality, followed by delivery, price/cost, manufacturing capability, service, management, and technology. In addition to the above literature, Chang et al., 2011 and Liao and Kao (2011) have summarized economic criteria that have appeared in previous articles and have concluded the most important criteria are quality, price, and delivery performance.

2.2.2. Green supplier selection criteria

The GSCM literature has focused on encouraging existing suppliers to improve their environmental performance by requiring these suppliers to acquire certifications or to introduce green practices. Supplier selection in GSCM has been identified as significant in making purchasing decisions (Seuring and Muller, 2008). In order to meet the environmental regulations, many scholars have studied the indicators of green supplier evaluation. For example, Noci (1997) applied an AHP model to design a green supplier rating system. Sarkis (1998) categorized environmentally conscious business practices into five major components: design for environment (Green design), life cycle analysis, total quality environmental management, green supply chain and environment related certificates such as ISO 14000. Handfield et al. (2002) utilized the Delphi method to collect environmental experts' opinions from different companies and proposed an environmentally conscious purchasing decision based on AHP. Sarkis (2003) utilized ANP to develop a six-dimension strategic decision framework for GSCM. Hsu and Hu (2009) presented new criteria of supplier selection to hazardous substance management including green purchasing, green materials coding and recording, capability of green design, inventory of hazardous substances, management for hazardous substances, legal-compliance competency, and environmental management systems. Lee et al. (2009a) proposed quality, technology capability, pollution control, environment management, green products and green competencies for green supplier selection in the high-tech industry. Awasthi et al. (2010) presented a fuzzy multi criteria approach for evaluating environmental performance of suppliers and mentioned that availability of clean materials, environmental efficiency, green image, environmental costs, green products, environmental and legislative management, and green process management are the most commonly referred criteria in green supplier evaluation literature. Bai and Sarkis (2010) used grey system and rough set methodologies to integrate sustainability into supplier selection and summarized environmental metrics as pollution controls, pollution prevention, environmental management system, resource consumption, and pollution production. Yeh and Chuang (2011) developed two multi-objective genetic algorithms for green partner selection, which involved four objectives such as cost, time, product quality, and a green appraisal score. They offer green image, product recycling, green design, green supply chain management, pollution treatment cost, and environment performance assessment criteria for green supplier selection. Govindan et al. (2013) proposed a fuzzy multi criteria approach for measuring sustainability of a supplier and considered pollution production, resource consumption, eco-design and environmental management system as environmental criteria.

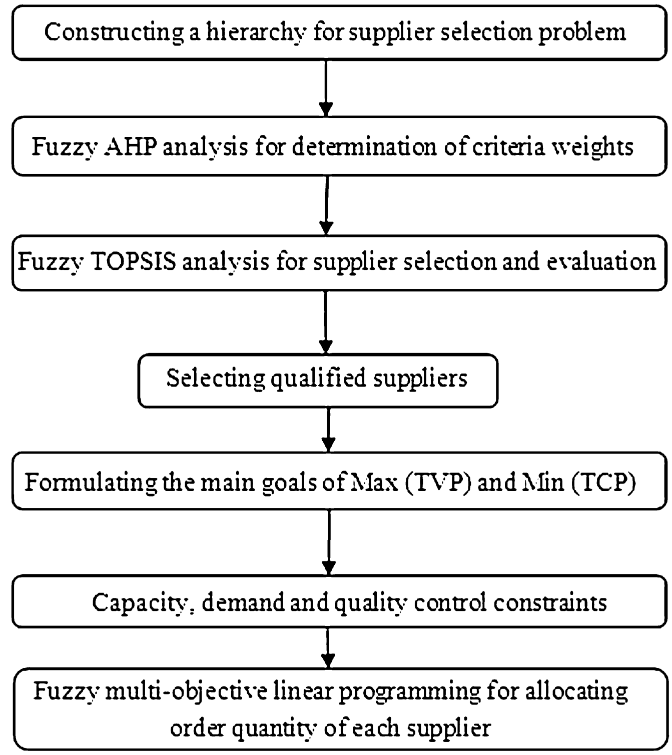

Fig. 2. A solution procedure for supplier selection and order allocation problem.

3. The proposed integrated approach for green supplier evaluation

This study integrates fuzzy AHP, fuzzy TOPSIS, and fuzzy MOLP to solve the problem of supplier selection and order allocation. At first we used fuzzy AHP to calculate the relative weights of supplier selection criteria; then, we used fuzzy TOPSIS for ranking of suppliers according to the selected criteria. Finally, the weights of the criteria and ranks of suppliers were incorporated into the MOLP model to determine the optimal order quantity from each supplier while being subjected to some resource constraints. The main steps in the solution procedure are presented in Fig. 2, and the detailed descriptions are depicted as follows.

3.1. Fuzzy set theory in MCDM

Under many conditions, exact data is inadequate for modeling real-life situations because human judgments and preferences are often subjective, uncertain and ambiguous, and cannot be estimated with exact numerical values (Mehrjerdi, 2012). Fuzzy set theory was conceived by Zadeh (1965, 1976) to resolve the vagueness and ambiguity of human cognition and judgment; it is a way of processing data by providing mathematical strengths to resolve such uncertainties associated with human thinking and reasoning and allowing partial set membership rather than crisp set membership. Fuzzy MCDM theory can strengthen the comprehensiveness and reasonableness of the decision-making process (Chen, 2000; Chen et al., 2006). Bellman and Zadeh (1970) presented some applications of fuzzy theories to the various decision making processes in a fuzzy environment, and introduced the fuzzy MCDM methodology.

Triangular fuzzy numbers are used in this paper to assess the preferences because it is easy for the DMs to use and calculate. A triangular fuzzy number is defined as (a, b, c) where $a \le b \le c$. The parameters a, b, and c represent the smallest possible value, the most promising value, and the largest possible value, respectively. Let X is a set of items, known as the universe, and its elements are denoted by x. A fuzzy subset A in X is represented by a membership function $f_A(x)$ and is associated with each element x in A and a real number between 0 and 1. A fuzzy set is defined by its membership function as following and is shown in Fig. 3.The basic definitions of fuzzy method were introduced in Zadeh (1965, 1976) and Zimmermann (2001).

$$f_A(x) = \begin{cases} 0 & x < a, x > c \\ \dfrac{x-a}{b-a} & a \le x \le b \\ \dfrac{c-x}{c-b} & b \le x \le c \end{cases} \tag{1}$$

3.2. FAHP methodology for determining criteria weights

AHP was first developed by Saaty (1980) who mainly conducts a MCDM problem by examining the pair-wise comparison of decision criteria. The hierarchical structure of the AHP model can enable users to imagine the problem in terms of criteria and sub-criteria. However, the DMs may feel uncertain of the pair-wise comparison. Therefore, FAHP was developed to help DMs solve the vague nature of alternative selection problems (Ku et al., 2010).

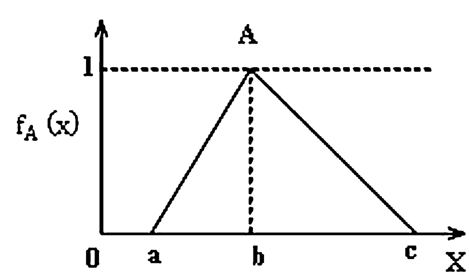

Fig. 3. Membership function of triangular fuzzy number *A*.

This paper utilizes the five step FAHP method (Chang (1996) to determine the criterion weight for the supplier selection problem. The steps are described below.

1. Identify DMs' supplier selection criteria and model the problem as a hierarchy containing the decision goal.
2. Perform pair-wise comparison about the relative importance of the supplier selection criteria by using a geometric mean method to integrate the opinions of DMs as follows:

$$R = (a,b,c), k = 1,2,\ldots,K(\text{R} : \text{triangular fuzzy number and K : no. of DMs}) \quad (2)$$

Where $a = (a_1 \times a_2 \times \ldots \times a_k)^{1/k}$, $b = (b_1 \times b_2 \times \ldots \times b_k)^{1/k}$, $c = (c_1 \times c_2 \times \ldots \times c_k)^{1/k}$

3. Aggregate all the DMs matrix of pair-wise comparisons and synthesize these judgments to yield a set of overall priorities for the hierarchy.
4. To make sure that the DMs do not make mistakes which may cause conflicting ratings, a final consistency of the judgments is calculated. If the consistency ratio (CR) is less than 0.1, the judgment is true for criteria weights.
5. Transform pair-wise comparison matrix of criteria weights into linguistic variables using Table 1. Calculate priority weights of each criterion using Chang (1996) method. The basic concept of FAHP for finding triangular fuzzy number weights is presented as follows:

1 let $X = \{x_1, x_2, x_3, \ldots, x_n\}$ an object set, and $G = \{g_1, g_2, g_3, \ldots, g_n\}$ be a goal set and $M_{g\,i}^{j}(i = 1,2,\ldots,n,\ j = 1,2,\ldots,m)$ all are triangular fuzzy numbers. The value of fuzzy synthetic extent of the ith object for m goals is defined as:

$$S_i = \sum_{j=1}^{m} M_{g\,i}^{j} \otimes \left[\sum_{i=1}^{n}\sum_{j=1}^{m} M_{g\,i}^{j}\right]^{-1} = \left(\frac{1}{\sum_{i=1}^{n} u_i}, \frac{1}{\sum_{i=1}^{n} m_i}, \frac{1}{\sum_{i=1}^{n} l_i}\right) \quad (3)$$

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

$$V(M_1 \geq M_2) = \sup_{x \geq y}[\min(\mu M_1(x), \mu M_2(y))) \quad (4)$$

Table 1
Linguistic variables for pair-wise comparisons of each criterion.

Linguistic variable	Fuzzy numbers
Extremely strong	(9,9,9)
Intermediate	(7,8,9)
Very strong	(6,7,8)
Intermediate	(5,6,7)
Strong	(4,5,6)
Intermediate	(3,4,5)
Moderately strong	(2,3,4)
Intermediate	(1,2,3)
Equally strong	(1,1,1)

$$V(M_1 \geq M_2) = \begin{cases} 1 & \text{if } m_2 \geq m_1 \\ 0 & \text{if } l_1 \geq u_2 \\ \dfrac{l_1 - u_1}{(m_2 - u_2) - (m_1 - u_1)} & \text{otherwise} \end{cases} \quad (5)$$

3 The degree of 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 $(M_1, M_2, \ldots M_K) = \min$ V $(M \geq M_i)$, $i = 1,2,\ldots,k$. can be defined by:

$$\text{d}(A_i) = \min\ V(S_i \geq S_k),\ \ k = 1,2,\ldots,n;\ \ k \neq I \quad (6)$$

4. The weight vector is given by:

$$W = (d(A_1),(A_2),\ldots d(A_n))^T, A_i(i = 1,2,\ldots,n)\text{are } n \text{ elements} \quad (7)$$

5. The normalized weight vector is calculated as:

$$NW_i = \frac{W_i}{\sum W_i} \quad (8)$$

3.3. The fuzzy TOPSIS method for ranking suppliers

TOPSIS, one of the classical methods for solving MCDM problem, was originally proposed by Hwang and Yoon (1981). A more detailed description about the TOPSIS can be found in Shih et al. (2007). TOPSIS has a simple computation process, systematic procedure, and a sound logic that represents the rationale of human choice. It includes an unlimited range of criteria and performance attributes and allows explicit trade-offs between attributes. Also pair-wise comparisons, required by methods such as the AHP, are avoided (Shih et al., 2007; Wang and Chang, 2007; Govindan et al., 2012). The TOPSIS method considers the distances to both the PIS and the NIS at the same time by defining "relative closeness to ideal solution". Finally, the ideal solution closest to the PIS and farthest to the NIS is obtained.

The TOPSIS solution method consists of the following steps: (Hwang and Yoon, 1981; Chen et al., 2006):

Step 1: The normalized fuzzy-decision matrix can be represented as:

$$\text{R} = [r_{ij}]_{m*n}$$

Where B and C are the sets of benefit and cost criteria, respectively, and

$$r_{ij} = \left(\frac{a_{ij}}{c_j^*}, \frac{b_{ij}}{c_j^*}, \frac{c_{ij}}{c_j^*}\right), j \in B \quad (9)$$

$$c_j^* = \max_i\ c_{ij}, j \in B$$

$$r_{ij} = \left(\frac{a_j^-}{c_{ij}}, \frac{a_j^-}{b_{ij}}, \frac{a_j^-}{a_{ij}}\right), j \in C$$
$$a_j^- = \min_i \; a_{ij}, j \in C \tag{10}$$

Step 2: Weighted normalized decision matrix v_{ij} is calculated by multiplying normalized matrix with the weights of the criteria.

$$\mathrm{V} = [v_{ij}]_{m*n} \quad i = 1,2,\ldots,m \quad j = 1,2,\ldots,n \tag{11}$$

Where $v_{ij} = r_{ij} \cdot w_j$ and w_j is the weight of the jth attribute or criterion.

Step 3: The positive-ideal solution (PIS, A^*) and negative-ideal solution (NIS, A^-) can be calculated as:

$$A^* = \left(v_1^*, v_2^*, \ldots, v_n^*\right) \tag{12}$$

$$A^- = \left(v_1^-, v_2^-, \ldots, v_n^-\right) \tag{13}$$

Where $v_j^* = \max_i\{v_{ij\,3}\}$ and $v_j^- = \min_i\{v_{ij\,1}\}$, $i = 1,2,\ldots,m$, $j = 1,2,\ldots,n$

Step 4: The distance of each alternative from PIS and NIS is calculated as:

$$d_i^* = \sum_{j=1}^{n} d_v\left(v_{ij}, v_j^*\right), i = 1,2,\ldots,m \tag{14}$$

$$d_i^- = \sum_{j=1}^{n} d_v\left(v_{ij}, v_j^-\right), i = 1,2,\ldots,m \tag{15}$$

Step 5: The closeness coefficient (CC_i) of each alternative is calculated as:

$$CC_i = \frac{d_i}{d_i^- + d_i^*}, i = 1,2,\ldots,m \tag{16}$$

Step 6: At the end of the analysis, the ranking of alternatives is determined by comparing CC_i values.

Alternative A_i is closer to the FPIS (A^*) and farther from FNIS (A^-) as CC_i approaches to 1. The ranking order of all alternatives determines according to the descending order of CC_i.

3.4. The proposed fuzzy MOLP model for order allocation

In this section, a fuzzy MOLP model is proposed for a supplier's order allocation. The objective function of MOLP includes a set of goals that should be compromised at the same time. Developing an optimal solution for MOLP is difficult. Generally, MOLP models have the advantage of being easy and offering the possibility of fast formulation of problems with different sizes. The aim of MOLP approaches is to find the most preferred solution among the most efficient points (Wang and Yang, 2009).

However, this paper proposes a fuzzy MOLP model for the supplier selection problem with multiple sourcing that includes two goals: not only minimizing total cost of purchasing (TCP) and maximizing total value of purchasing (TVP), but also including a set of system constraints such as buyer's demand, suppliers' capacities, quality control, and delivery lead time. The following assumptions are used in formulating the MOLP model:

Assumptions:

(i) Only one item is purchased from one supplier.
(ii) Quantity discounts are not taken into consideration.
(iii) No shortage of the item is allowed for any supplier.
(iv) Demand for the item is constant and known with certainty.

In order to formulate this model the following notations are defined:

Parameters:
N = the number of suppliers
D = Demand for the planning period
X_i = Order quantity from the ith supplier
C_i = Capacity of the ith supplier
W_i = the overall weight (priority value) of the ith supplier (obtained from the fuzzy TOPSIS model)
P_i = Unit purchasing price from the ith supplier
O_i = Unit ordering cost from the ith supplier
T_i = Unit transportation cost from the ith supplier
Q = Maximum acceptable defect ratio (percent)
q_i = Average defect percent from the ith supplier
$Y_i = 0$ if $X_i = 0$&$Y_i = 1$ if $X_i \geq 0$

Objective functions:

Total cost of purchasing: The total costs of purchasing considered in the MOLP model including product price, ordering, and transportation and holding costs. The objective function can be formed as follows:

$$\mathrm{Min(TCP)} = \sum_{i=1}^{N} P_i{*}X_i + Q_i{*}\sum_{i=1}^{N} Y_i + \sum_{i=1}^{N} T_i{*}X_i + \mathrm{H}\sum_{i=1}^{N} P_i{*}(X_i/2) \tag{17}$$

Total value of purchasing: we used the supplier's weights as coefficients of an objective function to allocate order quantities among the suppliers such that the total value of purchasing (TVP) becomes a maximum. The mathematical model is as follows:

$$\mathrm{Max(TVP)} = \sum_{i=1}^{N} W_i{*}X_i \tag{18}$$

Constraints:

Quality control – the total defect quantity of each item cannot exceed maximum total acceptable defect quantity:

$$\sum_{i=1}^{N} q_i{*}X_i \leq Q{*}D \tag{19}$$

Production demand – the total order quantity of each item from all suppliers must meet the demand quantity for the item:

$$\sum_{i=1}^{N} X_i \geq D \tag{20}$$

Suppliers' capacity – the order quantity of each item from the ith supplier cannot exceed each supplier's capacity:

$$X_i \leq C_i \tag{21}$$

Variable non-negativity constraints – the final constraints are non-negativity restrictions on the decision variables:

$$X_i \geq 0, X_i \text{ integers}, \quad i = 1,2,\ldots,N \tag{22}$$

The above MOLP model can be converted into a single objective model by using a maxi-min formulation as proposed by (Amid et al., 2006, 2011):

In many real situations, all objectives may not be achieved simultaneously under system constraints. The DM may define a tolerance limit and membership function $\mu\,(Z_j(x))$ for the jth fuzzy goals (Amid et al., 2011).

Zimmermann (1978) expressed objective functions Z_j, $j = 1,2,\ldots,u$ by fuzzy sets whose membership functions increase linearly from 0 to 1. In this approach, the membership function of objectives is formulated by separating each objective function into its maximum and minimum limits. The linear membership functions for minimization (Z_k) and maximization goals (Z_l) are given as following:

$$\mu_{z_k}(x) = \begin{cases} 1 & Z_k \geq z_k^- \\ 0 & Z_k \geq z_k^+ \\ f_{\mu z_k} = \dfrac{z_k^+ - z_k(x)}{z_k^+ - z_k^-} & z_k^- \leq Z_k(x) \leq z_k^+ \end{cases} \quad (23)$$

$$\mu_{z_l}(x) = \begin{cases} 1 & Z_l \geq z_l^+ \\ 0 & Z_l \geq z_l^- \\ f_{\mu_{z_l}} = \dfrac{z_l(x) - z_l^-}{z_l^+ - z_l^-} & z_l^- \leq Z_l(x) \leq z_l^+ \end{cases} \quad (24)$$

Where Z_l^+ and Z_k^- are the ideal solutions of the model which can be obtained by solving each of the single objective linear programming problems separately. Z_k^+ is the non-ideal solution (maximum value) of negative objective, and Z_l^- is the non-ideal solution (minimum value) of positive objective function.

Based on Lin's (2004) weighted max-min model, this problem is formulated as follows (Amid et al., 2011): The DMs provide the weight of objective functions.

$$\text{Max } \lambda \quad (25)$$

Subject to:

$$W_j\lambda \leq f_{\mu_{Z_j}(x)},\ J = 1,2,\ldots,u(\text{for all objective function}) \quad (26)$$

$$g_r(x) \leq \mathrm{b_r}(\text{for all problem's constraints}) \quad (27)$$

$$\lambda\in[0,1] \quad (28)$$

$$\sum\nolimits_{j=1}^{u} W_j = 1, W_j \geq 0 \quad (29)$$

$$Xi \geq 0, i = 1,2,\ldots,N \quad (30)$$

The weighted max-min model for multi-objective programming problem is formulated and solved according to Eq. (25)–(30) to obtain the optimal value of TVP and TCP and the optimal order quantities. The next section presents a case study to evaluate the application of the proposed model.

4. A case study

Globalization brings both opportunities and drivers for Iranian industries to improve their environmental performance through GSCM practices such as establishing stricter environmental regulations, promoting cleaner production, encouraging ISO 14000 certification, and improving the working relationship both upstream with suppliers and downstream with customers. As Iran plans to seek entry into the WTO, the automobile manufacturing sector will be one of the most affected industries. Working as suppliers to foreign companies and exporting products are the main drivers for Iranian automobile manufacturers to improve their environmental management practices, not only internally, but also with their suppliers. Strategic partnerships with environmentally and economically powerful suppliers should be integrated within the green supply chain to further improve the environmental and economic performance.

The Iranian automobile manufacturing company was established in 1966. This company planned for production of 760 thousand cars (including passenger cars, pick-ups, 4WDs, light and heavy vehicles, minibuses and buses) in 2011. This company has increased its market share and gained about 50 percent of Iran's passenger car market share during recent years. The company is implementing ISO 14000 principles in its supply chain and encourages suppliers to improve their environmental practices and performance. Hence, a case study of Iranian automobile manufacturing company is illustrated for considering the validity of the proposed integrated model. The suppliers of this case study provide a specific product which is used as a trim part of the automobile. The mentioned product has three suppliers which are named, for our purposes, as A1, A2, and A3.

The supplier selection criteria have already been discussed in Section 2.2. A detailed literature search with the concepts related to supplier selection criteria and discussion with a team of experts who have rich knowledge and experience in supply chain and environmental management was used to propose the criteria. Finally, five criteria have been determined by experts, and three possible suppliers (A1, A2, A3) thought to have green competencies are engaged for supplier selection and order allocation decision making. The definition of criteria is presented in Table 2. A survey was conducted through the distribution of a questionnaire among the automobile manufacturing company's experts to determine the

Table 2
The supplier selection criteria definition.

Criterion	Sub criteria	Definition
Cost (C1)	1.Product cost	The production cost that determines the final price of the product includes the processing cost, maintenance cost, and warranty cost
	2.Logistics cost	Sum of unit variable and allocated fixed transportation costs
	3.Quantity discount	Suppliers offer discount based on purchase quantity
Quality (C2)	1.Quality assurance	The attainment of quality assurance such as certificates
	2.Rejection ratio	Number of rejected incoming material detected by quality control
Delivery (C3)	1.Lead time	Time between placement and arrival of an order
	2.Order fulfillment rate	Compliance with the predetermined order quantities
Technology Capability (C4)	1.Technology level	Technology development of the supplier to meet current and future demand of the firm
	2.Capability of R&D	Capability of R&D of the supplier to meet current and future demand of the firm
	3.Capability of design	Capability of new product design of the supplier to meet current and future demand of the firm
Environmental competency (C5)	1.Pollution production	Average volume of air emission pollutant, waste water, solid wastes and harmful materials releases per day during measurement period
	2.Resource consumption	Resource consumption in terms of raw material, energy and water during the measurement period
	3.Environmental management system	Environmental certifications like ISO 14000, environmental policies, planning, checking and control of environmental activities
	4.Eco-design	Design of products for reduced consumption of material/Energy, design of products for reuse, recycle, recovery of material

Sources: Lee et al., 2009a; Bai and Sarkis, 2010; Buyukozkan and Cifci, 2011, 2012; Erol et al., 2011; Yeh and Chuang, 2011; Govindan et al., 2013.

importance weights of the criteria and ratings of suppliers. Decision makers are three experts from the purchasing department, environmental department, and production department who contribute to the decision-making process. Respondents were asked to use nine-scale preferences (from extremely strong to equally strong) for pair-wise comparisons of the relative importance of the supplier selection criteria and use a seven-point Likert-type scale (very poor, poor, medium poor, medium, medium good, good, very good) to express their opinions independently on the ratings of each supplier with respect to the five criteria. The relative importance of each pair of elements and the preferences of the DMs in the same hierarchy are calculated by using triangular fuzzy numbers.

The hierarchical structure of this decision problem is shown in Fig. 4. The decision problem consists of three levels: at the highest level, the objective of the problem is situated while in the second and third levels, the supplier selection criteria and the potential suppliers are listed respectively. The C1 and C3 are the cost criteria and the others are the benefit criteria. Steps of the proposed approach are applied as follows:

4.1. FAHP methodology for determining criteria weights

The DMs use the linguistic weighting variables (shown in Tables 3–5) to assess the importance of the criteria. The aggregated fuzzy pair-wise comparison matrix of criteria by using a geometric mean method is presented in Table 6.

The consistency property of each expert's comparison results is examined by calculating the *CR*. From *CR* = 0.05, 0.02, 0.06 respectively for DMs1, 2, 3 it shows that the judgment matrix processes consistency. The values of fuzzy synthetic extents with respect to the criteria weights are calculated as below (see Eq. (3)):

$$S_1 = (11.71,\ 14.89,\ 18.27) \times (1/56.91,\ 1/45.72,\ 1/35.23) = (0.206,\ 0.326,\ 0.519)$$

$$S_2 = (12.43,\ 16.10,\ 19.63) \times (1/56.91,\ 1/45.72,\ 1/35.23) = (0.218,\ 0.352,\ 0.557)$$

$$S_3 = (6.38,\ 8.58,\ 10.93) \times (1/56.91,\ 1/45.72,\ 1/35.23) = (0.112,\ 0.188,\ 0.310)$$

$$S_4 = (2.91,\ 4.13,\ 5.53) \times (1/56.91,\ 1/45.72,\ 1/35.23) = (0.051,\ 0.090,\ 0.157)$$

Table 3
The fuzzy pair-wise comparison matrix of criteria (DM1).

	C1	C2	C3	C4	C5
C1	(1,1,1)	(1/3,1/2,1)	(3,4,5)	(4,5,6)	(5,6,7)
C2	(1,2,3)	(1,1,1)	(2,3,4)	(3,4,5)	(6,7,8)
C3	(1/5,1/4,1/3)	(1/4,1/3,1/2)	(1,1,1)	(2,3,4)	(3,4,5)
C4	(1/6,1/5,1/4)	(1/5,1/4,1/3)	(1/4,1/3,1/2)	(1,1,1)	(1,2,3)
C5	(1/8,1/7,1/6)	(1/7,1/6,1/5)	(1/5,1/4,1/3)	(1/3,1/2,1)	(1,1,1)

$$S_5 = (1.79,\ 2.03,\ 2.54) \times (1/56.91,\ 1/45.72,\ 1/35.23) = (0.032,\ 0.044,\ 0.072)$$

The final FAHP importance criteria weights are calculated as below:

$$W_1 = (0.206,\ 0.326,\ 0.519)$$

$$W_2 = (0.218,\ 0.352,\ 0.557)$$

$$W_3 = (0.112,\ 0.188,\ 0.310)$$

$$W_4 = (0.051,\ 0.090,\ 0.157)$$

$$W_5 = (0.032,\ 0.044,\ 0.072)$$

4.2. Using fuzzy TOPSIS for evaluating suppliers

The linguistic variables for rating of criteria are defined in Table 7. The three DMs express their opinions on the ratings of each supplier with respect to the five criteria independently. Table 8 shows the original assessment information provided by the three DMs. The fuzzy decision matrix and fuzzy weights of criteria, normalized fuzzy decision matrix, weighted normalized fuzzy decision matrix, the distance of each supplier from FPIS and FNIS with respect to each criterion and the closeness coefficient of each supplier are shown respectively, in Tables 9–13. All the calculations were done by using Ms Excel.

4.3. Fuzzy MOLP model for order allocation

In this step we set the parameter values that are used in the LP model. The crisp formulation of the numerical example by using a maxi-min formulation is presented as follows:

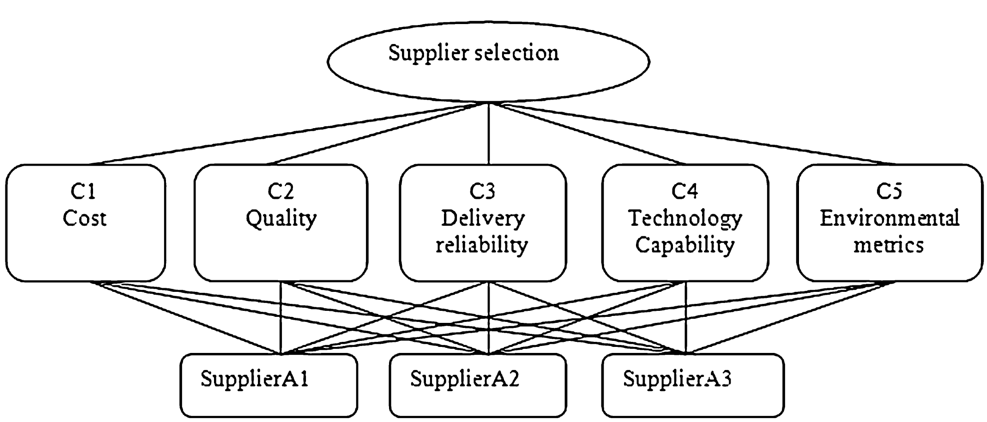

Fig. 4. Hierarchical structure of decision problem.

Table 4
The fuzzy pair-wise comparison matrix of criteria (DM2).

	C1	C2	C3	C4	C5
C1	(1,1,1)	(1,1,1)	(2,3,4)	(3,4,5)	(5,6,7)
C2	(1,1,1)	(1,1,1)	(1,2,3)	(3,4,5)	(5,6,7)
C3	(1/4,1/3,1/2)	(1/3,1/2,1)	(1,1,1)	(1,2,3)	(3,4,5)
C4	(1/5,1/4,1/3)	(1/5,1/4,1/3)	(1/3,1/2,1)	(1,1,1)	(2,3,4)
C5	(1/7,1/6,1/5)	(1/6,1/5,1/4)	(1/5,1/4,1/3)	(1/4,1/3,1/2)	(1,1,1)

Table 5
The fuzzy pair-wise comparison matrix of criteria (DM3).

	C1	C2	C3	C4	C5
C1	(1,1,1)	(1/3,1/2,1)	(2,3,4)	(3,4,5)	(4,5,6)
C2	(1,2,3)	(1,1,1)	(3,4,5)	(4,5,6)	(5,6,7)
C3	(1/4,1/3,1/2)	(1/5,1/4,1/3)	(1,1,1)	(2,3,4)	(4,5,6)
C4	(1/5,1/4,1/3)	(1/6,1/5,1/4)	(1/4,1/3,1/2)	(1,1,1)	(1,2,3)
C5	(1/6,1/5,1/4)	(1/7,1/6,1/5)	(1/5,1/4,1/3)	(1/3,1/2,1)	(1,1,1)

Objective function:

$$\mathrm{Min(TCP)} = \sum_{i=1}^{3} P^{*}X_i + 12^{*}\sum_{i=1}^{3} Y_i + \sum_{i=1}^{3} T_i^{*}\mathrm{X_i} + 0.03^{*}\sum_{i=1}^{3} P_i^{*}(X_i/2)$$

$$\mathrm{Min(TCP)} = 14.18\mathrm{X}_1 + 14.695\mathrm{X}_2 + 12.165\mathrm{X}_3 + 36$$

$$\mathrm{Max(TVP)} = \sum_{i=1}^{N} W_i^{*}X_i = 0.338X_1 + 0.359X_2 + 0.303X_3$$

Subjected to:

$$X_1 + X_2 + X_3 = 1200$$

$$X_1 \le 500, X_2 \le 600, X_3 \le 700$$

$$4.5\,X_1 + 3.5\,X_2 + 3.5\,X_3 \le 4500$$

$$X_i \ge 0, \mathrm{i} = 1,2,3$$

where, unit holding cost for planning period (H) is 3% of unit price, the order/setup cost is 12 $ for each order and maximum acceptable defect ratio (Q) is 0.00375. The unit price (P_i), supplier's capacity, unit transportation cost (T_i), and average defect percent from each supplier are given in Table 14. The demand is predicted to be about 1200. Based on the weighted max-min models (25)–(30), the crisp single objective formulation is as follows: Max λ

Subject to:

Table 7
Linguistic variable for rating of criteria.

Linguistic variable	Fuzzy numbers
Very poor (VP)	(0,0,1)
Poor (P)	(0,1,3)
Medium poor (MP)	(1,3,5)
Medium (M)	(3,5,7)
Medium good (MG)	(5,7,9)
Good (G)	(7,9,10)
Very good (VG)	(9,10,10)

Table 8
Ratings of the supplier by DMs under various criteria linguistic variable for rating of criteria.

Criterion	Suppliers	DMs		
		D1	D2	D3
C1	A1	G	MG	G
	A2	MG	G	MG
	A3	G	VG	G
C2	A1	G	G	VG
	A2	MG	G	G
	A3	G	MG	G
C3	A1	G	G	G
	A2	G	MG	MG
	A3	VG	G	VG
C4	A1	MG	G	MG
	A2	G	VG	MG
	A3	VG	G	G
C5	A1	MG	M	M
	A2	MG	G	G
	A3	M	G	M

$$0.5\lambda \le (17159.5 - (14.18\,X_1 + 14.695\,X_2 + 12.165\,X_3 + 36) \times)/1518$$

$$0.5\lambda \le (0.338\,X_1 + 0.359\,X_2 + 0.303\,X_3) - 381.1))/33.6$$

$$X_1 + X_2 + X_3 = 1200$$

$$X_1 \le 500, X_2 \le 600, X_3 \le 700$$

$$4.5\,X_1 + 3.5\,X_2 + 3.5\,X_3 \le 4500$$

$$X_i \ge 0, i = 1,2,3$$

$$0 \le \lambda \le 1$$

At first we solved the multi-objective problem as two separate single objective problems and found the lower and upper limits of solution for each objective. The obtained values are the ideal solutions (minimum values) and the non-ideal solutions (maximum values) of the model for any objective separately. The membership function is calculated using Eqs. (23) and (24). The data set for the

Table 6
The aggregated fuzzy pair-wise comparison matrix of criteria (for all DMs).

	C1	C2	C3	C4	C5
C1	(1,1,1)	(0.48,0.63,1)	(2.29,3.3,4.31)	(3.3,4.31,5.31)	(4.64,5.65,6.65)
C2	(1,1.59,2.08)	(1,1,1)	(1.82,2.88,3.91)	(3.3,4.31,5.31)	(5.31,6.32,7.32)
C3	(0.23,0.3,0.44)	(0.25,0.35,0.548)	(1,1,1)	(1.59,2.62,3.63)	(3.3,4.31,5.31)
C4	(0.19,0.23,0.3)	(0.19,0.23,0.301)	(0.27,0.38,0.63)	(1,1,1)	(1.26,2.29,3.3)
C5	(0.14,0.17,0.2)	(0.15,0.18,0.215)	(0.2,0.25,0.33)	(0.3,0.44,0.79)	(1,1,1)

Table 9
Fuzzy aggregated decision matrix and fuzzy weights of criteria.

	C1	C2	C3	C4	C5
Weights	(0.206, 0.326, 0.519)	(0.218, 0.352, 0.557)	(0.112, 0.188, 0.310)	(0.051, 0.09, 0.157)	(0.032, 0.044, 0.072)
A1	(6.26,8.28,9.65)	(7.61,9.32,10)	(7,9,10)	(5.59,7.61,9.32)	(3.56,5.59,7.61)
A2	(5.59,7.61,9.32)	(6.26,8.28,9.65)	(5.59,7.61,9.32)	(6.80,8.57,9.65)	(6.26,8.28,9.65)
A3	(7.61,9.32,10)	(6.26,7.4,9.65)	(8.28,9.65,10)	(7.61,9.32,10)	(3.98,6.08,7.88)

Table 10
Normalized fuzzy-decision matrix.

	C1	C2	C3	C4	C5
A1	(0.58,0.68,0.89)	(0.76,0.93,1)	(0.56,0.62,0.80)	(0.56,0.76,0.93)	(0.37,0.58,0.79)
A2	(0.6,0.73,1)	(0.63,0.83,0.97)	(0.60,0.73,1)	(0.68,0.86,0.97)	(0.65,0.86,1)
A3	(0.56,0.6,0.73)	(0.63,0.74,0.97)	(0.56,0.58,0.68)	(0.76,0.93,1)	(0.41,0.63,0.82)

Table 11
Weighted normalized fuzzy-decision matrix.

	C1	C2	C3	C4	C5
A1	(0.12,0.22,0.46)	(0.17,0.33,0.56)	(0.06,0.12,0.25)	(0.03,0.07,0.15)	(0.01,0.03,0.06)
A2	(0.12,0.24,0.52)	(0.14,0.29,0.54)	(0.07,0.14,0.31)	(0.03,0.08,0.15)	(0.02,0.04,0.07)
A3	(0.12,0.2,0.38)	(0.14,0.26,0.54)	(0.06,0.11,0.21)	(0.04,0.08,0.16)	(0.01,0.03,0.06)

Table 12
Distances between suppliers and A^*, A^- with respect to each criterion.

	C1	C2	C3	C4	C5		C1	C2	C3	C4	C5
$d(A1,A^*)$	0.26	0.19	0.09	0.04	0.29	$d(A1,A^-)$	0.27	0.11	0.07	0.03	0.21
$d(A2,A^*)$	0.29	0.17	0.08	0.04	0.28	$d(A2,A^-)$	0.25	0.15	0.08	0.04	0.24
$d(A3,A^*)$	0.30	0.19	0.08	0.04	0.31	$d(A3,A^-)$	0.24	0.09	0.08	0.03	0.16

values of the lower and upper limits of the objective functions are given in Table 15 and weights w_1 and w_2 of TCP and TVP goals respectively set as $w_1 = 0.5$, $w_2 = 0.5$ according to experts' opinions. The linear programming software Lingo 12 is used to solve this problem.

5. Results and sensitivity analysis

As seen in Table 16, the optimal solution for the above formulation is as follows:

$$X_1 = 300, X_2 = 425, X_3 = 475$$

Min (TCP) = 16313.95, Max (TVP) = 397.9 and achievement level objective functions are:

$$\mu_{z_1}(x) = 0.557, \ \ \mu_{z_2}(x) = 0.5.$$

The sensitivity analysis of the maxi-min model is also performed for different levels of objective's weights. The sensitivity analysis is conducted to evaluate the influence of objective weights on the order allocation of green suppliers. The results are summarized in Table 16 and Figs. 5–7. It is seen that by increasing w_1 and decreasing w_2 at the same time, the objective goals TCP and TVP have a decreasing trend and membership function $\mu_{z_1}(x)$ and $\mu_{z_2}(x)$ have an increasing trend. According to results of Table 16, the order quantity of supplier A3 increases by decreasing the weight of w_2. This is obvious because supplier A3 occupies the third rank in the supplier evaluation process, and decreasing the w_2 weight lessens the importance of supplier evaluation results. The decreasing of w_2 weights means the company may establish a strategy for paying less attention to economic and environmental issues in of green supplier selection criteria and would like to purchase more from supplier A3 (the worst green supplier) in contrast to supplier A2 (the best green supplier). Similarly, the order quantity of supplier A2 decreases by decreasing the weight of w_2. This means that the first rank of supplier A2 has less importance as w_2 weight decreases. Also, several conditions are implemented. For example, what happens if the supplier A1 and quality control constraint (No.19) are omitted? If supplier A1 can decrease the average defect percent of its products to maximum acceptable defect ratio (0.00375), then the quality control constraint will be omitted. As seen from the results in Table 17, if the supplier A1 capacity does not consider ($X_1 = 0$), the optimal value of TVP and TCP will decrease to 397.2 and 16152.5 respectively. For the second case, by omitting quality control constraint (No.19), the optimal value of TCP

Table 13
Computations of d^+, d^- and CC_i.

	d^+	d^-	CC_i	Normal weights	Rank
A1	0.871	0.688	0.441	0.338	2
A2	0.859	0.757	0.468	0.359	1
A3	0.923	0.602	0.395	0.303	3

Table 14
Supplier's quantitative data.

	Unit price	Capacity	Unit transportation cost	Average defect percent
Supplier A1	12	500	2	0.0045
Supplier A2	13	600	1.5	0.0035
Supplier A3	11	700	1	0.0035

Table 15
Data set for membership functions.

	$\mu = 0$	$\mu = 1$	$\mu = 0$
Z_1(Min TCP)	15641.5	17159.5	–
Z_2(Max TVP)	–	414.7	381.1

Table 16
Sensitivity analysis for different values of objective's weights.

	$w_1 = 0.45$	$w_1 = 0.5$	$w_1 = 0.55$	$w_1 = 0.6$
	$w_2 = 0.55$	$w_2 = 0.5$	$w_2 = 0.45$	$w_2 = 0.4$
X_1	300	300	300	300
X_2	455	425	395	365
X_3	445	475	505	535
TCP	16389.65	16313.75	16237.85	16161.95
TVP	399.58	397.9	396.22	394.54
$\mu_{z_1}(x)$	0.507	0.557	0.607	0.657
$\mu_{z_1}(x)$	0.45	0.5	0.55	0.6

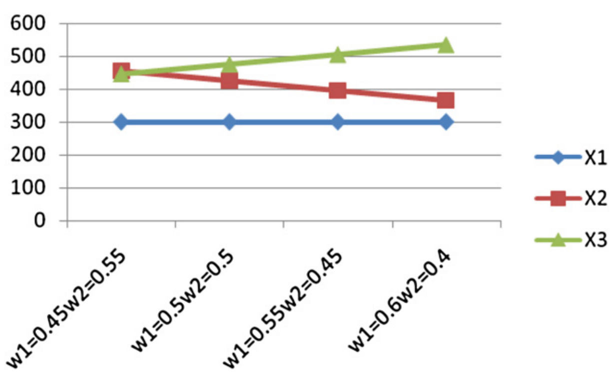

Fig. 5. Sensitivity analysis of order allocations for different values of w_1, w_2.

will increase to16400.5 and optimal value of TVP remains unchanged. By changing constraint (No.21) to $X_3 \leq 400$, the optimal value of TVP and TCP will increase to 402.1 and 16503.5 respectively.

6. Managerial implications

This case study provides additional insights for research and practical applications. The results of this study help firms to establish a systematic approach for selecting and evaluating green suppliers and allocating orders to each supplier. The results of such supplier evaluation and order allocation can include increasing

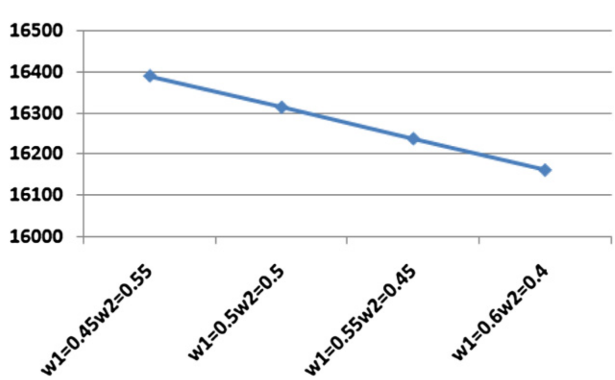

Fig. 6. Sensitivity analysis of TCP for different values of w_1, w_2.

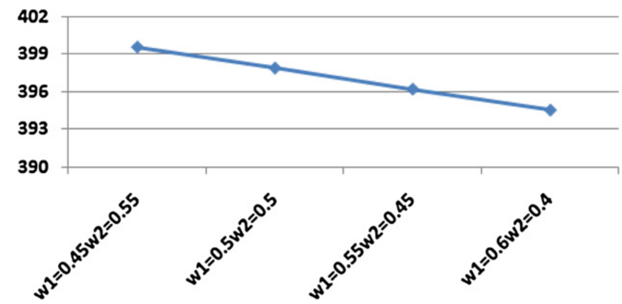

Fig. 7. Sensitivity analysis of TVP for different values of w_1, w_2.

Table 17
Optimal solutions for different kind of constraints.

Objective	Order quantity/TCP/TVP				
	X_1	X_2	X_3	TCP	TVP
Max TVP & min TCP by applying all constraints	300	425	475	16313.75	397.9
Max TVP & min TCP by omitting supplier A1($X_1 = 0$)	0	600	600	16152	397.2
Max TVP & min TCP by assuming $X_3 \leq 400$	300	500	400	16503.5	402.1
Max TVP & min TCP by omitting quality control constraints	500	300	400	16400.5	397.9

product development capability and quality, reducing cost and environmentally hazardous material in the supply chain, and finally increasing product market share. Also the proposed approach helps managers to reduce the risk of purchasing through evaluating each supplier against a set of qualitative and quantitative criteria and ordering from multiple suppliers. The suppliers' evaluation results guide suppliers to benchmark themselves against criteria used in the supplier selection process and finally lead to improving their performances.

7. Conclusions

The supplier selection problem of multiple sourcing includes both selecting suppliers and allocating optimal order quantity among the selected suppliers, based on criteria economic and environmental criteria. Traditionally, supplier selection was based on a supplier's ability to meet economic criteria such as quality, cost, and inventory management. But as environmental consciousness increased, sustainability became an important requirement for supply chains. According to the literature, only a few papers develop practical methods that combine economic and green supplier selections criteria and consider order allocation methods to solve multi-sourcing supplier selection problems in green supply chains. Therefore this paper developed a most prevalent integrated approach for green supplier selection and order allocation problem with the aim of improving GSCM initiatives. Based on the literature survey and with the help of an expert's opinion, possible green supplier evaluation criteria were defined and evaluation model was formulated. At first, a hierarchical structure for supplier selection was developed through the AHP, for obtaining the relative importance weights of quantitative and qualitative criteria. Next, a fuzzy TOPSIS method was used for evaluating the selected suppliers. Finally, a weighted max-min method is used for constructing a MOLP model for assigning order quantities. This model formulated TVP and TCP objects by considering some constraints such as buyer's demand and supplier's capacity. To illustrate the applicability of the proposed model, a case study and sensitivity analysis of results is presented.

This study contains some limitations. One of the limitations of this paper is the small/limited number of respondents. Future research should conduct questionnaires by increasing the number of respondents to ensure the validity of the research. Another limitation is that the maxi-min method may not be Pareto-efficient. However, evolutionary algorithms, such as genetic algorithms (NSGA – II) can be used to generate optimum Pareto front solutions. For future research, the problem can be formulated by other MCDM and MODM methods for comparisons of the results. Also, future researchers may focus on the case where suppliers are operating with a limited supply capacity or assigning DMs' weights according to their expertise, experience, and the responsibilities that are not really equal. Furthermore, we assumed that buyers demand is constant and certain. Another future research may propose a mathematical model with stochastic parameters for demands. In addition to the proposed TOPSIS method in this study, some other MCDM methods can be used in a fuzzy environment. Recently, greenhouse gas emissions and carbon footprints (Kannan et al., 2012) are rather important green considerations. Future research might explore this kind of environmental subject to develop a more practical method for green supplier selection.

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