Expert Systems with Applications 38 (2011) 7326–7333

Contents lists available at ScienceDirect

Expert Systems with Applications

journal homepage: www.elsevier.com/locate/eswa

Fuzzy multiple criteria forestry decision making based on an integrated VIKOR and AHP approach

Tolga Kaya [a,*], Cengiz Kahraman [b]

[a] Istanbul Technical University, Department of Management Engineering, 34367 Macka, Istanbul, Turkey
[b] Istanbul Technical University, Department of Industrial Engineering, 34367 Macka, Istanbul, Turkey

ARTICLE INFO

Keywords:
Fuzzy sets
Multicriteria
VIKOR
AHP
Forestation

ABSTRACT

Forestation and forest preservation in urban watersheds are issues of vital importance as forested watersheds not only preserve the water supplies of a city but also contribute to soil erosion prevention. The use of fuzzy multiple criteria decision aid (MCDA) in urban forestation has the advantage of rendering subjective and implicit decision making more objective and transparent. An additional merit of fuzzy MCDA is its ability to accommodate quantitative and qualitative data. In this paper an integrated VIKOR–AHP methodology is proposed to make a selection among the alternative forestation areas in Istanbul. In the proposed methodology, the weights of the selection criteria are determined by fuzzy pairwise comparison matrices of AHP. It is found that Ömerli watershed is the most appropriate forestation district in Istanbul.

1. Introduction

Making a forestry decision involves a process of balancing diverse ecological, social, and economic aspects over space and time. This balance is critical to the survival of forests, regional watersheds and to the prosperity of forest-dependent communities. Socio-economical and environmental aspects are usually represented in the form of multiple criteria and indicators that often express conflicting management objectives. As the complexity of decisions increases, it becomes more difficult for decision-makers to identify a management alternative that maximizes all decision criteria. In order to reduce conflicts in an optimizing framework, forestry decision making may depend upon the support and input of a wide range of stakeholders. As public involvement needs more effective, defensible techniques usable by managers, successful multiple criteria decision making (MCDM) models which promote participation in the sustainable-forestry context have to emerge in practice (Sheppard & Meitner, 2005; Varma, Ferguson, & Wild, 2000).

MCDM is a useful tool for suggesting solutions for forest management problems over the last three decades. Since the pioneering work of Field (1973), evaluating ecosystem services usually in a non-monetary manner, MCDM models improve the information basis of strategic planning, communication, and understanding in natural resource management. MCDM can be used in interactive decision making and a decision support system for policy makers (Ananda & Herath, 2009). Diaz-Balteiro and Romero (2008) reported more than 250 MCDM studies which deal with a wide range of forestry topics from forestation, biodiversity conservation, harvest scheduling and sustainability to areas like regional planning, risk and uncertainty management, and forestry industry. Among these studies harvest scheduling, biodiversity conversation, and forestation issues are the most popular ones.

Forestry decision making is a complex issue not only because of its broad scope but also because of the wide range of attributes that bear on its assessment. Operationally, forestry assessments must deal with attributes difficult to define and components that may involve both quantitative and qualitative factors. In terms of scope, an assessment may cover geographic areas whose boundaries may not be easily identifiable, and socioeconomic regions that affect various interest groups or stakeholders each with their own demands and socio-economic needs. In view of these difficulties, methods based on fuzzy logic may be quite useful in undertaking difficult assessment procedures. Fuzzy sets theory (Zadeh, 1965) was introduced to express the linguistic terms in decision-making process in order to resolve the vagueness, ambiguity and subjectivity of human judgment. Fuzzy methods are purposely designed for complex and ill defined problems such as forestry assessments (Mendoza & Prabhu, 2003). Hence, many researchers have attempted to use fuzzy MCDM methods like analytic hierarchy process (AHP), analytic network process (ANP), outranking methods, multiple objective linear programming (MOLP), goal programming, and cognitive mapping for forestry problems (Wolfslehner, Vacik, & Lexer, 2005; Diaz-Balteiro & Romero, 2008).

* Corresponding author. Tel.: +90 212 2931300x2789; fax: +90 212 2407260.
E-mail address: kayatolga@itu.edu.tr (T. Kaya).

0957-4174/$ - see front matter © 2010 Elsevier Ltd. All rights reserved.
doi:10.1016/j.eswa.2010.12.003

VIKOR is a multi-attribute decision making technique which has a simple computation procedure that allows simultaneous consideration of the closeness to ideal and the anti-ideal alternatives. In the literature, there are many studies which evaluate VIKOR approach in a comparative manner: Opricovic and Tzeng (2004) conducted a comparative analysis of VIKOR and TOPSIS methods with a numerical example. Tzeng, Lin, and Opricovic (2005) also compared the two methodologies to determine the best compromise solution among alternative fuel modes. Opricovic and Tzeng (2007) made a comparison of VIKOR with preference ranking organization method for enrichment evaluations (PROMETHEE), ELECTRE and TOPSIS approaches. Chu, Shyu, Tzeng, and Khosla (2007) provided a comparative analysis of simple additive weighting (SAW), TOPSIS and VIKOR which demonstrates the similarities and differences of the three methodologies in achieving group decisions.

In fuzzy VIKOR, linguistic preferences can easily be converted to fuzzy numbers (Cevikcan, Sebi, & Kaya, 2009). For the determination of the relative importance of selection criteria, fuzzy AHP can be used since it is based on pairwise comparisons and allows the utilization of linguistic variables. Although the pairwise comparison approach is the most demanding in terms of solicited input from the experts, it offers maximum insight, particularly in terms of assessing consistency of the experts' judgment. In this context, this technique is ideal for closer examination of a selected set of forestation criteria. The technique is also the most accurate when it comes to reflecting the relative weights of each criterion and indicator (Mendoza & Prabhu, 2000).

In this study, a modified fuzzy VIKOR methodology is proposed to make a multicriteria selection among alternative forestation districts. In the proposed methodology, the decision makers' opinions on the relative importance of the selection criteria are determined by a fuzzy AHP procedure. In order to demonstrate the potential of this methodology, an application in the urban forestation area will be presented.

The rest of the paper is organized as follows: In Section 2, a literature review about multicriteria forestation decision making is briefly given. In the third section, a modified fuzzy VIKOR methodology is presented. In Section 4, following the determination of the selection criteria and alternatives, the proposed methodology is applied to a forestation problem. Finally, in the last section, concluding remarks are given.

2. Forestation of urban watersheds

The problem of urban forest management may involve decisions on how to schedule investment, silvicultural, harvesting, forestation and preservation activities for a forestland over a long time horizon, while providing sustainability, maximizing the profit, referring to environmental objectives, and considering the public opinion. As such, a forestry problem is on the one hand a satisfactory attainment of multiple but conflicting objectives, and on the other it is exposed to imprecision originating from natural, technological and socio-economic factors what make forest management fundamentally problematic. Consequently, the decision maker in forestry is challenged with a long term, dynamic, multicriteria problem which requires the development of several decision support systems to aid human ability to understand, evaluate and rank forest management situations, scenarios, and plans (Stirn, 2006).

Forestation is the establishment of a forest, naturally or artificially, on an area, whether previously forested or not. Strategies of forestation and forest preservation in urban watersheds are essential categories of urban forest plans, as preserving the water supplies of a city is an issue of vital importance. Forested watersheds perform four basic and crucial functions. These functions can be called as umbrella, anchor, sponge, and pump.

Umbrella function: Tree leaves, branches and plants intercept rain before it reaches the ground. This slows down the velocity and force with which the water hits the soil. The "umbrella" reduces the rain's ability to erode soils and increases the infiltration of rain water into the ground. Fog condensing on trees and other vegetation is an important part of water resources.

Soil anchor function: The roots of trees and plants grip the steep mountain soils, preventing it from washing into the sea. This protects not only soil but also marine life.

Sponge function: A forested watershed acts like a sponge, soaking up rainfall into its soil, roots, mosses, ferns and leaves. When they are all fully saturated, they slowly release water, thus delivering a consistent and dependable source of water for eventual use by the forest, wildlife, and humans, long after the rain has fallen.

Pumping function: Plants use water, which is released back into the atmosphere through evaporation and transpiration. Both of these processes are increased by warm and sunny conditions. Cooler temperatures and cloudy conditions allow much of the rainfall and condensed fog to soak into the ground and move through the soil. Less water is "lost" into the atmosphere and more water is retained. Thus, forested watersheds "pump" water back into the soil, which appears later as clean water in underground and surface streams.

Since forestation decision making has a multi-objective nature, there is a vast multi-criteria decision making literature on the issue. Walker (1985) proposed a goal programming methodology for a reforestation planning case by taking several species and silvicultural activities into consideration. Mendoza (1986), employing the same case study, extended the methodology with a heuristic approach. Kangas (1993) defined a three-level hierarchical structure to deal with a problem in Finland using three main objectives: Timber production, amenity, and impact on water. Using the same case study, Kangas (1994) extended the analysis by including the attitude towards risk. Romero, Rios, and Diaz-Balteiro (1998) applied a compromise programming model to optimize the forest rotation age, by considering carbon sequestration and timber production.

Liu, Collins, and Yao (1998) used AHP to make a selection among four alternatives regarding regional forestation projects in China. Van Elegem, Embo, Muys, and Lust (2002) proposed a MCDM approach to solve an urban forest allocation problem. Espelta, Retana, and Habrouk (2003) applied a multi-criteria methodology in order to deal with a post-fire reforestation problem in Spain. Gilliams, Raymaekers, Muys, and Van Orshoven (2005a) compared AHP with ELECTRE and PROMETHEE to choose the best afforestation alternative in Belgium. The same authors (Gilliams et al., 2005b) used goal programming to design a decision support system to deal with an afforestation problem in agricultural lands.

3. An integrated VIKOR and AHP methodology

In the following, some basic definitions and notations of fuzzy sets are given briefly (Chen, 2000):

A fuzzy number is a fuzzy subset in the universe of discourse X that is both convex and normal. Fig. 1 shows a fuzzy number $\tilde{\tau}$ of the universe of discourse X which is both convex and normal.

The α-cut of a fuzzy number $\tilde{\tau}$ is defined:

$$\tilde{\tau}^{\alpha} = \left\{x_i : \mu_{\tilde{\tau}}(x_i) \geqslant \alpha,\ x_i \in X\right\}, \tag{1}$$

where $\lambda \in [0,1]$.

$\tilde{\tau}$ is a non-empty bounded closed interval contained in X and it can be denoted by $\tilde{\tau}^{\alpha} = \left[\tau_l^{\alpha}, \tau_u^{\alpha}\right], \tau_l^{\alpha}$ and τ_u^{α} are the lower and upper

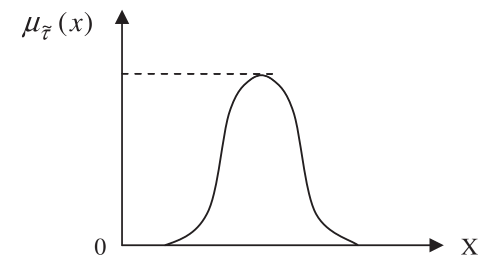

Fig. 1. A fuzzy number $\tilde{\tau}$.

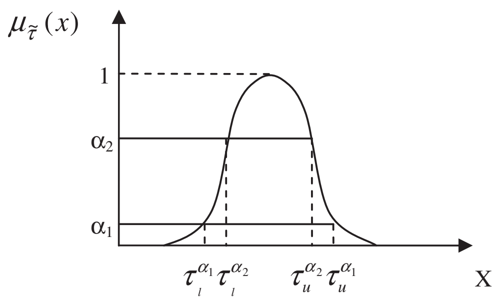

Fig. 2. Fuzzy number $\tilde{\tau}$ with α-cuts.

bounds of the closed interval, respectively. Fig. 2 shows a fuzzy number $\tilde{\tau}$with α-cuts, where

$$\tilde{\tau}^{\alpha_1} = \left[\tau_l^{\alpha_1},\ \tau_u^{\alpha_1}\right], \quad \tilde{\tau}^{\alpha_2} = \left[\tau_l^{\alpha_2},\ \tau_u^{\alpha_2}\right]. \tag{2}$$

From Fig. 2, we can see that if $\alpha_2 \geqslant \alpha_1$, then $\tau_l^{\alpha_2} \geqslant \tau_l^{\alpha_1}$ and $\tau_u^{\alpha_1} \geqslant \tau_u^{\alpha 2}$.

A triangular fuzzy number (TFN) $\tilde{\tau}$ can be defined by a triplet (τ_1, τ_2, τ_3) shown in Fig. 3. The membership function $\mu_{\tilde{\tau}}(x)$ is defined as in Eq. (3):

$$\mu_{\tilde{\tau}}(x) = \begin{cases} 0, & x_1 \leqslant \tau_1, \\ \frac{x-\tau_1}{\tau_2-\tau_1}, & \tau_1 \leqslant x \leqslant \tau_2, \\ \frac{x-\tau_3}{\tau_2-\tau_3}, & \tau_2 \leqslant x \leqslant \tau_3, \\ 0, & x \geqslant \tau_3, \end{cases} \tag{3}$$

If $\tilde{\tau}$ is a fuzzy number and $\tau_l^{\alpha} > 0$ for $\alpha \in [0,1]$, then $\tilde{\tau}$ is called a positive fuzzy number. Given any two positive fuzzy numbers $\tilde{\rho}, \tilde{\tau}$ and a positive real number r, the α-cut of two fuzzy numbers are $\tilde{\rho}^{\alpha} = [\rho_l^{\alpha}, \rho_u^{\alpha}]$ and $\tilde{\tau}^{\alpha} = [\tau_l^{\alpha}, \tau_u^{\alpha}]$ $(\alpha \in [0,1])$ respectively. According to the interval of confidence, some main operations of positive fuzzy numbers $\tilde{\rho}$ and $\tilde{\tau}$ can be expressed as follows (Kaufmann & Gupta, 1985):

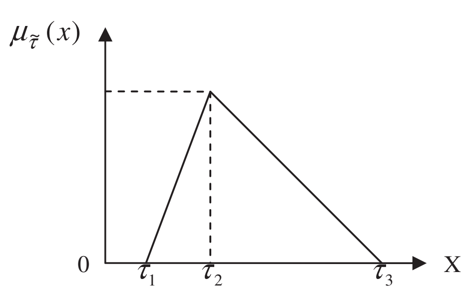

Fig. 3. A triangular fuzzy number $\tilde{\tau}$.

$$(\tilde{\rho}(+)\tilde{\tau})^{\alpha} = \left[\rho_l^{\alpha} + \tau_l^{\alpha},\ \rho_u^{\alpha} + \tau_u^{\alpha}\right], \tag{4}$$

$$(\tilde{\rho}(-)\tilde{\tau})^{\alpha} = \left[\rho_l^{\alpha} - \tau_u^{\alpha},\ \rho_u^{\alpha} - \tau_l^{\alpha}\right], \tag{5}$$

$$(\tilde{\rho}(\cdot)\tilde{\tau})^{\alpha} = \left[\rho_l^{\alpha} \cdot \tau_l^{\alpha},\ \rho_u^{\alpha} \cdot \tau_u^{\alpha}\right], \tag{6}$$

$$(\tilde{\rho}(:)\tilde{\tau})^{\alpha} = \left[\frac{\rho_l^{\alpha}}{\tau_u^{\alpha}},\ \frac{\rho_u^{\alpha}}{\tau_l^{\alpha}}\right], \tag{7}$$

$$(\tilde{\rho}^{\alpha})^{-1} = \left[\frac{1}{\rho_u^{\alpha}},\ \frac{1}{\rho_l^{\alpha}}\right], \tag{8}$$

$$(\tilde{\rho}(\cdot)r)^{\alpha} = \left[\rho_l^{\alpha} \cdot r,\ \rho_u^{\alpha} \cdot r\right], \tag{9}$$

$$(\tilde{\rho}(:)r)^{\alpha} = \left[\frac{\rho_l^{\alpha}}{r},\ \frac{\rho_u^{\alpha}}{r}\right], \tag{10}$$

If $\tilde{n}$ is a triangular fuzzy number and $\tau_l^{\alpha} > 0, \tau_u^{\alpha} \leqslant 1$ for $\alpha \in [0,1]$, then $\tilde{\tau}$ is called a normalized positive triangular fuzzy number (Zimmermann, 1991).

A linguistic variable is a variable whose values are linguistic terms (Zadeh, 1975). The concept of linguistic variable is very useful in dealing with situations which are too complex or too ill-defined to be reasonably described in conventional quantitative expressions. The linguistic values can be represented by fuzzy numbers.

A modified fuzzy approach to the classical VIKOR is proposed in this section. The importance weight of each criterion can be obtained by either directly assigning or indirectly using pairwise comparisons. Here, it is suggested that the decision makers use the linguistic variables in Table 1 to evaluate the importance of the criteria. Wang, Liang, and Ho (2006) calculates the weight of each criterion by summing the assigned weights by experts and then dividing the sum by the number of experts as in Eq. (11):

$$\tilde{w}_{ij} = \frac{1}{K}\left[\tilde{w}_j^1(+)\tilde{w}_j^2(+)\cdots(+)\tilde{w}_j^K\right], \tag{11}$$

where $\tilde{w}_j^K$ is the importance weight of the Kth decision maker.

Since a comparison matrix divides the problem into sub-problems which can be solved easier, a pairwise comparison matrix in the AHP method can be considered a good way of determining the weights of the criteria. Therefore, we propose modifying the classical weighting procedure of VIKOR methodology by using fuzzy comparison matrices. Chang (1996) extent analysis will be utilized for this purpose.

The stages of the extent analysis approach can be summarized as follows: Letting $C_j = \{C_1, C_2, \ldots, C_n\}$ be a criteria set, extent analysis values for each criterion can be obtained as follows: Let $\widetilde{M}_j (j = 1, 2, 3, \ldots, n)$ be TFNs.

The value of fuzzy synthetic extent for the degree of possibility of $\widetilde{M}_1 \geqslant \widetilde{M}_2$ are defined, respectively, as:

$$\widetilde{S}_j = \sum_{j=1}^{n} \widetilde{M}_j \otimes \left[\sum_{k=1}^{m}\sum_{j=1}^{n} \widetilde{M}_j\right]^{-1}. \tag{12}$$

In our case, n=m since a comparison matrix for criteria always has to be a square matrix:

Table 1
Fuzzy evaluation scores for the weights.

Linguistic terms	Fuzzy score
Absolutely strong (AS)	(2,5/2,3)
Very strong (VS)	(3/2,2,5/2)
Fairly strong (FS)	(1,3/2,2)
Slightly strong (SS)	(1,1,3/2)
Equal (E)	(1,1,1)
Slightly weak (SW)	(2/3,1,1)
Fairly weak (FW)	(1/2,2/3,1)
Very weak (VW)	(2/5,1/2,2/3)
Absolutely weak (AW)	(1/3,2/5,1/2)

$$V\left(\widetilde{M}_1 \geqslant \widetilde{M}_2\right) = \sup_{x \geqslant y}\left[\min\left(\mu_{\widetilde{M}_1}(x), \mu_{\widetilde{M}_2}(y)\right)\right], \quad (13)$$

when (x,y) exists such that $x \geqslant y$ and $\mu_{\widetilde{M}_1} = \mu_{\widetilde{M}_2} = 1, V(\widetilde{M}_1 \geqslant \widetilde{M}_2) = 1$ is obtained. Since $\widetilde{M}_1$ and $\widetilde{M}_2$ are convex fuzzy numbers, the following principle of the comparison of fuzzy numbers is applied:

$$V(\widetilde{M}_1 \geqslant \widetilde{M}_2) = 1 \quad \text{iff} \quad m_1 \geqslant m_2, \quad (14)$$

and

$$V\left(\widetilde{M}_2 \geqslant \widetilde{M}_1\right) = hgt\left(\widetilde{M}_1 \bigcap \widetilde{M}_2\right) = \mu(d), \quad (15)$$

where d is the ordinate of the highest intersection point D between $\mu_{\widetilde{M}_1}$ and $\mu_{\widetilde{M}_2}$. When $\widetilde{M}_1 = (l_1, m_1, u_1)$ and $\widetilde{M}_2 = (l_2, m_2, u_2)$, the following equation for the ordinate of the point D is given (see Fig. 4):

$$V\left(\widetilde{M}_2 \geqslant \widetilde{M}_1\right) = hgt\left(\widetilde{M}_1 \cap \widetilde{M}_2\right) = \begin{cases} 0, & \text{if } m_2 \geqslant m_1 \\ 1, & \text{if } l_1 \geqslant u_2 \\ \frac{l_1 - u_2}{(m_2 - u_2) - (m_1 - l_1)}, & \text{otherwise} \end{cases} \quad (16)$$

The values of $V(\widetilde{M}_1 \geqslant \widetilde{M}_2)$ and $V(\widetilde{M}_2 \geqslant \widetilde{M}_1)$ are required for comparing $\widetilde{M}_1$ and $\widetilde{M}_2$. The degree of possibility for a convex fuzzy number to be greater than p convex fuzzy numbers $(\widetilde{M}_j, j = 1, 2, 3, \ldots, n)$ is defined as:

$$\begin{aligned} V\left(\widetilde{M}_p \geqslant \widetilde{M}_1, \widetilde{M}_2, \ldots, \widetilde{M}_{p-1}, \widetilde{M}_{p+1}, \ldots, \widetilde{M}_n\right) &= V\left[\left(\widetilde{M}_p \geqslant \widetilde{M}_1\right) \text{ and } \left(\widetilde{M}_p \geqslant \widetilde{M}_2\right) \text{ and } \cdots \text{ and } \left(\widetilde{M}_p \geqslant \widetilde{M}_n\right)\right] \\ &= \min V\left(\widetilde{M}_p \geqslant \widetilde{M}_j\right) = d(C_j), \quad j \neq p, \end{aligned} \quad (17)$$

Consequently, the weight vector $W' = (d'(C_1), d'(C_2), \ldots, d'(C_n))^T$, $j = 1, 2, 3, \ldots, n$ is obtained. Finally, via normalization, the following normalized weight vector is obtained:

$$W = (d(C_1), d(C_2), \ldots, d(C_n))^T. \quad (18)$$

Obtaining the weight vector via extent analysis, we can continue implementing the steps of VIKOR. VIKOR method is based on the compromise programming of MCDM. The concepts of compromise solutions were first demonstrated by Yu (1973) and Zeleny (1982). The methodology simply works on the principle that each alternative can be evaluated by each criterion function; the compromise ranking will be presented by comparing the degree of closeness to the ideal alternative. In fuzzy VIKOR, it is suggested that decision makers use linguistic variables to evaluate the ratings of alternatives with respect to criteria. Table 2 gives the linguistic scale for the evaluation of alternatives. Assuming that a decision group has K people, the ratings of alternatives with respect to each criterion can be calculated as in Eq. (19) (Wang et al., 2006):

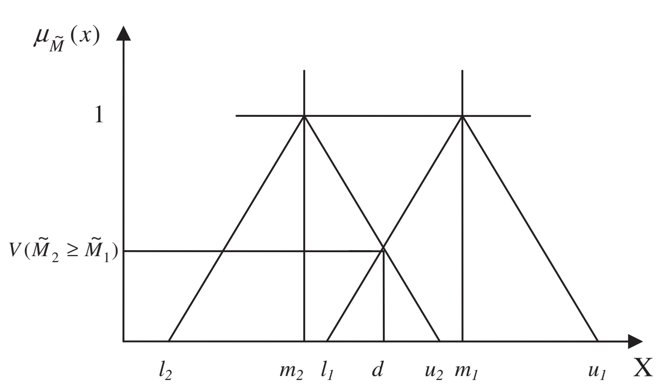

Fig. 4. The intersection between $\widetilde{M}_1$ and. $\widetilde{M}_2$.

Table 2
Fuzzy evaluation scores for the alternatives.

Linguistic terms	Fuzzy score
Very poor (VP)	(0,0,1)
Poor (P)	(0,1,3)
Medium poor (MP)	(1,3,5)
Fair (F)	(3,5,7)
Medium good (MG)	(5,7,9)
Good (G)	(7,9,10)
Very good (VG)	(9,10,10)

$$\tilde{x}_{ij} = \frac{1}{K}\left[\tilde{x}_{ij}^1 (+) \tilde{x}_{ij}^2 (+) \cdots (+) \tilde{x}_{ij}^K\right], \quad (19)$$

where $\tilde{x}_{ij}^K$ is the rating of the Kth decision maker for ith alternative with respect to jth criterion.

After obtaining the weights of criteria and fuzzy ratings of alternatives with respect to each criterion, we can now express the fuzzy multi-criteria decision-making problem in matrix format as:

$$\widetilde{D} = \begin{bmatrix} \tilde{x}_{11} & \tilde{x}_{12} & \cdots & \tilde{x}_{1n} \\ \tilde{x}_{21} & & \cdots & \tilde{x}_{2n} \\ \vdots & \vdots & \cdots & \vdots \\ \tilde{x}_{m1} & \tilde{x}_{m2} & \cdots & \tilde{x}_{mn} \end{bmatrix}, \quad W = [w_1, w_2, \ldots, w_n], \quad j = 1, 2, \ldots, n, \quad (20)$$

where $\tilde{x}_{ij}$ is the rating of the alternative A_i with respect to criterion j(i.e. C_j) and w_j denotes the importance weight of C_j.

Next step is to determine the fuzzy best value (FBV, $\tilde{f}_j^*$) and fuzzy worst value (FWV, $\tilde{f}_j^-$) of all criterion functions:

$$\tilde{f}_j^* = \max_i \tilde{x}_{ij}, \quad j \in B; \tilde{f}_j^- = \min_i \tilde{x}_{ij}, \quad j \in C. \quad (21)$$

Then, the values $\tilde{w}_j\left(\tilde{f}_j^* - \tilde{x}_{ij}\right)/\left(\tilde{f}_j^* - \tilde{f}_j^-\right), \widetilde{S}_i$ and $\widetilde{R}_i$ are computed in order to obtain:

$$\widetilde{S}_i = \sum_{j=1}^{n} \tilde{w}_j\left(\tilde{f}_j^* - \tilde{x}_{ij}\right) \Big/ \left(\tilde{f}_j^* - \tilde{f}_j^-\right) \quad (22)$$

$$\widetilde{R}_i = \max_j \left[\tilde{w}_j\left(\tilde{f}_j^* - \tilde{x}_{ij}\right) \Big/ \left(\tilde{f}_j^* - \tilde{f}_j^-\right)\right] \quad (23)$$

where $\widetilde{S}_i$ refers to the separation measure of A_i from the fuzzy best value, and $\widetilde{R}_i$ to the separation measure ofA_i from the fuzzy worst value.

In the next step, $\widetilde{S}^*, \widetilde{S}^-, \widetilde{R}^*, \widetilde{R}^- and \widetilde{Q}_i$ values are calculated:

$$\begin{aligned} &\widetilde{S}^* = \min_i \widetilde{S}_i, \quad \widetilde{S}^- = \max_i \widetilde{S}_i, \\ &\widetilde{R}^* = \min_i \widetilde{R}_i, \quad \widetilde{R}^- = \max_i \widetilde{R}_i, \end{aligned} \quad (24)$$

$$\widetilde{Q}_i = v\left(\widetilde{S}_i - \widetilde{S}^*\right) \Big/ \left(\widetilde{S}^- - \widetilde{S}^*\right) + (1 - v)\left(\widetilde{R}_i - \widetilde{R}^*\right) \Big/ \left(\widetilde{R}^- - \widetilde{R}^*\right). \quad (25)$$

The index $\min_i \widetilde{S}_i$ and $\min_i \widetilde{R}_i$ are related to a maximum majority rule, and a minimum individual regret of an opponent strategy, respectively. As well, v is introduced as weight of the strategy of the maximum group utility, usually v is assumed to be 0.5.

Next task is the defuzzification of the triangular fuzzy number $\widetilde{Q}_i$ and ranking the alternatives by the index $\widetilde{Q}_i$. Various defuzzification strategies which are defined as the process converting a fuzzy number into a crisp value were suggested. In this paper, graded mean integration approach is used. According to the graded mean integration approach, for triangular fuzzy numbers, a fuzzy number $\widetilde{C} = (c_1, c_2, c_3)$ can be transformed into a crisp number by employing the below equation (Yong, 2006):

$$P(\widetilde{C}) = C = \frac{c_1 + 4c_2 + c_3}{6} \quad (26)$$

Finally, the best alternative with the minimum of Q_i is determined.

To summarize the methodology, the steps of the modified fuzzy VIKOR approach are given in the following:

Step 1: A group of decision-makers identifies the evaluation criteria.
Step 2: Appropriate linguistic variables for the weights of the criteria and the alternatives are chosen.
Step 3: A pairwise comparison matrix for the criteria is constructed and experts' linguistic evaluations are aggregated to get a mean value for each pairwise comparison.
Step 4. Extent analysis approach is used to obtain the weights of the criteria.
Step 5. Linguistic evaluations of the experts are aggregated to get the fuzzy ratings of the alternatives with respect to each criterion.
Step 6: Fuzzy decision matrix is constructed for the implementation of VIKOR.
Step 7: Fuzzy best value (FBV$\tilde{f}_j^*$) and fuzzy worst value (FWV$\tilde{f}_j^-$) of all criterion functions are determined.
Step 8: Separation measures ($\widetilde{S}_i$ and $\widetilde{R}_i$) are calculated.
Step 9: $\widetilde{Q}_i$ values are calculated.
Step 10: $\widetilde{Q}_i$ values are defuzzified and the alternatives are ranked by the index Q_i.
Step 11: The best alternative with the minimum of Q_i is determined.

4. An application: watershed forestation in Istanbul

In this study, in order to evaluate the alternative watershed districts of Istanbul, below criteria will be used:

Watershed preservation (C_1): This criterion is based on the *sponge* and *pumping* functions of forested watersheds. In order to evaluate the alternatives according to this criterion, experts consider not only the capacities and occupancy rates of the dams next to the watersheds but also the current forestation status of the district.

Soil erosion prevention (C_2): This criterion is based on the *umbrella* and *soil* functions of forested watersheds. In order to evaluate the alternatives according to this criterion, experts consider erosion risk of the district.

Cost efficiency (C_3): This criterion takes unit planting and maintenance costs specific to the district into account. It is assumed to be a benefit criterion.

Land availability (C_4): This criterion takes the amount of free area suitable for forestation which is owned by Istanbul Metropolitan Municipality and unit land prices specific to the watershed district.

Social acceptability (C_5): This subjective criterion represents the social acceptability of a possible forestation project around the specific watershed district. Along with the *political acceptability*, this criterion takes residential settlement structure and the potential socio-economical effects of the forestation project to the inhabitants of the area into account.

Political acceptability (C_6): This subjective criterion represents the political acceptability of a possible forestation project around the specific watershed district. This criterion takes political consequences and risks of a possible forestation project into consideration.

Hierarchical structure of the forestation district selection problem is given in Fig. 5:

Fig. 6 gives the geographical distribution of alternative forestation districts considered in Istanbul (A_1: Terkos, A_2: Büyükçekmece, A_3: Sazlıdere, A_4: Pabuçdere A_5:Ömerli, A_6: Darlık):

Fig. 7 demonstrates the contribution of the considered watersheds to Istanbul's water reserves according to October 2009 figures:

After determining the evaluation criteria and the alternatives, the integrated fuzzy VIKOR–AHP algorithm is implemented. In order to assess the relative importance of each evaluation criterion, the experts used a nine point scale as in Table 1. As it is not possible to make arithmetical operations with linguistic terms, each term is associated with a triangular fuzzy number. Table 3 gives the results of the pairwise comparisons of the evaluation criteria made by three energy planning experts.

In the next step, using Tables 1 and 3, the fuzzy evaluation matrix for the criteria weights is obtained as in Table 4. In order to obtain this matrix, the arithmetic means of the fuzzy scores in are calculated. Next, in order to check the consistency ratio (CR) of the evaluation matrix, the graded mean integration approach (Eq. 26) is utilized for defuzzification. CR for the defuzzified version of the evaluation matrix is calculated as 0.019 and it is less than 0.10. Thus, the comparison results can be considered consistent and suitable for an AHP procedure.

Next, using Eq. (12) fuzzy synthetic extent values ($\widetilde{S}_i$) for the evaluation criteria are produced. After obtaining the synthetic extent values, Eqs. (13)–(17) are used for calculating the weight

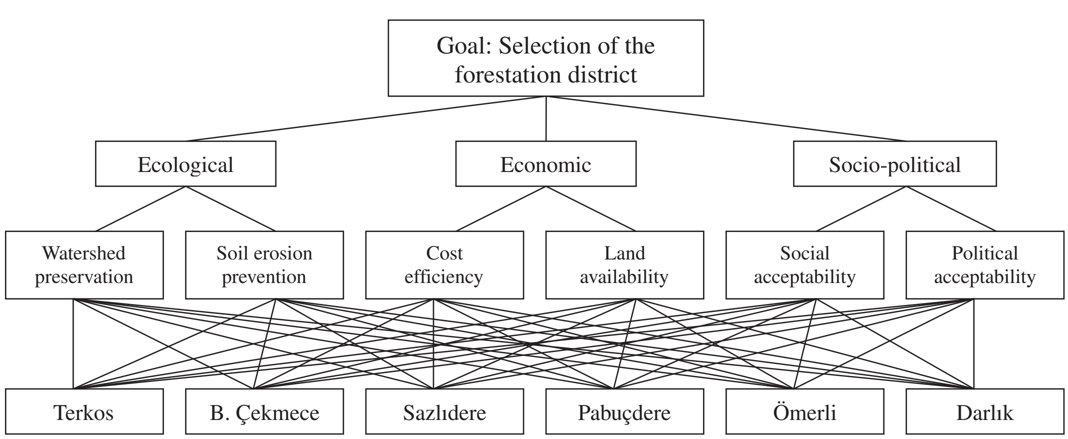

Fig. 5. Hierarchical structure of the forestation district selection problem.

Fig. 6. Geographical distribution of alternative forestation sites in Istanbul.

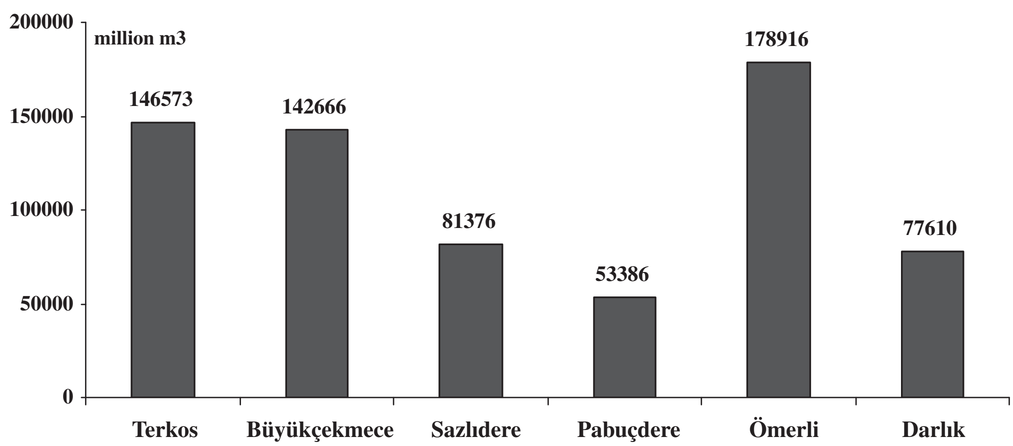

Fig. 7. Contribution of main watersheds to Istanbul's water reserves (October 2009).

Table 3
Pair-wise comparisons of evaluation criteria.

	C_1	C_2	C_3	C_4	C_5	C_6
C_1	1	E_1: SS E_2: E E_3: FS	E_1: VS E_2: FS E_3: VS	E_1: FS E_2: FS E_3: AS	E_1: FS E_2: SS E_3: FS	E_1: SS E_2: E E_3: FS
C_2	E_1: SW E_2: E E_3: FW	1	E_1: FS E_2: FS E_3: FS	E_1: E E_2: SS E_3: FS	E_1: SS E_2: FS E_3: SS	E_1: E E_2: FS E_3: SS
C_3	E_1: VW E_2: FW E_3: VW	E_1: FW E_2: FW E_3: FW	1	E_1: E E_2: E E_3: SS	E_1: SW E_2: E E_3: SW	E_1: E E_2: E E_3: E
C_4	E_1: FW E_2: FW E_3: AW	E_1: E E_2: SW E_3: FW	E_1: E E_2: E E_3: SW	1	E_1: SW E_2: E E_3: SS	E_1: SW E_2: SW E_3: SS
C_5	E_1: FW E_2: SW E_3: FW	E_1: SW E_2: FW E_3: SW	E_1: SS E_2: E E_3: SW	E_1: SS E_2: E E_3: SW	1	E_1: SW E_2: E E_3: SS
C_6	E_1: SW E_2: E E_3: FW	E_1: E E_2: FW E_3: SW	E_1: E E_2: E E_3: E	E_1: SS E_2: SS E_3: SW	E_1: SS E_2: E E_3: SW	1

vector. Finally, via normalization, normalized weight vector is obtained as in Table 5.

Next step is the determination of the best forestation area alternative with the proposed fuzzy VIKOR procedure. To do this, three experts evaluated the watershed alternatives with respect to each criterion using Table 5. Evaluation results are given in Table 6.

Calculating the arithmetic means of the associated fuzzy evaluation scores, fuzzy evaluation matrix is obtained as in Table 7:

Table 4
Fuzzy evaluation matrix for the weights.

	C_1	C_2	C_3	C_4	C_5	C_6
C_1	(1,1,1)	(1,1.17,1.5)	(1.33,1.83,2.33)	(1.33, 1.83,2.33)	(1,1.33,1.83)	(1,1.17,1.5)
C_2	(0.72,0.89,1)	(1,1,1)	(1,1.5,2)	(1,1.17, 1.5)	(1,1.17,1.67)	(1,1.17,1.5)
C_3	(0.43,0.56,0.78)	(0.5,0.67,1)	(1,1,1)	(1,1, 1.17)	(0.78,1,1)	(1,1,1)
C_4	(0.44,0.58,0.83)	(0.72,0.89,1)	(0.89,1,1)	(1, 1,1)	(0.89,1,1.17)	(0.78,1,1.17)
C_5	(0.56,0.78,1)	(0.61,0.89,1)	(1,1,1.33)	(0.89, 1,1.17)	(1,1,1)	(0.89,1,1.17)
C_6	(0.72,0.89,1)	(0.72,0.89,1)	(1,1,1)	(0.89,1, 1.33)	(0.89,1,1.17)	(1,1,1)

*Consistency ratio (CR) for the crisp version of this matrix is 0.019 < 0.10.

Table 5
Results of the fuzzy AHP procedure for the determination of the weights.

	$\widetilde{S}_j = \widetilde{M}_j = (l_j, m_j, u_j)$	$W'_j = d'(C_j)^T$	$W_j = d(C_j)^T$
C_1	(0.15,0.22,0.33)	1	0.303
C_2	(0.13,0.18,0.27)	0.75771	0.229
C_3	(0.11,0.14,0.19)	0.3008	0.091
C_4	(0.11,0.15,0.19)	0.35791	0.108
C_5	(0.11,0.15,0.21)	0.44999	0.136
C_6	(0.12,0.15,0.2)	0.43744	0.132

Then, using Eqs. (21)–(23), separation measure from the fuzzy best value $\widetilde{S}_i$ and separation measure from the fuzzy worst value $\widetilde{R}_i$ are computed as in Table 8.

In the next step, using Eq. (24) $\widetilde{S}^*, \widetilde{S}^-, \widetilde{R}^*$ and $\widetilde{R}^-$ fuzzy values are calculated (Table 9).

Then, using Eq. (25), $\widetilde{Q}_i$ values are computed. In the calculations, weight of the strategy of the maximum group utility (v) is assumed to be 0.5. Finally, $\widetilde{Q}_i$ values are defuzzified via graded mean integration method (Eq. 26) and ranked according to Q_i index

Table 8
Separation measures of A_i from the fuzzy best and fuzzy worst values.

	$\widetilde{S}_i$	$\widetilde{R}_i$
A_1	(−0.09,0.34,0.9)	(0.07,0.13,0.3)
A_2	(0.08,0.62,1.39)	(0.07,0.21,0.65)
A_3	(−0.06,0.49,1.32)	(0.08,0.3,0.82)
A_4	(0.39,0.8,1.4)	(0.18,0.23,0.48)
A_5	(−0.3,0.07,0.49)	(−0.03,0.05,0.13)
A_6	(−0.05,0.49,1.28)	(0.05,0.26,0.74)

Table 9
$\widetilde{S}^*, \widetilde{S}^-, \widetilde{R}^*$, and $\widetilde{R}^-$ values.

$\widetilde{S}^*$	(−0.3,0.07,0.49)
$\widetilde{S}^-$	(0.39,0.8,1.4)
$\widetilde{R}^*$	(−0.03,0.05,0.13)
$\widetilde{R}^-$	(0.18,0.3,0.82)

Table 6
Evaluation scores of the forestation area alternatives.

	C_1	C_2	C_3	C_4	C_5	C_6
A_1	E_1: VG E_2: G E_3: G	E_1: G E_2: VG E_3: VG	E_1: MG E_2: MG E_3: MG	E_1: F E_2: F E_3: MG	E_1: MP E_2: MP E_3: MP	E_1: P E_2: P E_3: MP
A_2	E_1: F E_2: G E_3: MG	E_1: MG E_2: MG E_3: MG	E_1: F E_2: MP E_3: VP	E_1: MG E_2: MG E_3: MG	E_1: MP E_2: MP E_3: P	E_1: P E_2: P E_3: MP
A_3	E_1: F E_2: MG E_3: F	E_1: MG E_2: F E_3: F	E_1: VG E_2: MG E_3: G	E_1: MP E_2: MP E_3: MP	E_1: G E_2: G E_3: MG	E_1: MG E_2: G E_3: G
A_4	E_1: VG E_2: G E_3: F	E_1: P E_2: VP E_3: VP	E_1: F E_2: P E_3: F	E_1: VP E_2: P E_3: VP	E_1: P E_2: MP E_3: P	E_1: MG E_2: P E_3: P
A_5	E_1: VG E_2: VG E_3: VG	E_1: VG E_2: G E_3: G	E_1: MG E_2: VG E_3: G	E_1: G E_2: F E_3: F	E_1: MG E_2: F E_3: MG	E_1: G E_2: G E_3: G
A_6	E_1: MG E_2: MG E_3: F	E_1: G E_2: MG E_3: G	E_1: G E_2: MG E_3: F	E_1: F E_2: MP E_3: MP	E_1: G E_2: G E_3: G	E_1: MP E_2: MP E_3: P

Table 7
Fuzzy evaluation matrix for the alternatives.

	C_1	C_2	C_3	C_4	C_5	C_6
A_1	(7.67,9.33,10)	(8.33,9.67,10)	(5,7,9)	(3.67,5.67,7.67)	(1,3,5)	(0.33,1.67,3.67)
A_2	(5,7,8.67)	(5,7,9)	(1.33,2.67,4.33)	(5,7,9)	(0.67,2.33,4.33)	(0.33,1.67,3.67)
A_3	(3.67,5.67,7.67)	(3.67,5.67,7.67)	(7,8.67,9.67)	(1,3,5)	(6.33,8.33,9.67)	(6.33,8.33,9.67)
A_4	(6.33,8,9)	(0,0.33,1.67)	(2,3.67,5.67)	(0,0.33,1.67)	(0.33,1.67,3.67)	(1.67,3,5)
A_5	(9,10,10)	(7.67,9.33,10)	(7,8.67,9.67)	(4.33,6.33,8)	(4.33,6.33,8.33)	(7,9,10)
A_6	(4.33,6.33,8.33)	(6.33,8.33,9.67)	(5,7,8.67)	(1.67,3.67,5.67)	(7,9,10)	(0.67,2.33,4.33)

Table 10
Integrated fuzzy VIKOR–AHP analysis results.

	$\widetilde{Q}_i$	Q_i	Rank
A_1	$(-0.37, 0.35, 1.66)$	0.45	2
A_2	$(-0.28, 0.7, 2.84)$	0.89	3
A_3	$(-0.34, 0.79, 3.2)$	1.00	6
A_4	$(-0.02, 0.86, 2.43)$	0.97	5
A_5	$(-0.55, 0, 0.95)$	0.07	1
A_6	$(-0.35, 0.7, 2.97)$	0.90	4

values. Table 10 gives the results of the integrated fuzzy VIKOR–AHP analysis results.

Based on the crisp Q_i index values, the ranking of the alternatives in descending order are A_5, A_1, A_2, A_6, A_4, and A_3. The best alternative is found to beA_5(Ömerli). The second best alternative isA_1 (Terkos). The rank order of the rest is Büyükçekmece, Darlık, Pabuçdere, and Sazlıdere.

5. Concluding remarks

Establishment of a forest on an urban watershed reduces the rain's ability to erode soils and increases the water infiltration into the ground. The roots of trees and plants grip the soil, preventing it from washing into the sea. As less water is lost into the air, a forested watershed pumps rain water back into the soil, which appears later as clean water in underground. More importantly, a forested watershed provides a consistent and dependable source of water for humans long after the rain has fallen.

Despite the ecological necessities, urban forestry decision making is a complex task not only because of its broad scope but also because of the wide range of economic, social and political attributes that bear on its assessment. Evaluation of these attributes may often include uncertainties and subjectivities. Fuzzy decision-making may successfully deal with non-probabilistic uncertainty and vagueness in the environment. Fuzzy approaches to decision-making are usually the most appropriate ones when human evaluations and the modeling of human knowledge are needed. A rational approach toward decision-making should take human subjectivity into account, rather than employing only objective probability measures.

In this paper, an integrated fuzzy VIKOR–AHP methodology is developed for the selection of the best forestation district alternative in Istanbul metropolitan region. VIKOR is a multi-criteria decision making technique which provides a compromise solution, providing a maximum group utility for the majority and a minimum of an individual regret for the opponent. In fuzzy VIKOR, linguistic evaluations of the experts can easily be converted to fuzzy numbers which are allowed to be used in calculations. In this study, weights of the selection criteria are determined based on a fuzzy AHP approach in order to allow both pairwise comparisons and the utilization of linguistic variables. Despite the demanding nature of the pairwise comparisons approach, as it is considered to offer maximum insight and consistency, we choose modifying the existing fuzzy VIKOR methodology with the weights of the extent analysis.

Watershed preservation, soil erosion prevention, cost, land availability, social acceptability, and political acceptability criteria were taken into consideration in order to evaluate the alternative watershed districts. Using the integrated approach, we compared six watershed districts of Istanbul and found that Ömerli is the most convenient watershed area among the alternatives.

For further research, the findings of our study can be compared with the results of other multicriteria techniques like fuzzy ELECTRE, fuzzy PROMETHEE or fuzzy TOPSIS.

References

Ananda, J., & Herath, G. (2009). A critical review of multi-criteria decision making methods with special reference to forest management and planning. *Ecological Economics, 68*, 2535–2548.

Chang, D. Y. (1996). Applications of the extent analysis method on fuzzy AHP. *European Journal of Operational Research, 95*, 649–655.

Chu, M.-T., Shyu, J., Tzeng, G.-H., & Khosla, R. (2007). Comparison among three analytical methods for knowledge communities group-decision analysis. *Expert Systems with Applications, 33*(4), 1011–1024.

Cevikcan, C., Sebi, S., & Kaya, I. (2009). Fuzzy VIKOR and fuzzy axiomatic design versus to fuzzy TOPSIS: An application of candidate assessment. *Journal of Multiple Valued Logic and Soft Computing, 15*, 181–208.

Chen, C. (2000). Extensions of the TOPSIS for group decision-making under fuzzy environment. *Fuzzy Sets and Systems, 114*, 1–9.

Diaz-Balteiro, L., & Romero, C. (2008). Making forestry decisions with multiple criteria: A review and an assessment. *Forest Ecology and Management, 255*, 3222–3241.

Espelta, J. M., Retana, J., & Habrouk, A. (2003). An economic and ecological multicriteria evaluation of reforestation methods to recover burned inus nigra forests in NE Spain. *Forest Ecology and Management, 180*, 185–198.

Field, D. B. (1973). Goal programming for forest management. *Forest Science, 19*, 125–135.

Gilliams, S., Raymaekers, D., Muys, B., & Van Orshoven, J. (2005a). Comparing multiple criteria decision methods to extend a geographical information system on afforestation. *Computers and Electronics in Agriculture, 49*, 142–158.

Gilliams, S., Van Orshoven, J., Muys, B., Kros, H., Heil, G. W., & Van Deursen, W. (2005b). AFFOREST sDSS: A metamodel based spatial decision support system for afforestation of agricultural land. *New Forests, 30*, 33–53.

Kangas, J. (1993). A multi-attribute preference model for evaluating the reforestation chain alternatives of a forest stand. *Forest Ecology and Management, 59*, 271–288.

Kangas, J. (1994). Incorporating risk attitude into comparison of reforestation alternatives. *Scandinavian Journal of Forest Research, 9*, 297–304.

Kaufmann, A., & Gupta, M. M. (1985). *Introduction to fuzzy arithmetic: Theory and applications*. New York: Van Nostrand Reinhold.

Liu, A., Collins, A., & Yao, S. (1998). A multi-objective and multi-design evaluation procedure for environmental protection forestry. *Environmental and Resource Economics, 12*, 225–240.

Mendoza, G. A. (1986). A heuristic programming approach in estimating efficient target levels in goal programming. *Canadian Journal of Forest Research, 16*.

Mendoza, G. A., & Prabhu, R. (2000). Multiple criteria decision making approaches to assessing forest sustainability using criteria and indicators: A case study. *Forest Ecology and Management, 131*, 107–126.

Mendoza, G. A., & Prabhu, R. (2003). Qualitative multi-criteria approaches to assessing indicators of sustainable forest resource management. *Forest Ecology and Management, 174*, 329–343.

Opricovic, S., & Tzeng, G. H. (2004). Compromise solution by MCDM methods: A comparative analysis of VIKOR and TOPSIS. *European Journal of Operational Research, 156*(2), 445–455.

Opricovic, S., & Tzeng, G. H. (2007). Extended VIKOR method in comparison with outranking methods. *European Journal of Operational Research, 178*, 514–529.

Romero, C., Rios, V., & Diaz-Balteiro, L. (1998). Optimal forest rotation age when carbon captured is considered: Theory and applications. *Journal of the Operational Research Society, 49*, 121–131.

Sheppard, S. R. J., & Meitner, M. (2005). Using multi-criteria analysis and visualisation for sustainable forest management planning with stakeholder groups. *Forest Ecology and Management, 207*, 171–187.

Stirn, L. Z. (2006). Integrating the fuzzy analytic hierarchy process with dynamic programming approach for determining the optimal forest management decisions. *Ecological Modeling, 194*, 296–305.

Tzeng, G., Lin, C., & Opricovic, S. (2005). Multi-criteria analysis of alternative-fuel buses for public transportation. *Energy Policy, 33*, 1373–1383.

Van Elegem, B., Embo, T., Muys, B., & Lust, N. (2002). A methodology to select the best locations for new urban forests using multicriteria analysis. *Forestry, 75*, 13–23.

Varma, V. K., Ferguson, I., & Wild, I. (2000). Decision support system for the sustainable forest management. *Forest Ecology and Management, 128*(1), 49–55.

Walker, H. D. (1985). An alternative approach to goal programming. *Canadian Journal of Forest Research, 15*, 319–325.

Wolfslehner, B., Vacik, H., & Lexer, M. J. (2005). Application of the analytic network process in multi-criteria analysis of sustainable forest management. *Forest Ecology and Management, 207*, 157–170.

Wang, T.-C., Liang, L.-J., & Ho, C.-Y. (2006). Multi-criteria decision analysis by using fuzzy VIKOR. In *Proceedings of international conference on service systems and service management* (Vol. 2, pp. 901–906).

Yong, D. (2006). Plant location selection based on fuzzy TOPSIS. *International Journal of Advanced Manufacturing Technologies, 28*, 839–844.

Yu, P. L. (1973). A class of solutions for group decision problems. *Management Science, 19*(8), 936–946.

Zadeh, L. (1965). Fuzzy sets. *Information Control, 8*, 338–353.

Zadeh, L. A. (1975). The concept of a linguistic variable and its application to approximate reasoning. *Information Sciences, 8*. pp. 199–249 (I), 301–357 (II).

Zeleny, M. (1982). *Multiple criteria decision making*. New York: McGraw-Hill.

Zimmermann, H. J. (1991). *Fuzzy set theory and its applications* (2nd ed.). Boston/Dordrech/London: Kluwer Academic Publishers.