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Assessment of health-care waste treatment alternatives using fuzzy multi-criteria decision making approaches

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ABSTRACT

Health-care waste (HCW) management is a high priority environmental, public and health concern in developing countries. The management and treatment of HCW are gaining more attention with the rising awareness. The objective of this research is to propose multi-criteria decision making techniques for conducting an analysis based on multi-level hierarchical structure and fuzzy logic for the evaluation of HCW treatment alternatives. The ideal and anti-ideal solutions are taken into consideration simultaneously in the developed approaches to account for the individuals' desire to be both as close as possible to the ideal and as distant as possible from the anti-ideal. The proposed decision approaches enable the decision-makers to use linguistic terms, and thus, reduce their cognitive burden in the evaluation process. Furthermore, a hierarchy of evaluation criteria and their related sub-criteria is employed in the presented approaches in order to conduct a more effective analysis. The computational procedures of the proposed frameworks are illustrated through a case study in Istanbul, the largest city of Turkey that is also listed among the world's most crowded cities. The HCW treatment alternatives considered in this study include "incineration", "steam sterilization", "microwave" and "landfill". The results obtained using the proposed decision approaches are analyzed in a comparative way.

1. Introduction

The concerns related to proper treatment of medical wastes and other toxic hazardous wastes have been increasing worldwide as a direct result of rapid industrialization and population growth (Mato and Kassenga, 1997). Health-care waste (HCW) is waste generated by health-care facilities. According to Medical Waste Control Regulation, wastes from health-care services have been classified into four main groups in Turkey as given in Table 1.

In the majority of the published works on health-care waste management (HCWM), health-care institutions generating the wastes are surveyed through the prepared questionnaires, field research and personnel interviews. Lee et al. (2004) examined generation volume and sources, composition, and treatment and disposal methods for regulated medical wastes. Diaz et al. (2005) explained some of the most common treatment and disposal methods utilized in the management of infectious health-care wastes in developing countries. Brent et al. (2007) developed an integrated framework which uses the analytic hierarchy process (AHP) with other systems approaches to establish primary HCWM systems that minimize infection risks in developing countries. Tudor et al. (2007) examined the limitations in the sustainable management of waste through a case study focusing on the health-care sector. Diaz et al. (2008) presented information on the quantities and properties of health-care wastes in various types of facilities located in developing countries, as well as in some industrialized countries. Recently, Mohamed et al. (2009) analyzed HCWM practices including waste generation, segregation, storage, collection, transportation, treatment, and disposal in the Kingdom of Bahrain.

Later, several studies have focused on HCWM practices in Istanbul, the largest city of Turkey with nearly 13 million inhabitants. Zeren (2004) proposed an institutional structure to resolve insufficient management of health-care wastes in the European side of Istanbul. Alagoz and Kocasoy (2007) examined technical information related to the available treatment technologies and compared capital investment cost, transportation/operational costs for each alternative method. Alagoz and Kocasoy (2008a) investigated the existing situation and management practices such as the amount of health-care wastes generated, segregation procedures, collection, temporary storage and transportation of the wastes within and outside of the institution, and developed the main priorities for safe handling and transportation of health-care wastes by considering environmental and economic factors. Alagoz and Kocasoy (2008b) proposed a health-care waste collection and transportation system for the city of Istanbul. More recently, Birpinar et al. (2009)

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Table 1
Categories of health-care wastes generated by health-care services (Ministry of Environment and Forestry of Turkey, 1993).

Waste category	Description and examples
I. Municipal wastes	A: General wastes Wastes derived from normal inpatient wards, outpatient examination rooms, first aid areas, administration, cleaning services, kitchens, stores and workshops B: Waste packaging All wastes reusable or recyclable generated within the health-care center by administration, kitchen, warehouses, workshops, e.g. paper, cardboard, plastics, glass and metal
II. Medical wastes	C: Infectious wastes Potentially infectious wastes that require special management inside and outside the health-care center, comprising: I. Microbiological laboratory wastes: Cultures and stocks Infectious body fluids Serologic wastes Other contaminated laboratory wastes II. Blood and blood containers III. Discarded surgery wastes such as soiled dressings, drapes, gowns, gloves IV. Wastes from dialysis V. Quarantine wastes VI. Air filters that contain bacteria and viruses VII. Infectious animal carcasses, body parts, blood and all the objects in contact with them D: Pathological wastes Tissues, organs and body parts and fluids removed by trauma or during surgery or autopsy or other medical procedure such as parts of human bodies generated in operating theatres, delivery rooms, morgues, autopsies, corps of animals used for biological experimentation, etc. E: Sharp wastes Wastes that could cause a cut or puncture such as needles, syringes, blood vials, broken glassware, etc.
III. Hazardous wastes	F: Hazardous wastes Wastes that are subject to special handling due to their physical or chemical properties or because of legal reasons such as hazardous chemicals, cytotoxic and cytostatic medicines, amalgam wastes, pharmaceutics wastes, heavy-metal containing wastes, pressurized vessels
IV. Radioactive wastes	G: Radioactive wastes Collected and removed according to Turkish Atomic Energy Council Act

conducted a survey about the current status of generation, collection, on-site handling, storage, processing, recycling, transportation, and safe disposal of medical waste.

Waste produced in health-care facilities in developing countries has raised serious concerns due to the inappropriate treatment and final disposal practices accorded to them (Diaz et al., 2005). In many countries, medical wastes are still handled and disposed of together with other domestic wastes, and thus pose significant health risks to municipal workers, the public and the environment (Mato and Kaseva, 1999). The HCW treatment alternatives considered in this study include "incineration", "steam sterilization", "microwave", and "landfill". Incineration is the controlled-flame combustion to decline waste materials to noncombustible residue or ash and exhaust gases; it is a remedial technology that destroys contaminants at high temperatures. Incineration has been used to dispose HCW generated by health-care institutions in Istanbul. Steam sterilization, or autoclaving, combines moisture, heat and pressure to inactivate microorganisms. Microwave disinfection is essentially a steam-based process, since disinfection occurs through the action of moist heat and stream generated by microwave energy. Sanitary landfilling is the preferred method of solid waste disposal in certain cases due to its low cost, minimal environmental impacts when designed and operated correctly, and effectiveness in controlling health risks. On the other hand, the primary objections to landfill disposal of hazardous HCW, especially untreated waste, are based on a perceived risk of release of pathogens to air and water.

The evaluation of HCW treatment alternatives, which considers the need to trade-off multiple conflicting criteria with the involvement of a group of experts, is a highly important multi-criteria group decision making problem. In classical multiple criteria decision making (MCDM) methods, the ratings and the weights of the criteria are assumed to be known precisely. In general, crisp data are inadequate to model real-life situations including HCWM that incorporate imprecision and vagueness. Moreover, when a large number of performance attributes are to be considered in the evaluation process, structuring them in a multi-level hierarchy is preferred to carry out the analysis more effectively. Hierarchical decomposition of the HCW treatment technology selection provides an efficient analysis enabling the mind to cope with diversity. Relevant details including the factors that contribute to the solution are considered to represent the problem thoroughly.

This study focuses on the detailed multi-attribute evaluation of HCW treatment alternatives to determine the most suitable one for Istanbul. Nonetheless, it is worth noting that the decision models presented here are not limited to this specific problem and could very well be applied to HCWM, in general. The objective of this study is to propose fuzzy multi-criteria group decision making approaches, which enable to conduct an analysis based on a multi-level hierarchical structure and to incorporate imprecise data represented as linguistic variables into the analysis, for identifying the most suitable HCW treatment alternative. The computational procedures of the proposed frameworks are illustrated through a case study in Istanbul. The proposed methodologies possess a number of advantages compared to other MCDM techniques presented in the literature for waste management. First, these methods are group decision making processes which enable the group to identify and better appreciate the differences and similarities of their judgments (Muralidharan et al., 2002). Second, the proposed approaches can handle evaluation criteria that are structured in multi-level hierarchies. Third, these methodologies are apt to incorporate imprecise data into the analysis using fuzzy set theory. Fourth, the presented decision making procedures account for both ideal and anti-ideal solutions simultaneously, considering that people prefer to be as close as possible to the ideal and as distant as possible from the anti-ideal (Zeleny, 1982). Finally, these approaches do not employ fuzzy number ranking methods that can produce inconsistent results or even rankings contrary to intuition while comparing alternatives. Considering the above-mentioned merits, proposed decision making frameworks are apt to conduct robust evaluation of the HCW treatment alternatives.

The rest of this paper is structured as follows. The subsequent section presents the proposed fuzzy decision making algorithms and the expert survey. In Section 3, results are provided along with discussion focusing on comparative analysis. Finally, conclusions and directions for future research are given in Section 4.

2. Materials and methods

In order to model real world problems incorporating vagueness and imprecision, deterministic or stochastic methods appear to be inappropriate (Karsak, 2002). Zadeh (1965) introduced the fuzzy set theory to express factors, which can be addressed by neither crisp values nor random process, in an effective way. A fuzzy set $\tilde{A}$ can be defined mathematically by a membership function $\mu_{\tilde{A}}(x)$, which assigns each element x in the universe of discourse X a real number in the interval [0, 1].

A convex and normalized fuzzy set defined on $\Re$ whose membership function is piecewise continuous is called a fuzzy number. A triangular fuzzy number $\tilde{A}$ can be defined by a triplet (a_1, a_2, a_3) with the membership function given as

$$\mu_{\tilde{A}}(x) = \begin{cases} \dfrac{x-a_1}{a_2-a_1}, & a_1 \le x \le a_2, \\ \dfrac{x-a_3}{a_2-a_3}, & a_2 \le x \le a_3, \\ 0, & \text{otherwise.} \end{cases} \quad (1)$$

The distance between the triangular fuzzy numbers $\tilde{A} = (a_1, a_2, a_3)$ and $\tilde{B} = (b_1, b_2, b_3)$ can be calculated using a distance measure as follows (Bojadziev and Bojadziev, 1995):

$$d_v\left(\tilde{A}, \tilde{B}\right) = \frac{1}{2}\left\{\max\left(\left|a_1-b_1\right|, \left|a_3-b_3\right|\right) + \left|a_2-b_2\right|\right\} \quad (2)$$

The distance formula provides the size of the trapezoidal area with lower base given by the larger value of $|a_1 - b_1|$ or $|a_3 - b_3|$, upper base given by $|a_2 - b_2|$, and height equal to one. Smaller the trapezoidal area, closer are the triangular fuzzy numbers $\tilde{A}$ and $\tilde{B}$.

In the following subsection, the group decision making techniques proposed for evaluating HCW treatment alternatives are presented. Subsection 2.2 outlines the structure of the problem and expert survey.

2.1. Multi-criteria group decision making approaches

A multi-level hierarchical structure enables us to conduct a more effective analysis for assessment of HCW treatment alternatives, which requires the consideration of a large number of performance attributes. While some of the attributes may be objective and measurable, the others are qualitative in nature that are difficult to measure. Since the judgments from experts are usually vague rather than certain, a judgment can be expressed by using linguistic variables which have the capability of representing imprecise data.

A linguistic variable is defined as a variable whose values are not numbers, but words or sentences in natural or artificial language. The concept of a linguistic variable is a useful means for providing approximate characterization of phenomena that are too complex or ill defined to be described in conventional quantitative terms (Zadeh, 1975).

MCDM is widely used in ranking a set of available alternatives with respect to multiple conflicting criteria. The use of multiple criteria analysis in waste management possesses the advantage of rendering subjective and implicit decision making more objective and transparent (Chung and Poon, 1996). While reviewing the types of models being used in waste management, Morrissey and Browne (2004) stressed that none of the earlier models considered environmental, economic and social aspects simultaneously. Fuzzy MCDM models have only been recently used in waste management to aggregate the decision-makers' subjective assessment about criteria weightings and appropriateness of alternatives versus selection criteria in particular for site selection (Chang et al., 2008).

This subsection outlines two alternative fuzzy MCDM methodologies for the evaluation of health-care waste management scenarios. The first one is a fuzzy group decision making approach based on the principles of fuzzy measure and fuzzy integral. The second one is the multi-expert version of the hierarchical distance-based fuzzy MCDM algorithm introduced by Karsak and Ahiska (2005). Schematic representation of these approaches is presented in Fig. 1. Both of these methods enable considering economic, environmental, technical and social factors simultaneously while conducting the analysis. In order to conduct a more effective analysis, both of these group decision making frameworks employ a hierarchy of evaluation criteria and their related sub-criteria. The problem is structured as a hierarchy that shows the criteria and sub-criteria and their relationships. Owing to the use of fuzzy set theory, these approaches enable imprecise data to be taken into consideration. Moreover, as individuals attempt to be both as close as possible to the ideal and as distant as possible from the anti-ideal, ideal and anti-ideal solutions are considered simultaneously in these decision making approaches.

2.1.1. Fuzzy decision making framework based on fuzzy measure and fuzzy integral

In here, a systematic group decision making approach, which incorporates imprecise data represented as linguistic variables into the analysis for a selection problem having a multi-level hierarchical structure, is presented. This approach is based on the principles of fuzzy measure and fuzzy integral. The proposed methodology does not require the assumption of the mutual independence of criteria. Basic notation and definitions regarding fuzzy measure and fuzzy integral are provided in the Appendix A. The stepwise representation of the proposed fuzzy MCDM algorithm is given below.

Step 1. Construct a decision-makers' committee of z experts ($l = 1, 2, \ldots, z$). Identify the alternatives, required selection criteria, and related sub-criteria in a hierarchical structure.

Step 2. Construct the decision matrices that denote the importance weights of criteria and related sub-criteria, and the fuzzy assessments corresponding to qualitative sub-criteria for each decision-maker.

Step 3. Let the fuzzy value assigned to alternative i ($i = 1, 2, \ldots, m$) with respect to sub-criterion k ($k = 1, 2, \ldots, p$) of criterion j ($j = 1, 2, \ldots, n$), importance weight of sub-criterion k of criterion j, and importance weight of criterion j for the lth decision-maker be $\tilde{x}_{ijkl} = (x^1_{ijkl}, x^2_{ijkl}, x^3_{ijkl})$, $\tilde{w}_{jkl} = (w^1_{jkl}, w^2_{jkl}, w^3_{jkl})$ and $\tilde{w}_{jl} = (w^1_{jl}, w^2_{jl}, w^3_{jl})$, respectively. If there exist crisp data x_{ijkl}, it can be represented as $\tilde{x}_{ijkl} = (x^1_{ijkl}, x^2_{ijkl}, x^3_{ijkl})$ in triangular fuzzy number format, where $x_{ijkl} = x^1_{ijkl} = x^2_{ijkl} = x^3_{ijkl}$. Compute aggregated fuzzy assessments of alternatives $\left(\tilde{x}_{ijk}\right)$, aggregated importance weights of sub-criteria $\left(\tilde{w}_{jk}\right)$, and aggregated importance weights of criteria $\left(\tilde{w}_j\right)$ as follows:

$$\tilde{x}_{ijk} = \sum_{l=1}^{z} v_l \tilde{x}_{ijkl} \quad (3)$$

$$\tilde{w}_{jk} = \sum_{l=1}^{z} v_l \tilde{w}_{jkl} \quad (4)$$

$$\tilde{w}_{j} = \sum_{l=1}^{z} v_l \tilde{w}_{jl} \quad (5)$$

where $v_l \in [0, 1]$ denotes weight assigned to the lth decision-maker, and $\sum_{l=1}^{z} v_l = 1$.

Hence, aggregated ratings of alternatives with respect to each sub-criterion can be calculated as $\tilde{x}_{ijk} = (x^1_{ijk}, x^2_{ijk}, x^3_{ijk})$, aggregated importance weights of sub-criteria can be computed as $\tilde{w}_{jk} = (w^1_{jk}, w^2_{jk}, w^3_{jk})$, and aggregated importance weights of criteria can be calculated as $\tilde{w}_j = (w^1_j, w^2_j, w^3_j)$.

Step 4. Normalize the aggregated decision matrix to obtain unit-free and comparable sub-criteria values. The normalized values

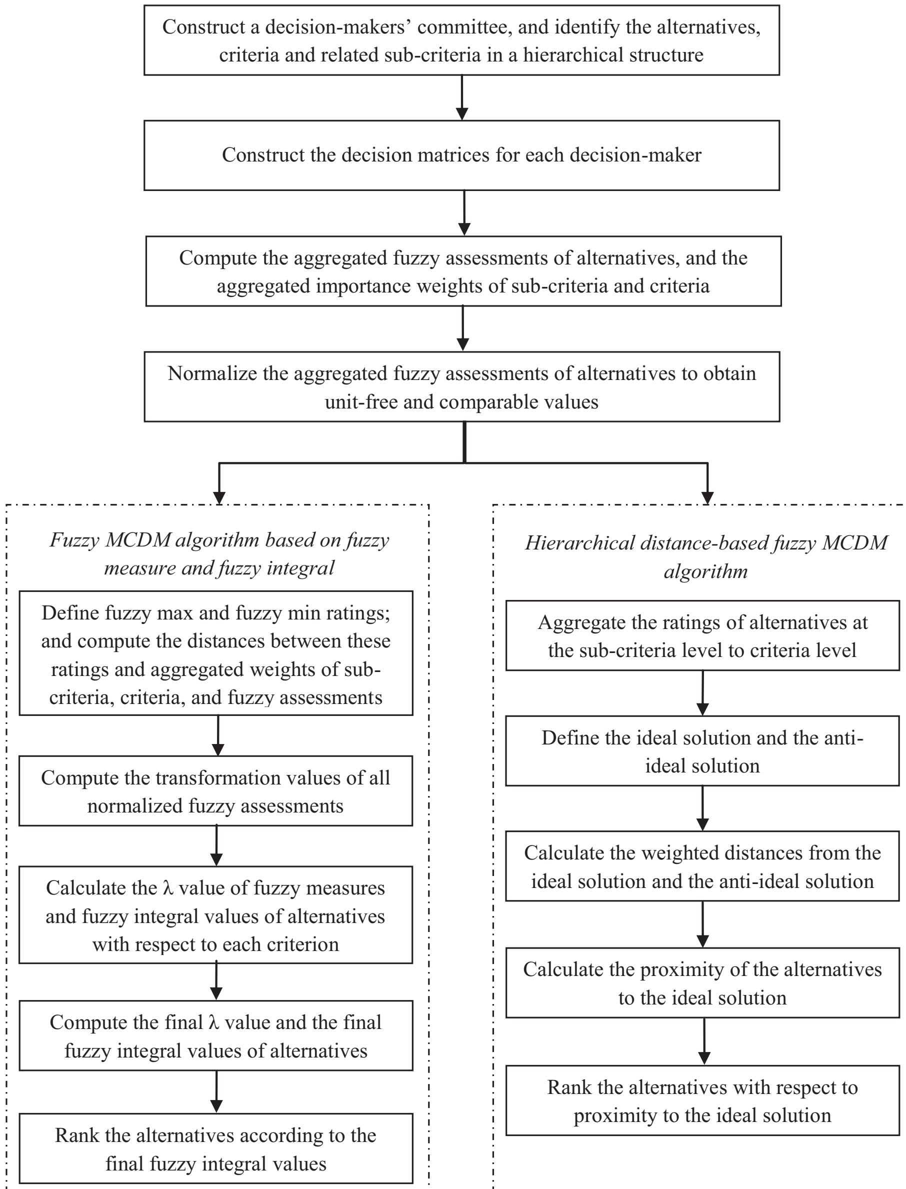

Fig. 1. Representation of the fuzzy MCDM algorithms.

for the data regarding benefit-related as well as cost-related sub-criteria are calculated via a linear scale transformation as

$$\tilde{r}_{ijk} = \left(r^1_{ijk}, r^2_{ijk}, r^3_{ijk}\right) = \begin{cases} \left(\dfrac{x^1_{ijk} - x^-_{jk}}{x^*_{jk} - x^-_{jk}}, \dfrac{x^2_{ijk} - x^-_{jk}}{x^*_{jk} - x^-_{jk}}, \dfrac{x^3_{ijk} - x^-_{jk}}{x^*_{jk} - x^-_{jk}}\right), & k \in CB_j; \quad i = 1, 2, \ldots, m; \quad j = 1, 2, \ldots, n \\ \left(\dfrac{x^*_{jk} - x^3_{ijk}}{x^*_{jk} - x^-_{jk}}, \dfrac{x^*_{jk} - x^2_{ijk}}{x^*_{jk} - x^-_{jk}}, \dfrac{x^*_{jk} - x^1_{ijk}}{x^*_{jk} - x^-_{jk}}\right), & k \in CC_j; \quad i = 1, 2, \ldots, m; \quad j = 1, 2, \ldots, n \end{cases} \tag{6}$$

where $\tilde{r}_{ijk}$ denotes the normalized value of $\tilde{x}_{ijk}$, $x^*_{jk} = \max_i x^3_{ijk}$, $x^-_{jk} = \min_i x^1_{ijk}$, m is the number of alternatives, n is the number of criteria, CB_j is the set of benefit-related sub-criteria of criterion j for which the greater the performance value the more its preference, and CC_j is the set of cost-related sub-criteria of criterion j for which the greater the performance value the less its preference.

Step 5. Define the fuzzy max rating $\tilde{P}^*$ and the fuzzy min rating $\tilde{P}^-$, and compute the distance between $\tilde{w}_{jk}$ and $\tilde{P}^*$ as $wd^*_{jk} = d_v\left(\tilde{w}_{jk}, \tilde{P}^*\right)$, $\tilde{w}_j$ and $\tilde{P}^*$ as $wd^*_j = d_v\left(\tilde{w}_j, \tilde{P}^*\right)$, and $\tilde{r}_{ijk}$ and $\tilde{P}^*$ as $d^*_{ijk} = d_v\left(\tilde{r}_{ijk}, \tilde{P}^*\right)$. Similarly, the distance between $\tilde{w}_{jk}$ and $\tilde{P}^-$, $\tilde{w}_j$ and $\tilde{P}^-$, and $\tilde{r}_{ijk}$ and $\tilde{P}^-$ are computed as $wd^-_{jk} = d_v\left(\tilde{w}_{jk}, \tilde{P}^-\right)$, $wd^-_j = d_v\left(\tilde{w}_j, \tilde{P}^-\right)$, and $d^-_{ijk} = d_v\left(\tilde{r}_{ijk}, \tilde{P}^-\right)$, respectively. For all these computations, $d_v(*, *)$ denotes the distance between two fuzzy numbers, which can be calculated by using Eq. (2).

Step 6. Compute the transformation values of fuzzy weights of all sub-criteria and criteria respectively as (Chen and Cheng, 2008)

$$RW_{jk} = \frac{wd_{jk}^-}{wd_{jk}^- + wd_{jk}^*} \tag{7}$$

and

$$RW_j = \frac{wd_j^-}{wd_j^- + wd_j^*} \tag{8}$$

Step 7. Compute the transformation values of all normalized fuzzy assessments as (Chen and Cheng, 2008)

$$RI_{ijk} = \frac{d_{ijk}^-}{d_{ijk}^- + d_{ijk}^*} \tag{9}$$

Step 8. Calculate the λ value of fuzzy measures and fuzzy integral (FI) values of all alternatives with respect to each criterion using Eqs. (A.4)–(A.6). In Eqs. (A.5) and (A.6), the function h is represented as the transformation values of normalized fuzzy assessments $\left(RI_{ijk}\right)$, and $g(K_1) = g^1 = RW_1$.
Step 9. Compute the final λ value and the final fuzzy integral values of alternatives.
Step 10. Rank the alternatives according to the final fuzzy integral values in descending order.

2.1.2. Hierarchical distance-based fuzzy MCDM approach

This subsection presents a robust fuzzy multi-criteria group decision making approach that can address decision problems having a multi-level hierarchical structure with qualitative performance attributes. Karsak (2002) introduced a distance-based fuzzy MCDM approach for technology selection that is based on the proximity to ideal solution concept and has the capability of incorporating both crisp and fuzzy data. The origins of Karsak's approach can be found in the multi-criteria decision aid named TOPSIS (technique for order preference by similarity to ideal solution) first developed by Hwang and Yoon (1981).

When a large number of performance attributes are to be considered in the evaluation process, it may be preferred to structure them in a multi-level hierarchy in order to conduct the analysis more effectively. In this subsection, the multi-expert version of the hierarchical distance-based fuzzy MCDM algorithm initially proposed by Karsak and Ahiska (2005) is presented. By considering the weighted distances from both ideal and anti-ideal solutions simultaneously, the proposed decision approach tackles the problem that an alternative with the shortest distance from the ideal may not have the farthest distance from the anti-ideal. The detailed presentation of the fuzzy multi-criteria approach is as follows:

Steps 1–4. The same as in the decision framework delineated in Subsection 2.1.1.
Step 5. Aggregate the performance ratings of alternatives at the sub-criteria level to criteria level as follows:

$$\tilde{y}_{ij} = (y_{ij}^1, y_{ij}^2, y_{ij}^3) = \frac{\sum_{k=1}^{p} \tilde{w}_{jk} \otimes \tilde{r}_{ijk}}{\sum_{k=1}^{p} \tilde{w}_{jk}}, \; i = 1, 2, \ldots, m; j = 1, 2, \ldots, n \tag{10}$$

where $\tilde{y}_{ij}$ represents the aggregate performance rating of alternative i with respect to criterion j and ⊗ is the fuzzy multiplication operator.

Step 6. Normalize the aggregate performance ratings at criteria level using a linear normalization procedure, which results in the best value to be equal to 1 and the worst one to be equal to 0, as follows:

$$\tilde{y}'_{ij} = (\tilde{y}'^1_{ij}, \tilde{y}'^2_{ij}, \tilde{y}'^3_{ij}) = \left(\frac{y_{ij}^1 - y_j^-}{y_j^* - y_j^-}, \frac{y_{ij}^2 - y_j^-}{y_j^* - y_j^-}, \frac{y_{ij}^3 - y_j^-}{y_j^* - y_j^-} \right), \quad i = 1, 2, \ldots, m; j = 1, 2, \ldots, n \tag{11}$$

where $y_j^* = \max_i y_{ij}^3$, $y_j^- = \min_i y_{ij}^1$, and $\tilde{y}'_{ij}$ denotes the normalized aggregate performance rating of alternative i with respect to criterion j.

Step 7. Define the ideal solution $A^* = (r_1^*, r_2^*, \ldots, r_n^*)$ and the anti-ideal solution $A^- = (r_1^-, r_2^-, \ldots, r_n^-)$, where $r_j^* = (1, 1, 1)$ and $r_j^- = (0, 0, 0)$ for $j = 1, 2, \ldots, n$.
Step 8. Calculate the weighted distances from ideal solution and anti-ideal solution (D_i^* and D_i^-, respectively) for each alternative as

$$D_i^* = \sum_{j=1}^{n} \frac{1}{2} \left\{ \max(\tilde{w}_j^1 \left|\tilde{y}'^1_{ij} - 1\right|, \tilde{w}_j^3 \left|\tilde{y}'^3_{ij} - 1\right|) + \tilde{w}_j^2 \left|\tilde{y}'^2_{ij} - 1\right| \right\}, \quad i = 1, 2, \ldots, m \tag{12}$$

$$D_i^- = \sum_{j=1}^{n} \frac{1}{2} \left\{ \max(\tilde{w}_j^1 \left|\tilde{y}'^1_{ij} - 0\right|, \tilde{w}_j^3 \left|\tilde{y}'^3_{ij} - 0\right|) + \tilde{w}_j^2 \left|\tilde{y}'^2_{ij} - 0\right| \right\}, \quad i = 1, 2, \ldots, m \tag{13}$$

Step 9. Calculate the proximity of the alternatives to the ideal solution, C_i^*, by considering the distances from ideal and anti-ideal solutions as

$$C_i^* = \frac{D_i^-}{D_i^* + D_i^-}, \quad i = 1, 2, \ldots, m. \tag{14}$$

Step 10. Rank the alternatives according to C_i^* values in descending order. Identify the alternative with the highest C_i^* as the best alternative.

2.2. Structure of the problem and experts survey

In order to illustrate the application of the proposed decision making methods to HCW treatment alternative selection, a case study conducted in Istanbul is presented. First, through interviewing the experts from Istanbul Metropolitan Municipality Environmental Protection and Waste Materials Valuation Industry and Trade Co. (ISTAC) that is responsible for collecting the HCW from hospitals in Istanbul, we reviewed and analyzed the current HCW treatment methods in Istanbul, and discussed the problems encountered in HCWM. It is reported that the amount of wastes collected and processed at the incineration plant in Istanbul has steadily increased as a result of the training efforts and the effect of the regulation (Birpinar et al., 2009). Even though the capacity of the incineration plant at Kemerburgaz-Odayeri is 24 tons per

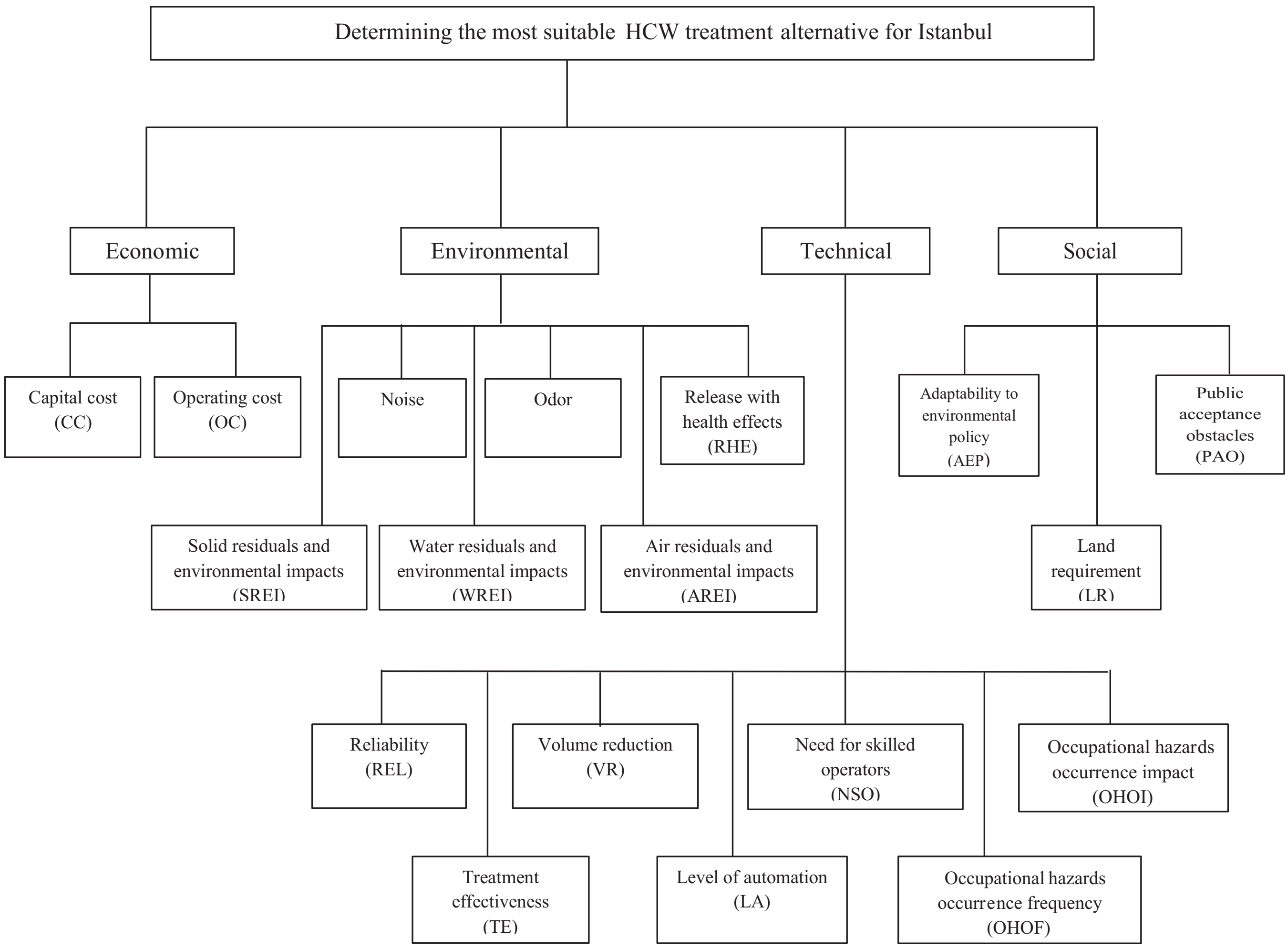

Fig. 2. Hierarchical structure of the problem.

day, approximately 42 tons of HCW is collected daily. Thus, the capacity of the existing incineration plant is not adequate to incinerate all the health-care wastes generated in Istanbul. As a result of discussions with experts from ISTAC, capacity of the alternative treatment technology is considered as 24 tons/day. Four possible treatment technologies are determined for health-care wastes in Istanbul. Treatment systems for steam sterilization and microwaving are selected with pre-shredding component exposing a greater surface area for treatment by utilizing a shredder that reduces the waste to a uniform and relatively small size matter. Alternatives can be listed as follows:

Alternative 1 (A_1): Incineration
Alternative 2 (A_2): Steam sterilization
Alternative 3 (A_3): Microwave
Alternative 4 (A_4): Landfill

Determining the most preferred HCW treatment technology depends on many specific factors. Benefiting from the literature on the evaluation of HCW treatment alternatives, economic, environmental, technical, and social criteria are identified as the selection criteria. Several relevant sub-criteria corresponding to these criteria are also identified in order to conduct a comprehensive evaluation of treatment alternatives. The hierarchical structure of the problem is depicted in Fig. 2.

The evaluation is conducted by a committee of five decision-makers, which consist of three field experts from ISTAC, who are professional environmental engineers working at managerial levels in ISTAC, a professor of industrial engineering, and a technical advisor specialized in waste management. A questionnaire is prepared concerning the evaluation criteria and the HCW treatment alternatives, and the experts are asked to provide their opinions on the importance weights of criteria and related sub-criteria, and the ratings with respect to qualitative criteria by using the linguistic variables provided in Table 2. The evaluations of five decision-makers (DM_1, DM_2, DM_3, DM_4 and DM_5) are given in Tables 3 and 4.

Based on the evaluations of the decision-making committee and the related literature, the operating cost figures for the HCW treatment alternatives are given as triangular fuzzy numbers as shown in Table 5. The operating cost estimates are provided as fuzzy numbers rather than crisp figures since techniques such as steam sterilization and microwave have not been previously used for treating HCW in Istanbul, and thus it is difficult to assign precise estimates. Furthermore, it is more practical to state operating cost estimates as ranges rather than point estimates due to the fact that these figures are likely to vary with respect to volume of HCW

Table 2
Linguistic term set.

Very low (VL)	(0, 0, 0.25)
Low (L)	(0, 0.25, 0.5)
Moderate (M)	(0.25, 0.5, 0.75)
High (H)	(0.5, 0.75, 1)
Very high (VH)	(0.75, 1, 1)

Table 3
Importance of the evaluation criteria and the related sub-criteria.

Criteria/Sub-criteria	DM_1	DM_2	DM_3	DM_4	DM_5
Economic	H	H	M	VH	H
CC	H	H	H	H	H
OC	VH	H	VH	VH	VH
Environmental	VH	VH	VH	VH	VH
SREI	H	H	H	H	H
WREI	VH	H	H	H	H
AREI	VH	VH	VH	H	VH
Noise	M	L	L	L	L
Odor	M	M	L	L	M
RHE	VH	VH	VH	VH	VH
Technical	M	H	H	H	H
REL	H	H	H	H	H
TE	VH	VH	VH	H	H
VR	M	H	M	VL	L
LA	H	M	H	M	H
NSO	H	M	M	M	M
OHOF	H	H	H	M	H
OHOI	H	VH	VH	H	H
Social	H	M	H	M	M
AEP	VH	H	H	VH	VH
PAO	H	H	M	VL	H
LR	VH	H	M	H	H

generated by the customers, frequency and distance for pickup in general, and equipment design and add-on pollution control equipment for incineration.

3. Results and discussion

Based on the data obtained from the interviews with the experts, the considered alternatives for the treatment of HCW are evaluated. The required computations of the proposed decision making algorithms relating to the abovementioned HCWM problem in Istanbul are summarized below.

By using Eqs. (3)–(5), the aggregated ratings of alternatives with respect to each sub-criterion, the aggregated importance weights of sub-criteria, and the aggregated importance weights of criteria are obtained through aggregating the decision-makers' evaluations. One shall note that $v_1 = v_2 = \ldots = v_5 = \frac{1}{5}$ in our case, since equal weights are assigned to decision-makers. The results are presented in Tables 6 and 7.

Then, employing Eq. (6), the aggregated ratings are normalized. The computational procedure for the two decision making approaches is identical up to and including the normalization step. First, the remaining steps of the fuzzy decision making framework based on fuzzy measure and fuzzy integral are summarized below.

The fuzzy max rating $\tilde{P}^*$ and the fuzzy min rating $\tilde{P}^-$ are defined as $\tilde{P}^* = (1,\ 1,\ 1)$ and $\tilde{P}^- = (0,\ 0,\ 0)$, respectively. Then, using Eqs. (2), (7) and (8), the transformation values of fuzzy weights of sub-criteria and criteria are computed as shown in Table 8.

The transformation values of all normalized fuzzy ratings are calculated as given in Table 9 by utilizing Eqs. (2) and (9).

By using Eqs. (A.4)–(A.6), the λ values of fuzzy measures and fuzzy integral values of all alternatives with respect to each criterion are computed as represented in Table 10.

The final λ value is calculated as $\lambda = -0.995$. The final fuzzy integral values for the HCW treatment alternatives are computed as $FI_1 = 0.693$, $FI_2 = 0.718$, $FI_3 = 0.713$, and $FI_4 = 0.702$. The ranking order of the alternatives is $A_2 \succ A_3 \succ A_4 \succ A_1$.

Table 4
Ratings of alternatives with respect to sub-criteria.

Sub-criteria		DM_1	DM_2	DM_3	DM_4	DM_5
CC	A_1	VH	VH	VH	VH	VH
	A_2	L	M	M	M	M
	A_3	M	M	M	H	M
	A_4	VL	L	L	L	L
SREI	A_1	L	M	L	M	L
	A_2	M	L	VL	M	M
	A_3	M	L	L	L	M
	A_4	H	VH	VH	H	VH
WREI	A_1	L	M	L	L	M
	A_2	L	L	VL	L	M
	A_3	VL	L	L	L	L
	A_4	M	VH	VH	H	VH
AREI	A_1	H	VH	VH	VH	VH
	A_2	L	L	VL	L	M
	A_3	VL	L	L	M	L
	A_4	M	H	M	H	L
Noise	A_1	M	M	H	VH	H
	A_2	L	L	L	M	M
	A_3	L	VL	M	M	M
	A_4	M	M	VL	VL	L
Odor	A_1	M	M	M	M	H
	A_2	L	L	L	H	M
	A_3	L	H	M	L	L
	A_4	VH	VH	VH	VH	M
RHE	A_1	H	VH	VH	M	VH
	A_2	L	L	VL	M	M
	A_3	L	L	L	L	L
	A_4	M	H	H	H	H
REL	A_1	H	VH	VH	VH	H
	A_2	H	M	VH	H	M
	A_3	M	M	M	M	M
	A_4	H	H	H	L	L
TE	A_1	H	H	H	H	H
	A_2	M	M	VH	M	M
	A_3	M	M	H	M	H
	A_4	L	L	VL	L	L
VR	A_1	M	M	H	VH	VH
	A_2	L	L	M	M	L
	A_3	L	L	M	M	VL
	A_4	VL	VL	VL	VL	VL
LA	A_1	H	H	H	M	H
	A_2	H	H	VH	H	M
	A_3	H	H	H	H	H
	A_4	M	L	L	VL	VL
NSO	A_1	H	VH	H	H	H
	A_2	M	H	M	M	M
	A_3	M	H	M	M	M
	A_4	L	M	L	L	L
OHOF	A_1	L	M	L	M	M
	A_2	L	M	VL	M	H
	A_3	L	L	L	M	M
	A_4	H	L	M	L	H
OHOI	A_1	H	H	H	VH	H
	A_2	H	H	M	H	M
	A_3	H	L	M	H	VH
	A_4	M	L	L	L	L
AEP	A_1	L	L	VL	M	M
	A_2	H	H	VH	H	H
	A_3	M	M	H	H	M
	A_4	L	L	VL	L	L
PAO	A_1	H	H	VH	VH	H
	A_2	M	L	L	L	L
	A_3	M	M	L	M	L
	A_4	H	H	VH	VH	VH
LR	A_1	H	M	H	L	H
	A_2	M	L	L	L	L
	A_3	M	L	L	L	M
	A_4	VH	VH	VH	VH	VH

Table 5
Operating cost estimates for the HCW treatment alternatives.

Sub-criteria	A_1	A_2	A_3	A_4
OC (US $ per kg)	(0.22, 0.24, 0.26)	(0.08, 0.10, 0.12)	(0.06, 0.10, 0.14)	(0.02, 0.07, 0.12)

Table 6
Aggregated ratings of alternatives with respect to sub-criteria.

Sub-Criteria	A_1	A_2	A_3	A_4
CC	(0.750, 1, 1)	(0.200, 0.450, 0.700)	(0.300, 0.550, 0.800)	(0, 0.200, 0.450)
OC	(0.110, 0.120, 0.130)	(0.040, 0.050, 0.060)	(0.030, 0.050, 0.070)	(0.010, 0.035, 0.060)
SREI	(0.100, 0.350, 0.600)	(0.150, 0.350, 0.600)	(0.100, 0.350, 0.600)	(0.650, 0.900,1)
WREI	(0.100, 0.350, 0.600)	(0.05, 0.250, 0.500)	(0, 0.200, 0.450)	(0.600, 0.850, 0.950)
AREI	(0.700, 0.950, 1)	(0.05, 0.250, 0.500)	(0.050, 0.250, 0.500)	(0.300, 0.550, 0.800)
Noise	(0.450, 0.700, 0.900)	(0.100, 0.350, 0.600)	(0.150, 0.350, 0.600)	(0.100, 0.250, 0.500)
Odor	(0.300, 0.550, 0.800)	(0.150, 0.400, 0.650)	(0.150, 0.400, 0.650)	(0.600, 0.850, 0.900)
RHE	(0.600, 0.850, 0.950)	(0.100, 0.300, 0.550)	(0, 0.250, 0.500)	(0.450, 0.700, 0.950)
REL	(0.650, 0.900, 1)	(0.450, 0.700, 0.900)	(0.250, 0.500, 0.750)	(0.300, 0.550, 0.800)
TE	(0.500, 0.750, 1)	(0.350, 0.600, 0.800)	(0.350, 0.600, 0.850)	(0, 0.200, 0.450)
VR	(0.500, 0.750, 0.900)	(0.100, 0.350, 0.600)	(0.100, 0.300, 0.550)	(0, 0, 0.250)
LA	(0.450, 0.700, 0.950)	(0.500, 0.750, 0.950)	(0.500, 0.750, 1)	(0.050, 0.200, 0.450)
NSO	(0.550, 0.800, 1)	(0.300, 0.550, 0.800)	(0.300, 0.550, 0.800)	(0.050, 0.300, 0.550)
OHOF	(0.150, 0.400, 0.650)	(0.200, 0.400, 0.650)	(0.100, 0.350, 0.600)	(0.250, 0.500, 0.750)
OHOI	(0.550, 0.800, 1)	(0.400, 0.650, 0.900)	(0.400, 0.650, 0.850)	(0.050, 0.300, 0.550)
AEP	(0.100, 0.300, 0.550)	(0.550, 0.800, 1)	(0.350, 0.600, 0.850)	(0, 0.200, 0.450)
PAO	(0.600, 0.850, 1)	(0.050, 0.300, 0.550)	(0.150, 0.400, 0.650)	(0.650, 0.900, 1)
LR	(0.350, 0.600, 0.850)	(0.050, 0.300, 0.550)	(0.100, 0.350, 0.600)	(0.750, 1, 1)

Table 7
Aggregated importance weights of criteria and related sub-criteria.

Criteria/Sub-criteria	Importance weight
Economic	(0.500, 0.750, 0.950)
CC	(0.500, 0.750, 1)
OC	(0.700, 0.950, 1)
Environmental	(0.750, 1, 1)
SREI	(0.500, 0.750, 1)
WREI	(0.550, 0.800, 1)
AREI	(0.700, 0.950, 1)
Noise	(0.050, 0.300, 0.550)
Odor	(0.150, 0.400, 0.650)
RHE	(0.750, 1, 1)
Technical	(0.450, 0.700, 0.950)
REL	(0.500, 0.750, 1)
TE	(0.650, 0.900, 1)
VR	(0.200, 0.400, 0.650)
LA	(0.400, 0.650, 0.900)
NSO	(0.300, 0.550, 0.800)
OHOF	(0.450, 0.700, 0.950)
OHOI	(0.600, 0.850, 1)
Social	(0.350, 0.600, 0.850)
AEP	(0.650, 0.900, 1)
PAO	(0.350, 0.550, 0.800)
LR	(0.500, 0.750, 0.950)

Table 9
Transformation values of normalized fuzzy ratings.

Criteria/Sub-criteria	A_1	A_2	A_3	A_4
Economic				
CC	0.111	0.540	0.460	0.735
OC	0.115	0.654	0.643	0.741
Environmental				
SREI	0.674	0.667	0.674	0.209
WREI	0.604	0.681	0.723	0.200
AREI	0.159	0.723	0.723	0.479
Noise	0.317	0.643	0.634	0.725
Odor	0.475	0.625	0.625	0.194
RHE	0.200	0.638	0.688	0.313
Technical				
REL	0.757	0.564	0.375	0.425
TE	0.700	0.571	0.580	0.265
VR	0.750	0.413	0.378	0.122
LA	0.646	0.681	0.688	0.239
NSO	0.277	0.479	0.479	0.688
OHOF	0.528	0.514	0.583	0.417
OHOI	0.277	0.396	0.404	0.688
Social				
AEP	0.347	0.735	0.580	0.265
PAO	0.239	0.688	0.604	0.200
LR	0.438	0.688	0.646	0.116

Table 8
Transformation values of fuzzy weights of all criteria and related sub-criteria.

Criteria/Sub-criteria	Transformation weights
Economic	0.694
CC	0.700
OC	0.848
Environmental	0.889
SREI	0.700
WREI	0.735
AREI	0.848
Noise	0.340
Odor	0.420
RHE	0.889
Technical	0.660
REL	0.700
TE	0.809
VR	0.429
LA	0.620
NSO	0.540
OHOF	0.660
OHOI	0.771
Social	0.580
AEP	0.809
PAO	0.551
LR	0.694

Second, the computational procedure of the hierarchical distance-based fuzzy multi-criteria group decision making approach after the normalization step is presented below.

Sub-criteria values are aggregated to criteria level using Eq. (10), and are represented in Table 11. The normalized values of these aggregate performance ratings are computed using Eq. (11), where 0 indicates the worst value and 1 indicates the best value. Then, the weighted distances from ideal and anti-ideal solutions, and the proximity of the alternatives to the ideal solution are calculated by employing Eqs. (12)–(14) respectively, as shown in Table 12. The ranking order of the HCW treatment alternatives is obtainedas

Table 10
λ values of fuzzy measures and fuzzy integral values.

	Economic	Environmental	Technical	Social
λ	−0.923	−0.999	−1	−0.966
A_1	0.115	0.632	0.742	0.405
A_2	0.637	0.716	0.637	0.726
A_3	0.615	0.722	0.644	0.630
A_4	0.740	0.545	0.658	0.247

Table 11
Criteria level aggregated values.

Criteria	A_1	A_2	A_3	A_4
Economic	(0, 0.047, 0.208)	(0.465, 0.615, 0.775)	(0.375, 0.571, 0.767)	(0.569, 0.795, 1)
Environmental	(0.165, 0.349, 0.655)	(0.458, 0.723, 0.959)	(0.483, 0.746, 0.993)	(0.064, 0.274, 0.544)
Technical	(0.303, 0.578, 0.831)	(0.248, 0.536, 0.790)	(0.226, 0.501, 0.791)	(0.148, 0.392, 0.678)
Social	(0.096, 0.306, 0.559)	(0.507, 0.763, 1)	(0.378, 0.637, 0.897)	(0, 0.108, 0.362)

$A_2 \succ A_3 \succ A_4 \succ A_1$, which is the same ranking given by the fuzzy decision making framework based on fuzzy measure and fuzzy integral.

The evaluation of four HCW treatment alternatives for Istanbul using the fuzzy multi-criteria decision making techniques yields the same ranking. We observe that "steam sterilization" ranks as the most suitable alternative, and it is followed by "microwave". "Steam sterilization" is the preferred alternative treatment method for Istanbul since it minimizes the impact on the environment and demonstrates a commitment to public health. It has also relatively low investment and operating cost when compared with other treatment alternatives. Non-incineration technologies are placed in the top ranks for the best alternative treatment technology since they appear to emit fewer pollutants and generate non-hazardous residues. While "landfill" is an economic alternative compared with other alternatives, it should only be used in a limited extent because of its significant pitfalls related to environment and public health. "Incineration" ranks after non-incineration alternative technologies since the incineration of HCW generates particulate matters and chemical compounds that can potentially affect human health and safety, and have a negative impact on the environment (Diaz et al., 2005). After the incineration processes, the volume and mass reduction of the HCW are very high. Although the operating cost of the process may seem low, the requirement for specially designed equipment and trained personnel in order to implement the improved standards, and the transportation of the residues/ashes of the incineration site to the landfills that are designed specifically for potentially hazardous wastes increase the cost of the incineration process. These increased costs, and the adverse effects of incineration on public health and the environment highlight the necessity to focus on alternative treatment techniques for HCW (Alagoz and Kocasoy, 2007). The construction of a central steam sterilization unit can be seen as the most cost effective and the most appropriate solution from the environmental and public health point of view.

Focusing on the usage of "steam sterilization" as a HCW treatment alternative for Istanbul has been stated as an objective in the Waste Management Action Plan (http://www.cygm.gov.tr/CYGM/Files/EylemPlan/atikeylemplani.pdf) prepared by the Ministry of Environment and Forestry of the Republic of Turkey. It is also worth noting that parallel to the findings of the research study presented herein, ISTAC has adopted the plan for constructing a sterilization plant for health-care waste with a capacity of 24 tons per day in Sile Kömürcüoda that is located at the Asian side of Istanbul (http://www.istac.com.tr/index.php?categoryid=29).

Table 12
Ranking of the HCW treatment alternatives.

A_i	D_i^*	D_i^-	C_i^*	Ranking
A_1	2.114	1.613	0.433	4
A_2	1.140	2.735	0.706	1
A_3	1.242	2.646	0.681	2
A_4	1.935	1.825	0.485	3

4. Conclusions

With the rising awareness of the environmental implications of waste disposal, the management and treatment of HCW are gaining more attention. HCWM is a high priority environmental concern in developing countries because poor management of HCW causes environmental pollution and health problems in terms of proliferation of diseases by viruses and micro-organisms, as well as contamination of ground water by untreated medical waste in landfills. Thus, the problems associated with treatment of HCW should be solved in a manner that minimizes the risks to the public health and human well-being, and the damage to the environment.

A sound treatment strategy for HCW in a large metropolis such as Istanbul can only be constructed using comprehensive analytical methods. Evaluation of HCW treatment alternatives is a critical group decision making problem that requires to trade-off multiple conflicting criteria with the involvement of a group of experts. The classical MCDM methods that consider deterministic or random processes cannot effectively handle group decision making problems including imprecise and linguistic information. In this paper, two alternative fuzzy multi-criteria group decision making frameworks are presented to rectify the problems encountered when using classical decision making methods in evaluating HCW treatment technologies. A hierarchy of evaluation criteria and their related sub-criteria is employed in order to conduct a more effective analysis. Besides having the capability of considering numerous attributes that are structured in a multi-level hierarchy, the proposed decision approaches enable the decision-makers to use linguistic terms, and thus, reduce their cognitive burden in the evaluation process. These approaches are apt to incorporate imprecise data represented as linguistic variables or triangular fuzzy numbers into the analysis. The proposed decision frameworks provide a direction to the process of generating new alternatives by establishing an ideal that stimulates creativity and invention of alternative ways to move towards it. As humans strive to be both as close as possible to the ideal and as distant as possible from the anti-ideal (Zeleny, 1982), both ideal and anti-ideal solutions are considered simultaneously in the presented approaches. Finally, these approaches do not employ fuzzy number ranking methods that can produce inconsistent results or even rankings contrary to intuition while comparing alternatives.

Both decision making approaches yield "steam sterilization", A_2, as the most suitable HCW treatment technology for Istanbul and "microwave", A_3, as the second alternative treatment technology. When the steam sterilization alternative is compared with other treatment methods, one shall note that the capital and the operating costs, and the adverse effects on health and the environment are relatively lower. The related authorities' focus on the usage of "steam sterilization" as a HCW treatment alternative for Istanbul supports the findings of the study. "Landfill" ranks as the third while "incineration" ranks as the last alternative according to both decision making frameworks mainly due to their adverse environmental and health impacts, and high capital and operating costs of the incineration method.

One shall note that the decision models presented here are not restricted to HCW treatment technology selection in Istanbul and could be applied to a similar HCWM problem in another location without any difficulty. It is also worth noting that the MCDM approaches proposed in here for evaluating HCW treatment alternatives can be easily programmed. Furthermore, the decision frameworks presented in this study can be straightforwardly applied to real-world group decision making problems in diverse disciplines including both crisp and fuzzy data. For further study, extensions of the proposed methodologies can be developed incorporating both subjective and objective weight assessments of the criteria and related sub-criteria.

Appendix A.

Definition 1. Consider a set of n evaluation criteria $K = \{s_1, s_2, \ldots, s_n\}$. If a function $g : 2^K \to [0,\ 1]$ has the following properties, g is called a fuzzy measure (Ishii and Sugeno, 1985).

$$(1)\ g(\phi) = 0, \quad g(K) = 1 \tag{A.1}$$

$$(2)\ A, B \in 2^K, \quad A \subset B \to g(A) \le g(B) \tag{A.2}$$

The triplet $\left(K,\ 2^K,\ g\right)$ is called a fuzzy measure space.

Definition 2. If a fuzzy measure g has the following properties, then g is a λ-measure (Ishii and Sugeno, 1985). If $A,\ B \in 2^K$ and $A \cap B = \phi$, then

$$g(A \cup B) = g(A) + g(B) + \lambda g(A) g(B) \tag{A.3}$$

where $\lambda \in [-1, \infty)$.

The value of λ is determined by solving the following equation (Chen and Chiou, 1999)

$$\lambda + 1 = \prod_{j=1}^{n} \left(1 + \lambda g^j\right) \tag{A.4}$$

Although $(n-1)$ roots will be obtained, there exists only a unique $\lambda \in [-1, \infty)$, and $\lambda \neq 0$, which satisfies Eq. (A.4).

Definition 3. Consider a fuzzy measure space $\left(K,\ 2^K,\ g\right)$. The fuzzy integral of a function $h : K \to [0,\ 1]$ with respect to g is defined as follows (Ishii and Sugeno, 1985).

$$\int_K h(s) \cdot g(\cdot) = \bigvee_{j=1}^{n} \left[h\left(s_j\right) \wedge g\left(K_j\right)\right] \tag{A.5}$$

where

$$h\left(s_j\right) \le h\left(s_j + 1\right), \quad \textit{for}\ 1 \le j \le n-1$$
$$K_j = \left\{s_1, s_2, \ldots, s_j\right\}, \quad j = 1, 2, \ldots, n.$$

The values of $g\left(K_j\right)$ can be determined recursively as (Chen and Chiou, 1999)

$$\begin{aligned} & g(K_1) = g(\{s_1\}) = g^1, \\ & g\left(K_j\right) = g^j + g\left(K_{j-1}\right) + \lambda g^j g\left(K_{j-1}\right), \quad \text{for } 1 < j \le n \end{aligned} \tag{A.6}$$

where $g^j = g\left(\left\{s_j\right\}\right)$, g^j is called the jth fuzzy density and interpreted as the degree of importance of the evaluation criteria s_j, $j = 1, 2, \ldots, n$. In addition, the value of λ is determined by solving Eq. (A.4).

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