EVALUATING SOLID WASTE MANAGEMENT SCENARIOS USING FUZZY MULTI-CRITERIA DECISION MAKING APPROACHES

(KATI ATIK YÖNETİMİ SENARYOLARININ BULANIK ÇOK ÖLÇÜTLÜ KARAR VERME YAKLAŞIMLARI İLE DEĞERLENDİRİLMESİ)

by

Mehtap DURSUN, B.S.

Thesis

Submitted in Partial Fulfillment

of the Requirements

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As environmental issues become increasingly important for organizations, the management of environmental decisions becomes critical. Solid waste management (SWM) is considered as an important part of the environmental management problems. Solid wastes can be defined as all of the undesirable and unavailing materials arising from routine or business or industrial human activity and animal activity. Due to the rise in the environmental problems caused by the solid wastes, it is necessary to construct an efficient waste management system, which considers numerous factors including environmental, economic, social and technical aspects. Some of these factors can be quantified, while others are qualitative at most. To deal with quantitative and qualitative considerations of the waste management problems, multi-criteria decision making (MCDM) techniques can be used.

This study focuses on the detailed multi-attribute evaluation of a number of solid waste management scenarios to determine the most suitable one for Istanbul. Economic, technical, environmental, and social criteria and their related sub-criteria, which incorporate both quantitative and qualitative data are employed to evaluate the alternative waste management scenarios.

I wish to express my sincere thanks to Prof. Dr. E. Ertuğrul KARSAK for his supervision, support and guidance of this study. Also, I wish to express all my gratitude to him, for the time that he devoted to me, for his criticisms and his patience.

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Mehtap DURSUN
May, 2007

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LIST OF SYMBOLS

SWM	: Solid waste management
MSWM	: Municipal solid waste management
MSW	: Municipal solid waste
MCDA	: Multi-criteria decision analysis
MCDM	: Multi-criteria decision making
MODM	: Multi-objective decision making
MADM	: Multi-attribute decision making
AHP	: Analytic hierarchy process
OWA	: Order weighted average
ELECTRE	: Elimination et choix traduisant la realité
PROMETHEE	: Preference ranking organization method for enrichment evaluation
DEA	: Data envelopment analysis
GIS	: Geographic information systems
TOPSIS	: Technique for order preference by similarity to ideal solution
ISTAC Co.	: Istanbul Metropolitan Municipality Environmental Protection and Waste Materials Valuation Industry and Trade Co.

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ABSTRACT

In the recent past, an increasing number of researchers have been focusing on working out realistic solutions to environmental problems. As environmental issues become increasingly important for organizations, the management of environmental decisions becomes critical. Solid waste management (SWM) is considered as an important part of the environmental management problems.

Solid wastes can be defined as all of the undesirable and unavailing materials arising from routine or business or industrial human activity and animal activity. It is possible to classify the solid wastes by their resource as municipal, commercial, industrial, open areas, treatment plant sites and agriculture solid wastes.

The strategy defined to achieve sustainable waste management practice, named as "waste hierarchy", is denoted in Figure 1.

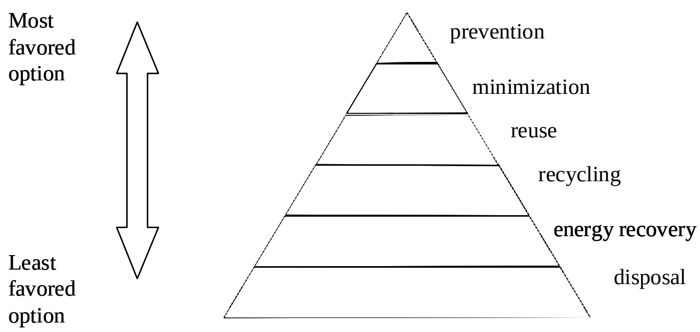


Figure 1. Waste hierarchy

Modeling of waste management is not a recent issue. The first waste management models were optimization models and dealt with specific aspects of the problem. As a result of the recent upsurge in environmental problems caused by the solid wastes, determining an efficient waste management system, which considers environmental, technical, economic and social factors, is of outmost importance. Some of these factors can be quantified, while others are qualitative at most. To deal with quantitative and qualitative considerations of the waste management problems, multi-criteria decision making (MCDM) techniques can be used.

This study focuses on the detailed multi-attribute evaluation of a number of solid waste management scenarios to determine the most suitable one for Istanbul. In classical 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. Fuzzy set theory can be used in real-world decision making problems for quantifying the qualitative data. After gathering the data, an appropriate multiple criteria decision analysis method is selected for either determining the most suitable alternative solutions or ranking them.

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 a more effective analysis. Real-world decision problems such as the selection of the best SWM scenario for Istanbul often involve the consideration of numerous performance attributes, yielding in general a multi-level hierarchical structure.

In this study, both the hierarchical fuzzy MCDM algorithm proposed by Karsak and Ahiska (2005), and the fuzzy analytic hierarchy process (AHP) method proposed by Chang (1996) have been employed for addressing the solid waste management problem in Istanbul including recycling, landfill, incineration, and composting processes. Economic, technical, environmental, and social criteria and their related sub-criteria, which incorporate both quantitative and qualitative data, are employed to evaluate the alternative waste management scenarios.

Karsak and Ahıska’s MCDM algorithm is based on the proximity to the ideal solution concept and it can address decision problems containing both crisp and fuzzy data. The origins of the proposed decision-making procedure are found in the multi-criteria decision tool named TOPSIS (technique for order preference by similarity to ideal solution). TOPSIS is based on the intuitive principle that the preferred alternative should have the shortest distance from the ideal solution and the farthest distance from the anti-ideal solution. TOPSIS is a widely accepted multi-attribute decision making technique due to its sound logic, simultaneous consideration of the ideal and the anti-ideal solutions, and easily programmable computation procedure. Although TOPSIS has numerous advantages, it requires quantitative attributes expressed as crisp numbers. Karsak and Ahıska's algorithm can handle crisp data and fuzzy data expressed in linguistic terms or triangular fuzzy numbers. This ability will facilitate the use of the algorithm in SWM scenario selection process requiring both quantitative and qualitative aspects to be taken into consideration.

A different systematic approach that uses both the linguistic assessments and numerical values for the alternative selection problem having multi-level hierarchical structure is named as fuzzy analytic hierarchy process. Fuzzy AHP uses the concepts of fuzzy set theory and hierarchical structure analysis for the selection of the most appropriate alternative among set of feasible alternatives. In this study, we use Chang's extent analysis method. The extent analysis method represents performance scores by membership functions and uses entropy concepts to calculate aggregate weights. The method is based on both probability and possibility measures.

After the evaluation of different SWM scenarios for Istanbul using two fuzzy multiple criteria decision making methods, the rankings are obtained. The rankings obtained from two MCDM methods appear to be very close. With the two methods, we obtained the fourth scenario as the best alternative for Istanbul, due to higher percentages of recycling and composting. Although, landfill has several drawbacks for the environment, the scenarios with high landfill percentages rank after scenario four since landfill is a highly economic alternative compared with incineration. Finally, the scenarios with high incineration percentages are found at the lowest ranks because of the high cost and adverse environmental impacts of incineration.

RESUME

Dans le passé récent, un nombre croissant des chercheurs s'est concentré mettant au point des solutions réalistes de problèmes environnementaux. Comme des questions environnementales deviennent de plus en plus importantes pour des organisations, la gestion de décisions environnementales devient critique. On considère la gestion des déchets solide comme une partie importante des problèmes de gestion environnementaux.

Des déchets solides peuvent être définis comme tous les matières indésirables et inutiles résultant de l'activité humaine ordinaire ou d'affaires ou industrielle et l'activité animale. Il est possible de classifier les déchets solides par leur ressource comme des secteurs municipaux, commerciaux, industriels, ouverts, des sites d'usine de traitement et des déchets solides d'agriculture.

La stratégie définie pour réaliser la gestion des déchets durable, nommée comme "la hiérarchie de déchets", est dénotée dans la Figure 1.

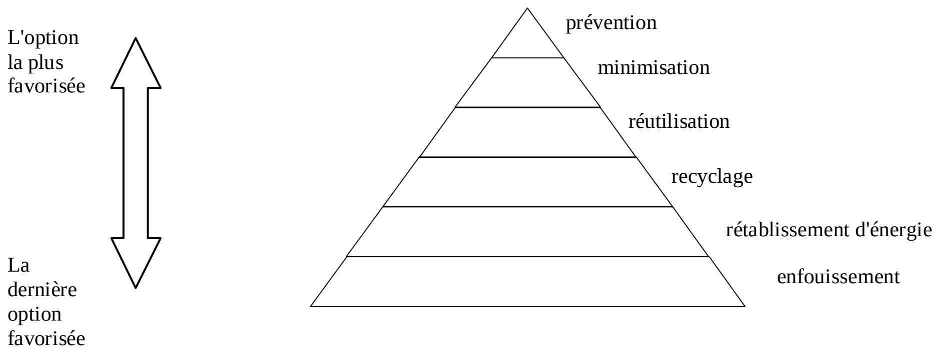


Figure 1. Hiérarchie de déchets

Modeler de la gestion des déchets n'est pas une issue récente. Les premiers modèles de gestion des déchets étaient des modèles d'optimisation et traité des aspects spécifiques du problème. Suite à l'augmentation récente de problèmes environnementaux causés par les déchets solides, déterminant un système de gestion des déchets efficace, qui considère des facteurs environnementaux, techniques, économiques et sociaux, ont d'importance. Certains de ces facteurs peuvent être évalués quantitativement, tandis que d'autres sont qualitatifs au plus. Pour traiter avec les considérations quantitatives et qualitatives des problèmes de gestion des déchets, la méthode d'aide à la décision multicritère peut être utilisée.

Cette étude se concentre sur l'évaluation d'un certain nombre de scénarios de gestion de déchets solides pour déterminer le plus approprié pour Istanbul. Dans des méthodes d'aide à la décision multicritère classiques, on assume que les évaluations et les poids des critères sont connus avec précisément. En général, des données précisées soient insatisfaisantes pour modeler des situations réelles. La théorie des ensembles flous peut être employée dans des problèmes de décisions réalistes pour mesurer les données qualitatives.

Quand un grand nombre d'attributs doivent être considérés dans le processus d'évaluation, il peut préférer les structurer dans une hiérarchie à multi niveaux afin de conduire une analyse plus efficace. Les problèmes réels de décision tels que le choix du meilleur scénario de gestion des déchets pour Istanbul impliquent souvent la considération de nombreux attributs, rapportant en général une structure hiérarchique à multi niveaux.

Dans cette étude, l'algorithme proposé par Karsak et Ahiska (2005), et l'analytique hierarchy processus (AHP) floué proposée par Chang (1996) ont été utilisés pour adresser le problème de gestion de déchets solides à Istanbul comprenant la recyclage, l'enfouissement des déchets, l'incinération, et le compostage processus. Des critères économiques, techniques, environnementaux, et sociaux et leurs relatifs sub-critères, qui incorporent des données quantitatives et qualitatives, sont utilisés pour évaluer les scénarios de gestion des déchets alternatifs.

L'algorithme d'aide à la décision multicritère de Karsak et d'Ahıska est basé sur la proximité de la solution idéale et il peut adresser des problèmes de décision contenant des données précisés et floués. Les origines de la méthode proposée sont trouvées dans la décision outil appelé TOPSIS (technique de multicritère pour la préférence d'ordre par similitude à la solution idéale). TOPSIS est basé sur le principe intuitif que l'alternative préférée devrait avoir la distance la plus courte de la solution idéale et la distance la plus lointaine de la solution anti-idéale. TOPSIS est largement admis la méthode d'aide à la décision multi attribue grâce à sa logique saine, considération simultanée des solutions idéales et anti-idéales. Bien que TOPSIS ait de nombreux avantages, il exige des attributs quantitatifs exprimés comme des nombres précisés. L'algorithme de Karsak et d'Ahıska peut manipuler des données précisées et des données flouées exprimées en termes linguistiques ou nombres floues triangulaires.

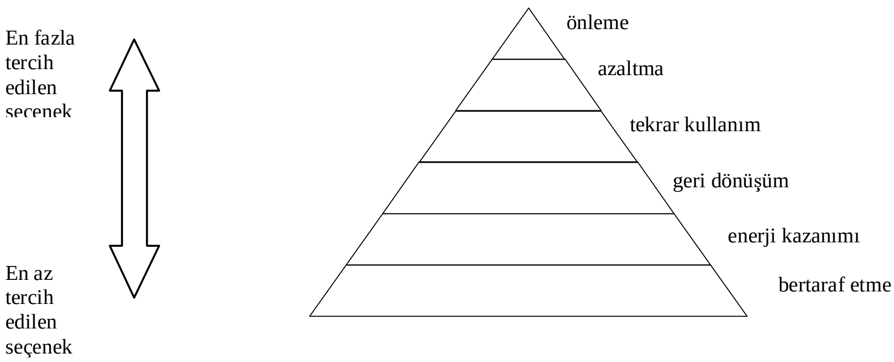
Une approche systématique différente qui emploie les évaluations linguistiques et des valeurs numériques pour le problème choix d'alternatif ayant la structure hiérarchique à multi niveaux est appelée l'analytique hierarchy processus floué. AHP floué emploie les concepts de la théorie des ensembles floues et de l'analyse hiérarchique de structure pour le choix de l'alternative la plus appropriée parmi l'ensemble de solutions possibles.

Après l'évaluation de différents scénarios de gestion des déchets pour Istanbul en utilisant deux méthodes, les rangs sont obtenus. Les rangs obtenus à partir de deux méthodes d'aide à la décision multicritère semblent être très étroits. Avec les deux méthodes d'aide à la décision multicritère, nous avons obtenu le quatrième scénario comme la meilleure alternative pour Istanbul, grâce à des pourcentages plus élevés du recyclage et du compostage. Bien que, l'enfouissement des déchets ait plusieurs inconvénients pour l'environnement, les scénarios avec des pourcentages élevés de l'enfouissement des déchets se rangent après le scénario quatre puisque l'enfouissement des déchets est une alternative fortement économique comparée à l'incinération. En conclusion, les scénarios avec des pourcentages élevés d'incinération sont trouvés aux plus bas rangs en raison du coût élevé et des incidences sur l'environnement défavorables de l'incinération.

ÖZET

Günümüzde, çevre sorunlarına etkin çözüm bulabilmek için yürütülen çalışmaların sayısı hızla artmaktadır. Organizasyonlar için çevresel sorunların önemi arttıkça, çevresel kararların yönetilmesi kritik hale gelmiştir. Katı atıklar, çevresel yönetim probleminin önemli bir kısmını oluşturmaktadır. Katı Atıkların Kontrolü Yönetmeliği'ne göre katı atıklar, üreticisi tarafından atılmak istenen ve toplumun huzuru ile özellikle çevrenin korunması bakımından düzenli bir şekilde bertaraf edilmesi gereken katı maddeler ve arıtma çamurları, olarak tanımlanmaktadır.

Katı atık yönetimi, atık maddelerin, insan sağlığı üzerindeki etkilerini azaltmak için, toplanması, taşınması, işlenmesi, geri kazanılması veya yok edilmesi olarak tanımlanabilir. Sürdürülebilir atık yönetimine ulaşabilmek için belirlenmiş olan ve "atık hiyerarşisi" olarak adlandırılan strateji Şekil 1'de görülmektedir.



Şekil 1. Atık hiyerarşisi

Atık hiyerarşisinde yer alan geri dönüşüm, atıkların bir üretim prosedürüne tabi tutularak, orijinal amaçlı ya da enerji geri kazanımı hariç olmak üzere, organik geri dönüşüm dahil diğer amaçlar için yeniden işlenmesi olarak tanımlanmaktadır. Enerji geri kazanımı ise yanabilir ambalaj atıklarının; ısının geri kazanımı amacıyla, doğrudan tek başına ya da diğer atıklarla birlikte yakılarak enerji üretilmesini ifade etmektedir.

Katı atıkları bertaraf etme yöntemleri düzenli depolama ve yakma süreçlerini içermektedir.

Katı atık yönetimi modellerinin oluşturulması ve katı atık yönetim sistem ve teknolojilerinin seçiminde karar verme yöntemlerinden faydalanılması yeni bir araştırma alanı olmasa da, konunun önem kazanması ve gelişmiş tekniklerden faydalanılması özellikle son dönemlere rastlamaktadır. Gerek bir işletmenin gerekse bir şehrin katı atık yönetiminde, yıllardan beri süregelen şekilde düşük maliyet ölçütünün dikkate alınması, en uygun alternatifin belirlenmesinde tek başına yeterli olmamakta; artan çevre bilinci ve sınırlı doğal kaynak rezervleri, düşük maliyet ölçütünün yanı sıra sosyal, çevresel ve teknik etmenlerin de göz önüne alınmasını gerektirmektedir. Katı atık yönetim sistemi seçim problemi, birbiriyle çelişen ve hiyerarşik yapıya sahip, farklı ölçütler içeren yapısıyla çok ölçütlü karar verme yöntemlerinin uygulanmasına uygun bir zemin oluşturmaktadır.

Bu çalışmanın amacı, İstanbul için en uygun katı atık yönetim senaryosunun belirlenmesidir. Klasik çok ölçütlü karar verme yöntemlerinde, ölçütlerin ağırlıklarının veya önem derecelerinin kesin olarak bilindiği varsayılmaktadır. Kesin veriler gerçek hayat durumlarını modellemede yetersiz kalmaktadır. Nitel veriler içeren ölçütlerin sayısallaştırılmasında bulanık küme teorisinden yararlanılabilmektedir.

Bu çalışmada, geri dönüşüm, düzenli depolama, yakma ve kompostlama süreçlerinden bir veya birkaç tanesini içeren, İstanbul için belirlenmiş alternatif katı atık yönetim senaryoları Karsak ve Ahıska (2005) tarafından önerilmiş olan hiyerarşik bulanık çok ölçütlü karar verme yöntemi ve Cheng (1996) tarafından önerilmiş olan bulanık analitik hiyerarşi süreci (analytic hierarchy process - AHP) yöntemi kullanılarak değerlendirilmiştir. Ekonomik, teknik, çevresel ve sosyal ölçütler ve bunların alt ölçütlerinin hiyerarşik yapısı, alternatif katı atık yönetim senaryolarının değerlendirilmesinde kullanılmıştır.

Karsak ve Ahıska'nın önermiş olduğu yöntem ideal çözüme yakınlık olgusuna dayanan ve hem bulanık hem de kesin verilerin bir arada değerlendirilmesine olanak sağlayan bir yaklaşımla karar vericiye ışık tutmaktadır. Klasik çok ölçütlü karar verme yöntemlerinde, ölçütlerin ağırlıklarının ve önem derecelerinin kesin olarak bilindiği varsayılmaktadır. Kesin veriler gerçekte karşılaşılan problemleri modellemede yetersiz kalmaktadır. Önerilen karar verme yöntemleri, ölçütleri hiyerarşik bir yapıda modellemekle birlikte, karar vericiye sözel değişkenleri kullanma olanağı sağlamaktadır. Sonuç olarak, bu çalışmada kullanılan karar verme yöntemleri, karar vericinin kesin olmayan varsayımlarını sayısallaştırmasındaki etkinliği ile kullanışlı ve sağlıklı sonuçlar veren karar verme yöntemleri olarak belirmektedir.

Elde edilen sonuçlar irdelendiğinde, kullanılan iki yöntem ile bulunan sonuçların birbirine benzer olduğu görülmektedir. Senaryo 4'ün, diğer senaryolarla kıyaslandığında daha yüksek geri dönüşüm ve kompostlama oranına sahip olması nedeniyle en iyi katı atık yönetim senaryosu olarak belirlendiği görülmektedir. Düzenli depolama ekonomik bir alternatif olduğu için, düzenli depolama oranı yüksek olan senaryoların S_4'ten sonra sıralandığı, yakma oranı yüksek olan senaryoların ise yüksek maliyet ve olumsuz çevre etkileri nedeni ile son sıralarda yer aldığı gözlenmektedir.

1. INTRODUCTION

Recently, an increasing number of researchers have been focusing on working out realistic solutions to environmental problems. As environmental issues become increasingly important for organizations, the management of environmental decisions becomes critical. Solid waste management (SWM) is considered as an important part of the environmental management problems.

Table 1.1 Classification of solid wastes [1]

Source	Activities & location	Types of solid wastes
Municipal	Single-family and multi-family dwellings, low, medium and high rise apartments	Food waste, rubbish, ashes, special wastes
Commercial	Stores, restaurants, markets, office buildings, hotels, print shops, auto repair shops, medical facilities and institutions, etc.	Food waste, rubbish, ashes, demolition and construction wastes, occasionally hazardous wastes
Industrial	Construction, fabrication, light and heavy manufacturing, refineries, chemical plants, lumbering, mining, power plants, demolition, etc.	Food waste, rubbish, ashes, demolition and construction wastes, special wastes, hazardous wastes
Open areas	Streets, alleys, parks, vacant lots, playgrounds, beaches, highways, recreational areas, etc.	Special wastes, rubbish
Treatment plant sites	Water, waste water and industrial treatment processes, etc.	Treatment plant wastes principally composed of residual sludge
Agriculture	Field and row crops, orchards, vineyards, diaries, feedlots, farms, etc.	Spoiled food wastes, agricultural wastes, rubbish, hazardous wastes

Solid wastes can be defined as all of the undesirable and unavailing materials arising from routine or business or industrial human activity and animal activity. It is possible to classify the solid wastes by their resource as in Table 1.1. For a robust environment, these wastes should be effectively disposed both in economical and ecological terms within the context of waste hierarchy.

Istanbul, with more than 12 million inhabitants, is the most crowded city of Turkey and approximately 10000 ton/day of solid wastes are produced in this metropolitan. Until 1953, the wastes of Istanbul were thrown away to sea, from that day forward the wastes have been started to be dumped in wide areas without any control. Consequently, environmental pollution was imminent. In 1995, the government terminated that implementation and solid waste disposal techniques have been started to be used. Six transfer centers were constructed and the wastes collected were initially stored in these centers, and then, they were transported to disposal areas.

The composition of solid wastes in Istanbul varies to the seasons. The average composition of material groups is shown in Figure 1.1.

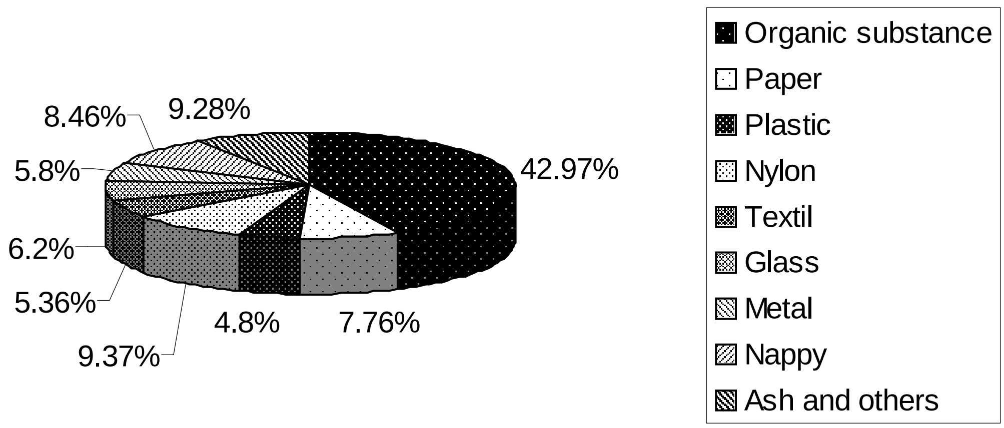


Figure 1.1 Average composition of material groups in Istanbul [2]

Modeling of waste management is not a recent concept [3]. The first waste management models were optimization models and dealt with specific aspects of the problem [4]. Most waste management models consider economic and environmental factors, but very few of them consider social aspects. For a waste management system to be sustainable, it needs to be environmentally effective, economically affordable and socially acceptable [3]. To deal with quantitative and qualitative considerations of the waste management problems, multi-criteria decision analysis (MCDA) techniques can be used [5].

MCDA is both an approach and a set of techniques, with the goal of providing an overall ordering of options, from the most preferred to the least preferred option [6]. MCDA is divided in two groups as multi-objective decision making (MODM) and multi-attribute decision making (MADM). The intention of MCDA methods is to improve the quality of decisions by making choices more explicit, reasonable and effective [7].

This study focuses on the detailed multi-attribute evaluation of a number of solid waste management scenarios to determine the most suitable one for Istanbul. In most real-world solid waste management problems, uncertainty plays an important role [8]. Fuzzy set theory can be used in real-world decision making problems for quantifying the qualitative data. In our study, we have used both the crisp and fuzzy data.

The rest of the study is organized as follows: In section 2, literature review on waste management is given. Section 3 analyzes the different waste management strategies. Section 4 reviews multi-criteria decision making, and the fifth section presents the basics of fuzzy set theory. Section 6 analyzes the fuzzy decision making methodologies employed in this study for the evaluation of alternative waste management scenarios. Section 7 presents the application of the proposed models to Istanbul's waste management problem. Finally, conclusions are provided in section 8.

2. LITERATURE REVIEW

In the literature, there are a number of studies that evaluate the SWM strategies. We can classify these studies according to the methods used.

Analytic hierarchy process (AHP)-based methods were used in the first group. Seo et al. [9] executed AHP for evaluating the best alternative for a solid waste management system. Karamouz et al. [10] introduce a new framework to develop a master plan for solid waste management by using AHP. Gemitzi et al. [11] applied the AHP and order weighted average (OWA) to determine the site of municipal solid waste landfills.

Outranking methods were used in the second group. Hokkanen and Salminen [12] employed preference ranking organization method for enrichment evaluation (PROMETHEE) to the location of a waste treatment facility in eastern Finland. Chung and Poon [13] used dominance pairwise comparison to determine the preferred waste management option for Hong Kong. Hokkanen and Salminen [14] employed ELECTRE III method for choosing a SWM system in the Oulu region, Finland. Karagiannidis and Moussiopoulos [15] ranked the municipal solid waste alternatives by applying elimination et choix traduisant la realité (ELECTRE) III.

In the third group, fuzzy techniques were used. Chang and Wang [16] executed nonlinear fuzzy goal programming to evaluate various types of solid waste management planning scenarios. Chang and Lu [17] proposed fuzzy global criterion technique and fuzzy multi-objective mixed integer programming for the long term planning of metropolitan solid waste management systems. Chang and Wang [8] employed fuzzy goal programming for the optimal planning of solid waste management systems in a metropolitan region. Huang et al. [18] developed interval-parameter fuzzy integer programming for the planning of waste flow allocation and facility expansion. Sadiq et al. [19] employed AHP, aggregation and defuzzification methods for the selection of the best drilling waste discharge option. Different fuzzy MCDM techniques to resolve the insufficiencies in policy impact analysis used for decision making in Taiwan are applied for developing a decision making model of municipal SWM by Su et al [20].

In the fourth group, integer programming was employed. Chang et al. [21] presented a sustainable waste management strategy in which the decision makers and the environmental analysts may put forward their views on the assimilative capacity of environment by using mixed integer programming model. Chang et al. [22] presented mixed integer programming and dynamic optimization approaches to present sustainable waste management strategies in which the decision makers may put forward their views on material recycling and the assimilative capacity of the environment. Chang and Wang [23] applied multi-objective mixed integer programming for reasoning the potential conflict between environmental and economic goals and evaluating sustainable strategies for waste management in a metropolitan region. Chang et al. [24] implemented mixed-integer programming for the collection vehicle routing and scheduling. Ferrell and Hizlan [25] constructed an integrated municipal solid waste management plan in several South Carolina counties by using mixed-integer programming model. Berger et al. [26] proposed mixed-integer linear programming to help regional decision-makers in the long term planning of solid waste management activities. Vaillancourt and Waaub [27] elaborated the waste management plans on a regional scale by employing mixed integer linear programming. Maqsood et al. [28] presented an inexact two-stage mixed integer linear programming approach for Planning of regional solid waste management system under uncertainty. Li and Huang [29] developed interval-parameter two-stage mixed integer linear programming for the long-term planning of waste management activities in the City of Regina. Recently, Pati et al. [30] determined the facility location, route and flow of different varieties of recyclable wastepaper by using mixed integer goal programming model. Chang and Davila [31] used minimax regret integer programming model for improving SWM strategies in the Lower Rio Grande Valley based on different environmental, economic, legal, and social conditions.

The papers that used linear programming can be classified into the fifth group. Everett and Modak [32] used piecewise linear approximation method and linear programming for the long-term scheduling of disposal and diversion options in a regional integrated solid waste management system. Chang and Wang [33] employed goal programming to evaluate the compatibility issues between municipal solid waste (MSW) recycling and incineration. Amouzegar and Moshirvaziri [34] implemented linear bi-level programming for waste capacity planning and treatment facility location. Cosmi et al. [35] evaluated the feasibility of the model in representing the waste management system to estimate the environmental impact of the waste processing technologies in the context of the whole productive system by applying linear programming model. Sarkis and Weinrach [36] used data envelopment analysis (DEA) to evaluate environmentally conscious waste treatment technologies. Linear programming has been used to assist in identifying alternative SWM strategies that meet cost, energy, and environmental emissions objectives by Solano et al. [37]. Najm and El-Fadel [38] planned a regional waste management strategy by using linear programming model. Lin et al. [39] assessed different municipal solid waste management (MSWM) policies, especially regionalization strategies, and their impact on MSWM systems in the Taipei metropolitan area by using linear programming model.

Non-linear programming was utilized in the sixth group. Fiorucci et al. [40] helped decision-makers of a municipality in the development of incineration, disposal, treatment and recycling integrated programs by employing non-linear optimization model. Costi et al. [41] helped decision makers of a municipality in the development of incineration, disposal, treatment and recycling integrated programs by using non-linear programming model.

The papers that used grey programming can be found in the seventh group. Huang et al. [42, 43, 44, 45] developed grey fuzzy quadratic programming and grey linear programming for allocating the waste flow within a municipal solid waste management system in two different studies. They also used grey dynamic programming and grey fuzzy linear programming for the planning of solid waste management systems in separate studies. Huang and Baetz [46] proposed grey quadratic programming to allocation the waste flow within a municipal solid waste management system. Huang et al. [47] utilized grey fuzzy linear programming and grey integer programming models for planning the waste management facility expansion/utilization within a regional solid waste management system. Huang et al. [48] proposed grey programming model for the planning of solid waste management systems. Huang and Baetz [49] developed grey integer programming model to formulate the capacity planning of an integrated waste management system under uncertainty. Davila and Chang [50] developed grey integer programming model to expand decision alternatives using the uncertainty surrounding waste generation, incidence of recyclables, routing distance, recycling participation, and other planning components. Recently, Chang and Davila [51] proposed grey minimax regret integer programming to determine an optimal regional coordination of solid waste routing and possible landfill/incinerator construction under an uncertain environment.

In the eighth group, stochastic programming was used. Huang et al. [52] proposed inexact fuzzy-stochastic mixed integer linear programming for the long-term planning of waste management activities in the City of Regina. Further, Huang et al. [53] proposed fuzzy-stochastic linear programming for the planning of integrated solid waste management options, and answering questions regarding timing, sitting and sizing of the related waste management activities under uncertainty. Maqsood and Huang [54] proposed two-stage interval-stochastic programming for the planning of solid-waste management systems under uncertainty.

The studies that used economical analyses methods can be classified into the ninth group. Chang and Wang [55] used risk analysis for the regulation of the impacts of air pollution, leachate, traffic congestion, and noise increments in the long-term planning of metropolitan solid waste management systems. Doberl et al. [56] evaluated the selected waste management scenarios with regard to the goals of the Austrian Waste Management Act, taking into account long-term environmental protection and resource conservation as well as costs by utilizing Cost-benefit analysis and modified cost-effectiveness analysis. Kumar et al. [57] proposed a new plan for municipal solid waste management with the objective of landfill gas recovery by executing cost-benefit analysis. Nunes et al. [58] employed net present value method and breakeven analysis for analyzing of construction and demolition waste management and recycling in Brazil.

Statistical analysis techniques were utilized in the tenth group. Weng and Chang [59] applied statistical modeling to investigate the development track of sanitary landfills, to review the technology scenarios and to conduct a multivariate statistical analysis with respect to construction and operating costs. Al-Yaqout et al. [60] presented statistical analysis approach for sitting municipal solid waste landfills in Kuwait. Weighted linear index model, correlation and regression analysis are employed by Clarke and Maantay [61] to identify the geographic patterns of recycling participation in New York City, and characterize the communities using socio-demographic indicators. Tsilemou and Panagiotakopouls [62] employed statistical analyses to suggest a procedure for generating cost functions relating initial set-up cost and operating cost with facility size; and present such cost functions, relevant to European states, for selected types of solid waste treatment and disposal facilities. Calvo et al. [63] employed statistical analyses for determining the environmental impact, location suitability, design and exploitation of deposit points in the area to establish measures for minimizing environmental hazards.

There exist papers which have employed simulation-optimization. Liu et al. [64] proposed Monte Carlo simulation for analyzing environmental risks of groundwater contamination at waste landfill site. Yeomans [65] used simulation optimization for solving the solid waste management problems containing significant sources of uncertainty.

The studies that used system analysis take place in the twelfth group. Chang et al. [66] designed and implemented nationwide computer-aided system for handling enormous amount of information flows for SWM among various environmental protection agencies. Joos et al. [67] used Delphi expert questioning to assure social compatibility of a waste management program. Klang et al. [68] used system analyses to investigate which aspects the elected representatives and municipal officers regard as the most important ones to include in a waste management systems analysis, and how they perceive the value and usefulness of systems analysis as a decision-support tool.

Life cycle assessment was used in the thirteenth group. Clift et al. [69] employed life cycle assessment model to develop a municipal solid waste management system used by the UK Environment Agency. Powell [70] ranked the waste management scenarios in the waste collection authorities of Gloucestershire with the assistance of life cycle inventory model. Wilson [71] used life cycle inventory model to evaluate the environmental performance of municipal solid waste management options. Arena et al. [72] assessed the environmental performance of alternative solid waste management options that could be used in an area of the South of Italy by the aid of life cycle assessment. Lundie and Peters [73] used life cycle impact assessment to evaluate the In-Sink-Erator food waste processor system and compare it with the alternative options. Finnveden et al. [74] evaluate different strategies for treatment of solid waste in Sweden by using life cycle impact assessment. Dahlbo et al. [75] ranked the waste management alternatives by using life cycle impact assessment.

In the fourteenth group, we find the studies in which the authors applied geographic information systems (GIS). Leão et al. [76] quantified the relationship between the demand and supply of suitable land for waste disposal over time by employing geographic information systems and dynamic modeling. Leão et al.[77] devised and articulated a systematic and comprehensive model to spatially and dynamically model the demand and allocation of facilities for urban solid waste disposal in urban regions under development by utilizing geographic information systems, cellular automata and urban modeling. Gautam and Kumar [78] proposed GIS for the design of solid waste system considering the waste generation, allocation, recycling options, and locating drop-off stations. Ghose et al. [79] used GIS and optimal routing model to determine the minimum cost/distance efficient collection paths for transporting the solid wastes to the landfill.

Also, there are few papers that applied integrated techniques. Chang and Wang [80] applied cost analysis and statistical regression modeling for the development of material recovery facilities in the United States. Cheng et al. [5] applied different MCDM techniques to solve the landfill selection problem in Regina of Saskatchewan Canada. Huang et al. [81] integrated different MCDM techniques and multi-objective programming for finding the optimal food waste management schemes. Huang et al. [82] combined evolutionary simulation-optimization with grey programming model for generating policy alternatives of Hamilton-Wentworth in Canada. Aye and Widjaya [83] employed life cycle assessment and cost-benefit analysis together to assess the potential options of handling waste from traditional markets in Indonesia. Shmelev and Powell [84] integrated linear mixed integer programming, life cycle impact assessment and GIS for providing a new methodological background for the regional solid waste management modeling taking into account spatial and temporal patterns of waste generation and processing, environmental as well as economic impacts of the system development with a particular emphasis on public health and biodiversity.

Other than the aforementioned groups, there exist few papers that examine the SWM strategies. Chambal et al. [85] introduced value-focused thinking method for ranking competing MSW alternatives based on how well they meet the decision maker's strategic objective. Vasiloglou [86] used undoubted evaluation to determine the potential location of new landfill areas with wide community participation and acceptance.

A complete list of these studies are provided in Table 2.1.

Table 2.1 Literature review on SWM

Year	Author(s)	Method(s)	Reference Number
1993	Huang et al.	Grey linear programming	[43]
1993	Huang et al.	Grey fuzzy linear programming	[45]
1994	Huang et al.	Grey dynamic programming	[44]
1994	Huang et al.	Grey fuzzy quadratic programming	[42]
1995	Huang and Baetz	Grey quadratic programming	[46]
1995	Huang et al.	Grey fuzzy linear programming, grey integer programming	[47]

Table 2.1 Literature review on SWM (cont.)

Year	Author(s)	Method(s)	Reference Number
1995	Chang and Wang	Cost analysis, statistical regression modeling	[80]
1996	Chang et al.	Mixed integer programming	[21]
1996	Everett and Modak	Piecewise linear approximation method, linear programming	[32]
1996	Chung and Poon	Dominance pair wise comparison	[13]
1996	Chang et al.	Mixed integer programming, dynamic optimization	[22]
1996	Huang et al.	Grey programming	[48]
1996	Chang and Wang	Nonlinear fuzzy goal programming	[16]
1996	Chang and Wang	Multi-objective mixed integer programming	[23]
1996	Chang and Wang	Risk analysis	[55]
1997	Hokkanen and Salminen	PROMETHEE	[12]
1997	Chang and Lu	Fuzzy global criterion technique, fuzzy multi objective mixed integer programming	[17]
1997	Chang et al.	Mixed-integer programming	[24]
1997	Hokkanen and Salminen	ELECTRE III	[14]
1997	Karagiannidis and Moussiopoulos	ELECTRE III	[15]
1997	Ferrell and Hizlan	Mixed-integer programming	[25]
1997	Chang and Wang	Goal programming	[33]
1997	Chang and Wang	Fuzzy goal programming	[8]

Table 2.1 Literature review on SWM (cont.)

Year	Author(s)	Method(s)	Reference Number
1997	Huang and Baetz	Grey integer programming	[49]
1998	Chang et al.	Client/server computer network system, computer network system	[66]
1999	Berger et al.	Mixed-integer linear programming	[26]
1999	Joos et al.	Delphi-expertquestioning	[67]
1999	Amouzegar and Moshirvaziri	Linear bi-level programming	[34]
2000	Cosmi et al.	Linear programming	[35]
2000	Clift et al.	Life cycle assessment	[69]
2000	Powell	Life cycle inventory	[70]
2001	Leão et al.	GIS, dynamic modeling	[76]
2001	Sarkis and Weinrach	Data envelopment analysis	[36]
2001	Huang et al.	Inexact fuzzy-stochastic mixed integer linear programming	[52]
2001	Huang et al.	Fuzzy-stochastic linear programming	[53]
2001	Weng and Chang	Statistical modeling	[59]
2002	Wilson	Life cycle inventory	[71]
2002	Al-Yaqout et al.	Statistical analysis	[60]
2002	Doberl et al.	Cost-benefit analysis, modified cost-effectiveness analysis	[56]
2002	Solano et al.	Linear programming	[37]
2002	Vaillancourt and Waaub	Mixed integer linear programming	[27]

Table 2.1 Literature review on SWM (cont.)

Year	**Author(s)**	**Method(s)**	**Reference Number**
2002	Huang et al.	Interval-parameter fuzzy integer programming	[18]
2002	Cheng et al.	Simple weighted addition method, weighted product method, technique for order preference by similarity to ideal solution (TOPSIS), cooperative game theory, ELECTRE.	[5]
2003	Fiorucci et al.	Non-linear optimization	[40]
2003	Maqsood and Huang	Two-stage interval-stochastic programming	[54]
2003	Seo et al.	AHP	[9]
2003	Arena et al.	Life cycle assessment	[72]
2003	Chambal et al.	Value-focused thinking	[85]
2004	Costi et al.	Non-linear programming	[41]
2004	Najm and El-Fadel	Linear programming	[38]
2004	Vasiloglou	Undoubted evaluation	[86]
2004	Liu et al.	Monte Carlo simulation	[64]
2004	Sadiq et al.	AHP, aggregation, first of maximum defuzzification method	[19]
2004	Kumar et al.	Cost-benefit analysis	[57]
2004	Maqsood et al.	Inexact two-stage mixed integer linear programming	[28]
2004	Leão et al.	GIS, cellular automata, urban modeling	[77]
2005	Lundie and Peters	Life cycle impact assessment	[73]
2005	Finnveden et al.	Life cycle impact assessment	[74]

Table 2.1 Literature review on SWM (cont.)

Year	Author(s)	Method(s)	Reference Number
2005	Hung et al.	Fuzzy AHP, fuzzy weighting method, simple additive method, centralized weights method, multi objective programming	[81]
2005	Gautam and Kumar	GIS	[78]
2005	Davila and Chang	Grey integer programming	[50]
2006	Huang et al.	Evolutionary simulation-optimization, grey programming	[82]
2006	Clarke and Maantay	Weighted linear index model, correlation and regression analysis	[61]
2006	Aye and Widjaya	Life cycle assessment, cost-benefit analysis	[83]
2006	Lin et al.	Linear programming	[39]
2006	Shmelev and Powell	Linear mixed integer programming, life cycle impact assessment	[84]
2006	Tsilemou and Panagiotakopouls	Statistical analyses	[62]
2006	Ghose et al.	GIS optimal routing model	[79]
2006	Dahlbo et al.	Life cycle impact assessment	[75]
2006	Klang et al.	System analyses	[68]
2006	Chang and Davila	Grey mini-max regret integer programming	[51]
2006	Li and Huang	Interval-parameter two-stage mixed integer linear programming	[29]
2006	Su et al.	Fuzzy AHP, policy impact potential analysis, fuzzy weighting method, simple additive method, optimal index method, ELECTRE	[20]

Table 2.1 Literature review on SWM (cont.)

Year	**Author(s)**	**Method(s)**	**Reference Number**
2006	Pati et al.	Mixed integer goal programming	[30]
2006	Nunes et al.	Net present value method, breakeven point analysis	[58]
2007	Chang and Davila	Minimax regret integer programming model	[31]
2007	Karamouz et al.	AHP	[10]
2007	Gemitzi et al.	AHP, OWA	[11]
2007	Calvo et al.	Statistical analyses	[63]
2007	Yeomans	Simulation-optimization	[65]

3. WASTE MANAGEMENT STRATEGIES

Waste management is the collection, transport, processing, recycling or disposal of waste materials, usually ones produced by human activity, in an effort to reduce their effect on human health or local aesthetics or amenity. A sub focus in recent decades has been to reduce waste materials' effect on the natural world and the environment and to recover resources from them [87]. The strategy defined to achieve sustainable waste management practice, named as "waste hierarchy", is denoted in Figure 3.1.

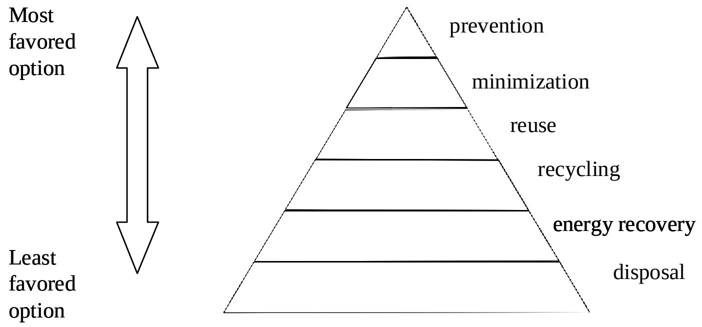


Figure 3.1 Waste hierarchy [87]

The waste hierarchy classifies waste management policies according to their preference. The aim of the waste hierarchy is to extract the maximum practical benefits from products and to generate the minimum amount of waste [87].

According to the waste hierarchy, to have a more sustainable waste management strategy, the first priority is the minimization of waste production. Then reuse, which is defined as to prolong the lifespan of an object by repairing it or by affecting a new place to it, comes. The objective is keeping its initial function however. The next level is the waste recovery category, which incorporates materials recycling, composting and recovery of energy from waste. Waste disposal is placed at the bottom of the waste hierarchy, as the least attractive waste management strategy. However, waste disposal has to be accomplished at high standards to make it as sustainable as possible [87].

3.1 Waste Reduction

Waste reduction can be defined as an overall waste management strategy that seeks to reduce the amount of waste generated at each stage of a product's life span. It can be done on two levels: reduction of the material consumption or reduction of the energy consumption. The objective of this step is:

- to limit the quantities of objects intended for a single use (for example, packing of foodstuffs should be made of glass rather than plastic),
- to support the re-use of the products,
- to design the machines according to requirements (for example, not to make turn on a washing machine with half charges or not to buy a refrigerator larger than its needs which will unnecessarily consume more electricity).
- to ensure efficient use of resources within existing processes.

Waste minimization usually requires knowledge of the production process, cradle-to-grave analysis (the tracking of materials from their extraction to their return to earth) and detailed knowledge of the composition of the waste [88].

3.2 Waste Reuse

In conventional reuse procedure, products are designed to be used a number of times before they are discarded. Reuse will usually represent an environmental gain.

The advantages of re-use can be summarized as follows [89]:

- Reduces the amount of manufactured products, consequently, reduces the costs and needs of raw materials.
- Reusable product is often cheaper than the non-reusable products, so re-use provides cost savings for business and consumers.
- Generally, older items are more precious in value.

Also several disadvantages are apparent [89]:

- Re-use necessitates cleaning or transport.
- Some re-use items can be less energy efficient as they continue to be used.
- Reusable products required to be more robust than single use products, so the production of such a product needs more raw materials.
- Sorting and preparing items for reuse takes time, this is inconvenient for consumers and costs money for businesses.

The households, like the supermarkets, have a big responsibility in helping reuse products as engaging with their customers in reuse of plastic carrier bags, plastic garment hangers, etc. There are many other practical ways for householders to reuse waste.

3.3 Waste Recovery

Waste recovery represents the process by which waste is converted either into a usable form or energy that is derived out of the waste [90]. There exist three sub-categories of waste recovery:

3.3.1 Waste Recycling

Waste recycling is a process by which the materials of a manufacture are re-used at the end of its lifespan, to constitute a usable raw material or a new product. They will thus be reintroduced in production cycle. Recycling process can be determined as a loop that includes the activities of collecting recyclable materials, sorting and processing recyclables into raw materials, and manufacturing new products from these raw materials.

During previous years, the volume of waste produced by each inhabitant was increased. That presented a real problem and menace for the environment, because we destroyed these wastes either by burning or by landfill. Change of mentality was necessary to overcome this problem. Instead of systematically eliminated the waste totally, we put these wastes in re-use.

Recycling permits to save raw material and thus to preserve the natural resources. It also reduces the volume and the weight of produced waste and thus diminishes the risks of air and land pollution.

3.3.2 Waste Composting

Composting is defined as a controlled biological process of conversion and valorization of the organic matter (by-products of the biomass, organic waste of biological origin...) in a product stabilized, hygienic, rich in humic compounds.

Composting is an operation which consists of fermentation of the organic wastes in the presence of oxygen, under controlled conditions. There exist two phenomena in a process of composting. The first phenomenon that brings the wastes into fresh compost, is an intense aerobic fermentation. It means the decomposition of the fresh organic matter at high temperature (50-70°C) by the bacteria. The second phenomenon transforms the fresh compost into a ripe compost, rich in humus. This phenomenon of maturation, which occurs at lower temperature (35-45°C), led to the biosynthesis of humic compounds by mushrooms.

Benefits of compost for the ground and soil can be summarized as follows [91]:

- Increases the gap volume,
- Facilitates processing,
- Increases the capability to keep water,
- Increases organic material value,
- Enables that the nutritive materials are better used.

3.3.3 Energy from Waste

Energy from waste is a process by which energy stored in the waste is extracted in the form of fuel or electric power, which can then be used as power source for various applications [92].

Two main ways of recovering energy from wastes have been employed in practice [92]:

- **Waste incineration:** Incineration is the controlled burning of waste at high temperatures. It is used in two principal fields:
    - Technical funerary
    - Method of urban or industrial waste disposal

Certain incineration factories recover the energy produced by the waste combustion to heat buildings and/or to produce electricity that means energy valorization.

The incineration is criticized because the dioxides carcinogenic are produced by the incinerators, especially by the old installations. The combustion of waste rejects also carbon dioxide, which is known as greenhouse gas. It causes the reheating of the Earth. The lack of current knowledge on the effects of the incinerator fume on human health makes the incinerators rejected by their vicinity.

The ash is the solid residues of the waste incineration. 5% of the entering quantities arise in the form of ash. They are mixtures of metals, glass, silica, alumina, limestone, lime, unburned residues and water. They undergo a sorting in order to detach various metals which can be recycled. According to their quality and stability, the remainder of the ash is either stored in discharge, or used in the chemical industries.

Newer incineration methods include gasification and pyrolysis, where wastes are heated to very high temperature with limited oxygen to produce low-to-medium-heating fuel gases, together with tars, char and ash. These methods are more effective than direct incineration since, more energy can be recovered and used. The pyrolysis transforms materials into solid, liquid or gas products. Pyrolytic oil and the gases can be burned to produce energy or to be refined in other products. The gasification is used to directly transform organic matter into a gas synthesis, which is composed of carbon monoxide and hydrogen. This gas is then burned to produce electricity and vapor.

- **Using biogas (landfill gas):** In a landfill site, the methane generated by biological processes must be controlled for minimizing its effect on environment. Collecting and using methane as a fuel has two benefits as preventing pollution and generating energy. However, the energy recovered from landfill is considerably less efficient than incineration.

3.4 Waste Disposal

Waste disposal is the last option in the waste hierarchy. Several disposal options have been used. Landfill and incineration can be listed among disposal strategies. Disposal options depend on the type of waste streams. Some wastes are not suitable for landfill. Likewise, some wastes are not suitable for incineration because of their low calorific value.

Landfill is the most traditional waste disposal method, and currently major countries employ this method. As compared with the other disposal techniques, landfill seems to be inexpensive and hygienic and a wide variety of wastes are suitable for landfill. It is worth noting that ultimately, many other waste treatment and disposal options require that the final disposal route for the residues require landfill [93]. But it also has a number of adverse environmental impacts. Landfill by-products contain harmful wastes and landfill gas which composed of methane and carbon dioxide. These gases are known as greenhouse gases and they have divers harmful effects on earth and humans. Also, landfill gas causes aesthetic problems such as odor. To avoid these problems, disposal waste must be compacted and covered. Landfills are also equipped with landfill gas extraction systems installed to extract gas produced by the decomposing waste materials. With this system, biogas is burned in a boiler to produce electricity. For the environment, burning of biogas is more preferable than allowing it to the atmosphere. Because, it consumes methane, which is more harmful than carbon dioxide. A part of this biogas can also be used as fuel.

Incineration is a waste disposal method that involves the combustion of waste at high temperatures. Incineration and other high temperature waste treatment systems are described as thermal treatment [87]. Due to issues such as emission of pollutant gases and high cost, incineration is not a favored disposal method.

4. MULTI-CRITERIA DECISION ANALYSIS

Multi-criteria decision analysis is both an approach and a set of techniques, with the aim of providing an overall ordering of options, from the most preferred to the least preferred option [6]. MCDA approaches provide a systematic procedure to help decision makers choose the most desirable and satisfactory alternative under uncertain situation [94]. MCDA approaches are classified into two groups [95]. This classification makes distinction between MODM and MADM. The main distinction between the two groups of methods is based on the number of alternatives under evaluation. In MCDM problems, there exist a relatively small number of alternatives and these alternatives are denoted in terms of attributes. Multi-objective decision problems have a very large number of feasible alternative and the objectives and the constraints are depend on the decision variables [95]. MADM methods are designed for selecting discrete alternatives while MODM are more adequate to deal with multi-objective planning problems, when a theoretically infinite number of continuous alternatives are defined by a set of constraints on a vector of decision variables [96]. MADM methods provide simple and intuitive tools for making decisions on problems that involve uncertain and subjective information [94]. These methods have the advantage that they can assess a variety of options according to a variety of criteria that have different units. This is a very important advantage over traditional decision aiding methods where all criteria need to be converted to the same unit. Another significant advantage of most MADM methods is that they have the capacity to analyze both quantitative and qualitative evaluation criteria together [97].

The differences between MODM and MADM are systematically summarized in Table 4.1.

Table 4.1 Comparison of MODM and MADM approaches [98]

Criteria for comparison	MODM	MADM
Criteria defined by	Objectives	Attributes
Objectives defined	Explicitly	Implicitly
Attributes defined	Implicitly	Explicitly
Constraints defined	Explicitly	Implicitly
Alternatives defined	Implicitly	Explicitly
Number of alternatives	Infinite (large)	Finite (small)
Decision maker's control	Significant	Limited
Decision modeling paradigm	Process-oriented	Outcome-oriented
Relevant to	Design/search	Evaluation/choice

MCDA have six basic functions as follows [7]:

1. Structure the decision.
2. Show the differences among criteria.
3. Help people to reflect, to articulate and to apply their judgments concerning of the alternatives.
4. Help people to make more coherent and reasonable evaluations of risk and uncertainty.
5. Facilitate negotiation.
6. Document how the decisions are made.

The intention of MCDA is to improve quality of decisions by making choices more explicit, reasonable and effective. MCDA provides decision makers with powerful capabilities in analyzing, exploring and comparing a set of incompatible alternatives. It can help them gain insight on the problem as well as confidence when making a decision. MCDA can be used for a wide variety of multi-attribute selection problems [94]. Also there exist several inconvenient of MCDA [94]. MADA problems involve subjective parameters such as public and political concerns. For this reason, one might argue that the results obtained would not be meaningful. It is possible to find an ideal solution using a particular method for a decision maker, but a different solution could be more appropriate when another method is used.

Applying MCDA has the following steps [6]:

1. Set up the context of the decision
   1.1. Determine decision makers and other important performers and construct the objectives of the MCDM.
   1.2. Create the socio-technical system to organize the MCDM.
   1.3. Think about the context of the evolution.

2. Define the alternatives to be evaluated.

3. Define the objectives and criteria
   3.1. Define the criteria for estimating the outcomes of each alternative.
   3.2. Group the criteria under high level and lower lever objectives in a hierarchy to organize them.

4. "Assessment of the scores". The performance of each alternative with respect to the criteria must be evaluated.
   4.1. Identify the outcomes of the alternatives.
   4.2. Score the alternatives on the criteria.
   4.3. Examine the agreement of the scores on each criterion.

5. "Assessment of the weights". Assign weight for the criterion that shows importance of the criterion to the decision.

6. Congregate the weights and scores for each alternative to develop an overall value.

7. Review the results.

8. Perform sensitivity analysis.
   8.1. Organize a sensitivity analysis: Using other choices or weights has an influence on the ranking of the alternatives?

8.2. Check the advantages and drawback of chosen options, than perform a pairwise comparison.

8.3. Try to form new potential options that could be more successful than those originally thought.

8.4. Repeat the steps above until a “required model” is acquired.

As a result of the recent upsurge in environmental problems caused by the solid wastes, determining an efficient waste management system, which considers environmental, economic and social factors, is of outmost importance. A solid waste management program often involves multiple conflicting economical, environmental, and socio-ecological objectives**.** Hence, finding the optimal SWM system can be possible by reaching a compromise among the conflicting criteria. To deal with quantitative and qualitative considerations of the waste management problems, multiple criteria decision analysis techniques can be used [5].

5. FUZZY SET THEORY

Fuzzy set theory, which was introduced by Zadeh [99] to deal with problems in which a source of vagueness is involved, has been utilized for incorporating imprecise data into the decision framework.

A fuzzy set $\tilde{A}$ can be defined mathematically by a membership function $\mu_{\tilde{A}}(x)$, which assign each element x in the universe of discourse X a real number in the interval [0,1]. This terms the membership grade of the element with the concept represented by the fuzzy set.

In the following paragraph, we briefly review some basic definitions of the fuzzy sets [100]. These basic definitions and notations below will be used in the following paragraphs, unless otherwise stated.

Definition 1: A fuzzy set $\tilde{A}$ is convex if and only if for all x_1 and $x_2 \in X$:

$$\mu_{\tilde{A}}(\lambda x_1 + (1-\lambda)x_2) \geq \min\left(\mu_{\tilde{A}}(x_1), \mu_{\tilde{A}}(x_2)\right), \lambda \in [0,1] \tag{5.1}$$

Definition 2: A fuzzy set $\tilde{A}$ is called a normal fuzzy set implying

$$\exists\, x_i \in X, \mu_{\tilde{A}}(x_i) = 1 \tag{5.2}$$

Definition 3: α cut is defined as

$$\tilde{n}^{\alpha} = \{x_i : \mu_{\tilde{n}}(x_i) \geq \alpha, x_i \in X\} \tag{5.3}$$
$$where \quad \alpha \in [0,1]$$

$\tilde{n}^{\alpha}$ is a limited nonempty bounded interval contained in X and it can be noted by $\tilde{n}^{\alpha} = \left[n_l^{\alpha}, n_u^{\alpha}\right]$, n_l^{α} and n_u^{α} are the lower and higher bounds respectively of the closed interval.

A triangular fuzzy number $\tilde{n}$ can be defined by a triplet (n_1, n_2, n_3). The membership function $\mu_{\tilde{n}}(x)$ is defined as

$$\mu_{z_{12}} = \begin{cases} 0, & x \le n_1 \\ \dfrac{x - n_1}{n_2 - n_1}, & n_1 \le x \le n_2 \\ \dfrac{x - n_3}{n_2 - n_3}, & n_2 \le x \le n_3 \\ 0, & x \ge n_3 \end{cases} \tag{5.4}$$

Definition 4: If $\tilde{n}$ is a fuzzy number and $n_1^{\alpha} > 0$ for $\alpha \in [0, 1]$ then $\tilde{n}$ is named as a positive fuzzy number.

Any two positive fuzzy numbers $\tilde{m}$ and $\tilde{n}$ and a positive real number r, the α –cut of two fuzzy numbers is $\tilde{m}^{\alpha} = \left[m_l^{\alpha}, m_u^{\alpha}\right]$, and $\tilde{n}^{\alpha} = \left[n_l^{\alpha}, n_u^{\alpha}\right]$, ($\alpha \in [0,1]$), respectively. According to the confidence interval, some principal operations of positive fuzzy numbers can be expressed as follows [7]:

$$(\tilde{m}(+)\tilde{n})^{\alpha} = \left[m_l^{\alpha} + n_l^{\alpha}, m_u^{\alpha} + n_u^{\alpha}\right] \tag{5.5}$$

$$(\tilde{m}(-)\tilde{n})^{\alpha} = \left[m_l^{\alpha} - n_u^{\alpha}, m_u^{\alpha} - n_l^{\alpha}\right] \tag{5.6}$$

$$(\tilde{m}(*)\tilde{n})^{\alpha} = \left[m_l^{\alpha} * n_l^{\alpha}, m_u^{\alpha} * n_u^{\alpha}\right] \tag{5.7}$$

$$\left(\tilde{m}(\div)\tilde{n}\right)^{\alpha} = \left[\frac{m_l^{\alpha}}{n_u^{\alpha}}, \frac{m_u^{\alpha}}{n_l^{\alpha}}\right] \tag{5.8}$$

$$\left(\tilde{m}^{\alpha}\right)^{-1} = \left[\frac{1}{m_u^{\alpha}}, \frac{1}{m_l^{\alpha}}\right] \tag{5.9}$$

$$\left(\tilde{m}(*)r\right)^{\alpha} = \left[m_l^{\alpha} * r, m_u^{\alpha} * r\right] \tag{5.10}$$

$$\left(\tilde{m}(\div)r\right)^{\alpha} = \left[\frac{m_l^{\alpha}}{r}, \frac{m_u^{\alpha}}{r}\right] \tag{5.11}$$

Definition 6: If $\tilde{n}$ is a fuzzy number and $n_l^{\alpha} > 0$, $n_u^{\alpha} \leq 1$ for $\alpha \in [0,1]$, then n is called a normalized positive fuzzy number [100].

6. FUZZY DECISION MAKING METHODOLOGIES

In this section, we present two alternative fuzzy MCDM methodologies for the evaluation of alternative waste management scenarios in Istanbul.

6.1 Hierarchical Fuzzy MCDM Approach

Real-world decision problems such as the selection of the best SWM scenario for Istanbul often involve the consideration of numerous performance attributes, yielding in general a multi-level hierarchical structure. Further, in general, crisp data are inadequate to model real-life situations. Since human judgments regarding preferences are often vague, one cannot estimate his/her preference with an exact numerical value. A more realistic approach may be to use linguistic assessments instead of numerical values, that is, to suppose that the ratings and weights of the criteria in the problem are assessed by means of linguistic variables [101].

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 a more effective analysis. In this study, the hierarchical distance-based fuzzy MCDM algorithm introduced by Karsak and Ahiska [102] is employed for determining the best SWM scenario for Istanbul. This MCDM algorithm is based on the proximity to the ideal solution concept and which can address the problems containing both crisp and fuzzy data. The origins of the proposed decision making procedure are found in the multi-criteria decision tool named TOPSIS [103]. TOPSIS is based on the intuitive principle that the preferred alternative should have the shortest distance from the ideal solution and the farthest distance from the anti-ideal solution [104]. One direct MCDM technique would be to select the alternative that has the minimum distance from the ideal alternative [105]. Since an alternative with the shortest distance from the ideal may not have the farthest anti-ideal, and vice versa, TOPSIS considers the distances from both the ideal and anti-ideal simultaneously [106]. The traditional TOPSIS approach uses the Euclidean norm to normalize the original attribute values, and the Euclidean distance to calculate each alternative's distance from the ideal and anti-ideal solutions. The ideal solution is named as the one having the best attribute values attainable, and the anti-ideal solution is determined as the one possessing the worst attribute values attainable. The relative proximity (similarity) of each alternative to the ideal solution is calculated based on its distances from both the ideal and anti-ideal solutions at the same time. The preference of the alternatives is determined by ranking the calculated proximity measures in a descending order [106].

TOPSIS is a widely accepted multi-attribute decision-making technique due to its sound logic, simultaneous consideration of the ideal and the anti-ideal solutions, and easily programmable computation procedure [107]. Although TOPSIS has numerous advantages, it requires quantitative attributes expressed as crisp numbers. In here, an easily applicable decision-making algorithm, that can handle crisp data and fuzzy data expressed in linguistic terms or triangular fuzzy numbers, is presented. This ability will facilitate the use of the algorithm in SWM scenario selection process requiring both quantitative and qualitative aspects to be taken into consideration [106].

The proposed fuzzy MCDM approach can be described as follows:

***Step* 1.** Construct the decision matrix that denotes the fuzzy assessments corresponding to qualitative sub-criteria and the crisp values corresponding to quantitative sub-criteria for the considered alternatives.

***Step* 2.** Normalize the crisp data to obtain unit-free and comparable sub-criteria values. The normalized values for crisp data regarding benefit-related as well as cost-related quantitative sub-criteria are calculated via a linear scale transformation as

$$y'_{ijk} = \begin{cases} \dfrac{y_{ijk} - y^{-}_{jk}}{y^{*}_{jk} - y^{-}_{jk}}, & k \in CB_j;\ i = 1,2,\ldots,m;\ j = 1,2,\ldots,n \\[2ex] \dfrac{y^{*}_{jk} - y_{ijk}}{y^{*}_{jk} - y^{-}_{jk}}, & k \in CC_j;\ i = 1,2,\ldots,m;\ j = 1,2,\ldots,n \end{cases} \tag{6.1}$$

where y'_{ijk} denotes the normalized value of y_{ijk}, which is the crisp value assigned to alternative i with respect to the sub-criterion k of criterion j, m is the number of alternatives, n is the number of criteria, CB_j is the set of benefit-related crisp sub-criteria of criterion j and CC_j is the set of cost-related crisp sub-criteria of criterion j, $y^*_{jk} = \max_i y_{ijk}$ and $y^-_{jk} = \min_i y_{ijk}$. The normalized values for crisp data can be represented as $\tilde{y}_{ijk} = (y'_{aijk}, y'_{bijk}, y'_{cijk})$ in triangular fuzzy number format, where $y'_{aijk} = y'_{bijk} = y'_{cijk} = y'_{ijk}$.

***Step* 3.** Aggregate the performance ratings of alternatives at the sub-criteria level to criteria level as follows:

$$\tilde{x}_{ij} = (x_{aij}, x_{bij}, x_{cij}) = \frac{\sum_k \tilde{w}^1_{jk} \otimes \tilde{y}_{ijk}}{\sum_k \tilde{w}^1_{jk}}, \forall i, j \tag{6.2}$$

where $\tilde{x}_{ij}$ represents the aggregate performance rating of alternative i with respect to criterion j, $\tilde{w}^1_{jk}$ indicates the average importance weight assigned to sub-criterion k of criterion j, and $\otimes$ is the fuzzy multiplication operator.

***Step* 4.** 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:

$$\tilde{r}_{ij} = (r_{aij}, r_{bij}, r_{cij}) = \left(\frac{x_{aij} - x^-_{aj}}{x^*_{cj} - x^-_{aj}}, \frac{x_{bij} - x^-_{aj}}{x^*_{cj} - x^-_{aj}}, \frac{x_{cij} - x^-_{aj}}{x^*_{cj} - x^-_{aj}} \right), \forall i, j \tag{6.3}$$

where $x^*_{cj} = \max_i x_{cij}$, $x^-_{aj} = \min_i x_{aij}$, and $\tilde{r}_{ij}$ denotes the normalized aggregate performance rating of alternative i with respect to criterion j.

***Step* 5.** 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* 6.** Calculate the weighted distances from ideal solution and anti-ideal solution (D_i^* and D_i^-, respectively) for each alternative as

$$D_i^* = \sum_j 1/2 \left\{ \max(w_{aj}^1 \left| r_{aij} - 1 \right|, w_{cj}^1 \left| r_{cij} - 1 \right|) + w_{bj}^1 \left| r_{bij} - 1 \right| \right\}, i = 1,2,...,m \tag{6.4}$$

$$D_i^- = \sum_j 1/2 \left\{ \max(w_{aj}^1 \left| r_{aij} - 0 \right|, w_{cj}^1 \left| r_{cij} - 0 \right|) + w_{bj}^1 \left| r_{bij} - 0 \right| \right\}, i = 1,2,...,m . \tag{6.5}$$

***Step* 7.** Calculate the proximity of the alternatives to the ideal solution, P_i^*, by considering the distances from ideal and anti-ideal solutions as

$$P_i^* = D_i^- \Big/ \left(D_i^* + D_i^- \right), i = 1,2,...,m. \tag{6.6}$$

Step 8. Rank the alternatives according to P_i^* values in descending order. Identify the alternative with the highest P_i^* as the best alternative.

The presented MCDM framework possesses a number of merits compared with the alternative approaches employed in SWM system selection [106]. The proposed decision approach enables the decision-makers to use linguistic terms while making qualitative assessments, and thus, reduces their cognitive burden in the evaluation process. Both the vaguely defined quantitative as well as qualitative criteria values and precisely defined criteria values are integrated in the decision-making process. The computational efficiency of the developed approach is not affected considerably when the number of criteria and/or alternatives increases. The decision framework provides 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 [105], the ideal and anti-ideal solutions are considered at exactly the same time in the presented approach. By considering the weighted distances from both the ideal and anti-ideal 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. Finally, this approach does not employ fuzzy number ranking methods that can produce inconsistent results or even rankings contrary to intuition while comparing alternatives.

6.2 Fuzzy Analytic Hierarchy Process

A different systematic approach, named as fuzzy analytic hierarchy process, that uses both the linguistic assessments and numerical values for the alternative selection problem having multi-level hierarchical structure will be represented.

Fuzzy AHP uses the concepts of fuzzy set theory and hierarchical structure analysis for the selection of the most appropriate alternative among a set of feasible alternatives. The earliest fuzzy AHP method was proposed by Van Laarhoven and Pedrycz [108] in which the fuzzy numbers with triangular membership functions describe the fuzzy comparing judgment. Buckley [109] found out the fuzzy priorities of comparison ratios with trapezoidal membership functions. Boender et al. [110] extended van Laarhoven and Pedrycz’s method and developed a more robust approach to the normalization of the local priorities. Chang [111] proposed a new method with the use of triangular fuzzy numbers and extent analysis method for the pairwise comparison scale of fuzzy AHP and the synthetic extent values of the pairwise comparisons, respectively. Cheng [112] evaluated naval tactical missile systems by using fuzzy AHP based on grade value of membership function. Furthermore, many AHP methods developed by various authors can be found in literature. However, the methods mentioned above have important differences in their theoretical structures [97]. In Table 6.1, the comparison of these fuzzy AHP methods is given.

Table 6.1 Comparison of different fuzzy AHP methods [113]

Sources	**The main characteristics of the method**	**Advantages (A) and disadvantages (D)**
Van Laarhoven and Pedrycz (1983)	• Direct extension of Saaty's AHP method with triangular fuzzy numbers • Lootsma's logarithmic least square method is used to derive fuzzy weights and fuzzy performance scores	(A) The opinions of multiple decision- makers can be modeled in the reciprocal matrix (D) There is not always a solution to the linear equations (D) The computational requirement is tremendous, even for a small problem (D) It allows only triangular fuzzy numbers to be used
Buckley (1985)	• Extension of Saaty's AHP method with trapezoidal fuzzy numbers • Uses the geometric mean method to derive fuzzy weights and performance scores	(A) It is easy to extend to the fuzzy case (A) It guarantees a unique solution to the reciprocal comparison matrix (D) The computational requirement is tremendous
Boender, de Grann and Lootsma (1989)	• Modifies van Laarhoven and Pedrycz's method • Presents a more robust approach to the normalization of the local priorities	(A) The opinions of multiple decision makers can be modeled (D) The computational requirement is tremendous
Chang (1996)	• Synthetical degree values • Layer simple sequencing • Composite total sequencing	(A) The computational requirement is relatively low (A) It follows the steps of crisp AHP. It does not involve additional operations (D) It allows only triangular fuzzy numbers to be used
Cheng (1997)	• Builds fuzzy standards • Represents performance scores by membership functions • Uses entropy concepts to calculate aggregate weights	(A) The computational requirement is not tremendous (D) Entropy is used when probability distribution is known (D) The method is based on both probability and possibility measures

In this study, we use Chang's extent analysis method [111] due to its steps that relatively easier than the other fuzzy AHP approaches and similar to the conventional AHP.

The method can be described as follows:

Let $X = \{x_1, x_2, ..., x_n\}$ be an object set and $U = \{u_1, u_2, ..., u_m\}$ be a goal set. According to Chang's extent analysis [111], each object is taken and extent analysis for each goal, g_i, is performed, respectively. Therefore, *m* extent analysis values for each object can be obtained, with the following signs:

$$M_{g_i}^1, M_{g_i}^2, ..., M_{g_i}^m, \quad i = 1,2,...,n \tag{6.7}$$

where all the $M_{g_i}^j \; (j = 1,2,...,m)$ are triangular fuzzy numbers whose parameters are *a*, *b*, and *c*.

***Step* 1.** The value of fuzzy synthetic extent with respect to the i^{th} object is defined as

$$S_i = \sum_{j=1}^{m} M_{g_i}^j \otimes \left[\sum_{i=1}^{n} \sum_{j=1}^{m} M_{g_i}^j \right]^{-1} \tag{6.8}$$

***Step* 2.** The degree of possibility of $M_2 = (a_2, b_2, c_2) \geq M_1 = (a_1, b_1, c_1)$ is defined as

$$V(M_2 \geq M_1) = \sup_{y \geq x} \left[\min\left(\mu_{M_1}(x), \mu_{M_2}(y) \right) \right] \tag{6.9}$$

and it can be represented as follows:

$$V\left(M_2 \geq M_1\right) = \text{hgt}\left(M_1 \cap M_2\right) = \mu_{M_2}(d) = \begin{cases} 1, & \text{if } b_2 \geq b_1 \\ 0, & \text{if } \mathrm{a}_1 \geq c_2 \\ \dfrac{a_1 - c_2}{\left(b_2 - c_2\right) - \left(b_1 - a_1\right)}, & \text{otherwise} \end{cases} \tag{6.10}$$

where d is the ordinate of the highest intersection point D between μ_{M_1} and μ_{M_2}.

To compare M_1 and M_2, we need both the values of $V\left(M_1 \geq M_2\right)$ and $V\left(M_2 \geq M_1\right)$.

***Step* 3.** For a convex fuzzy number, the degree of possibility to be greater than k convex fuzzy numbers $M_i \; (i = 1,2,\ldots,k)$ can be given by

$$V\left(M \geq M_1, M_2, \ldots, M_k\right) = V\left[\left(M \geq M_1\right) \text{and} \left(M \geq M_2\right) \text{and} \ldots \text{and} \left(M \geq M_k\right)\right] = \min V\left(M \geq M_i\right), i = 1,2,3,\ldots,k. \tag{6.11}$$

Assume that

$$d'\left(A_i\right) = \min V\left(S_i \geq S_k\right) \quad \text{for} \quad k = 1,2,\ldots,n; \; k \neq i \tag{6.12}$$

then the weight vector is expressed as

$$W' = \left(d'\left(A_1\right), d'\left(A_2\right), \ldots, d'\left(A_n\right)\right)^{\mathrm{T}} \tag{6.13}$$

***Step* 4.** Via normalization, the normalized weight vectors are obtained as

$$W = \left(d\left(A_1\right), d\left(A_2\right), \ldots, d\left(An\right)\right)^{\mathrm{T}} \tag{6.14}$$

where W is a nonfuzzy number.

7. APPLICATION OF THE FUZZY MCDM METHODS TO SOLID WASTE MANAGEMENT PROBLEM IN ISTANBUL

This section gives the application of the proposed models to Istanbul's waste management problem. First the application background is analyzed, and then the results of hierarchical fuzzy MCDM method and the results of fuzzy AHP are presented.

7.1 Application Background

In Istanbul, approximately 10.000 tons of municipal solid waste is produced per day. The solid wastes in Istanbul were collected from street corners till 1995 but there was no suitable separation. The solid wastes were sent to open "wild storages". Because of unhealthy transports, spilled garbage, and garbage leakage, this system was not economic and it caused terrible odor for the environment. The people and municipalities were saved from this harmful problem in 1995. After that, a number of different projects were combined under the title "Environmental Protection" and they were put into practice [114].

In this concept:

- In 1995, "Medical Waste Project" was started. During the project, medical wastes that was always arranged together with other wastes were moved apart from other wastes, and they were exposed to a separate process and collected in a specific way.
- Healthy and sanitary landfill was set up in 1995.
- Kömürcüoda Sanitary Landfill was put into service on Anatolian side of Istanbul.
- The wild dump areas had ended officially in December 1995.

- Regular Storing Fields Solid Waste Transfer Stations were established to get rid of the solid
- Park and Gardens Directorate of Istanbul Metropolitan Municipality put into practice a "Forestation Project" which was prepared in three years starting from 1997.
- Compost and Recovery Plant and Electric Generation system from Landfill Gas were created in 2001.

As a result of discussions with experts from Ministry of Environment and Forestry, ISTAC Co. (Istanbul Metropolitan Municipality Environmental Protection and Waste Materials Valuation Industry and Trade Co.) and Istanbul Metropolitan Municipality Directorate of Waste Management, we have defined seven possible scenarios for the management of solid wastes in Istanbul. The scenarios can be defined as follows:

Scenario 1: 100% landfill.
Scenario 2: 20% recycling, 80% landfill.
Scenario 3: 20% recycling, 10% composting, 70% landfill.
Scenario 4: 40% recycling, 50% composting, 10% landfill.
Scenario 5: 20% recycling, %10 incineration, %70 landfill.
Scenario 6: 70% incineration, 20% recycling, 10% landfill.
Scenario 7: 75% incineration, 20% composting, 5% landfill.

Benefiting from the literature on the evaluation of solid waste management alternatives, economic criteria, environmental criteria, technical criteria, and social criteria, and their related sub-criteria are identified as the selection attributes as in Figure 7.1.

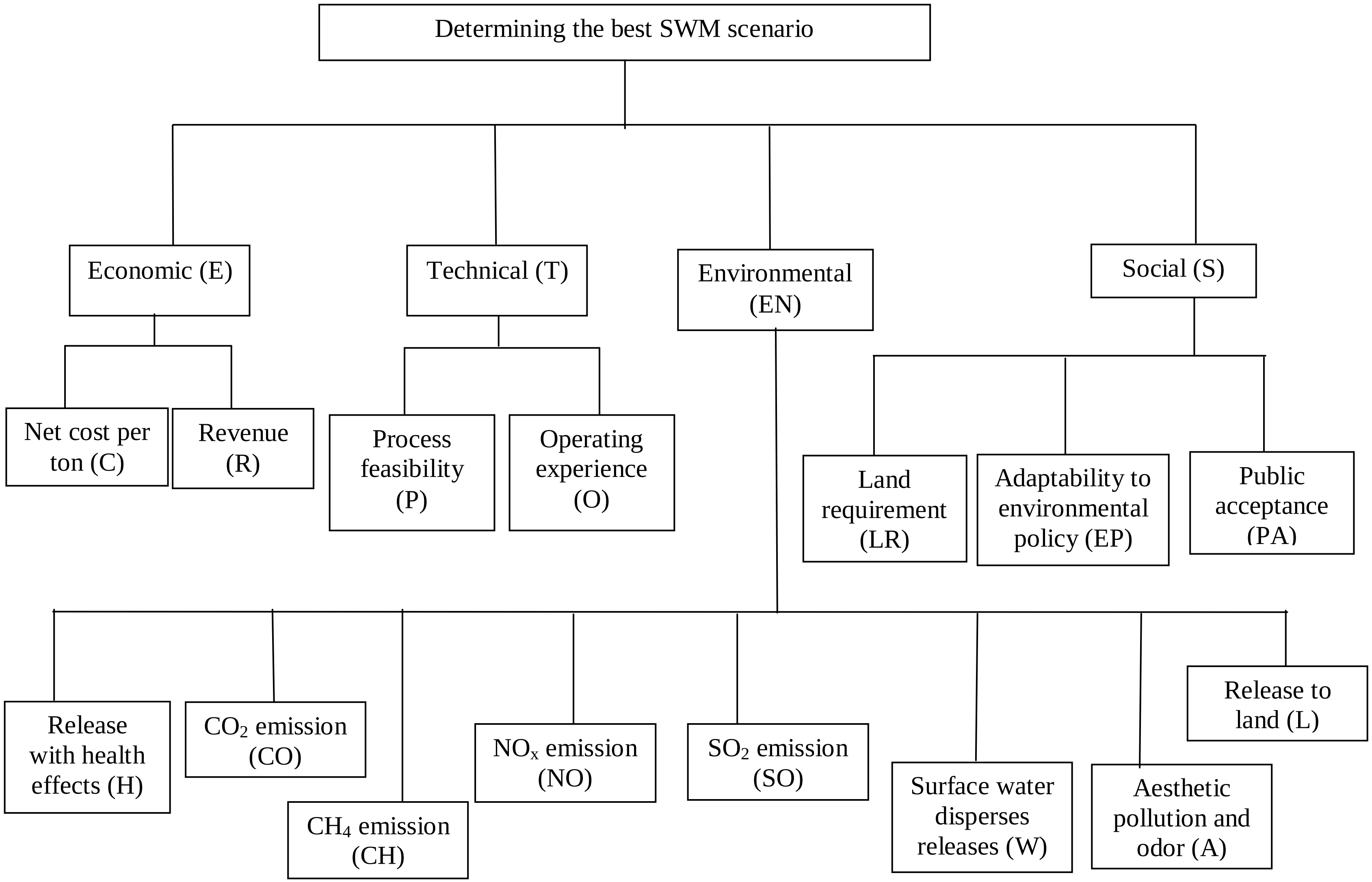


Figure 7.1 Hierarchical structure of the SWM scenario evaluation problem

- Net cost per ton criterion represents the total annual cost per waste ton of given waste management scenario. It considers both the capital and the operating and maintenance expenditures. The capital expenditure is the initial cost of factory construction.
- Revenue criterion presents the income from resource recovery of given waste management scenario.
- Process feasibility explains the applicability of proposed waste management scenario.
- Operating experience indicates the scenario's useful life.
- Release with health effects criterion denotes the effects of heavy metals as cadmium and lead and organic compounds to air and water which affect health.
- CO_2 and CH_4 are known as greenhouse gases and they contribute to global warming. The augmentation of their concentration in atmosphere cause serious environmental problems.
- The emissions of SO_2 and NO_x specify acidificative emissions. They have the effects on public health and environmental safety.
- Surface water disperses releases criterion covers the risk of groundwater contamination. This impact is particularly high in the area where the landfill and composting plants are located.
- The compounds such as H_2S, ester and hydrocarbon that cause odor are found in gas produced during waste disposal process. These compounds are generally toxical. Aesthetic pollution and odor criterion represents the unaesthetic conditions cause by these toxic.
- Release to land criterion indicates the land pollution induced by waste disposal process.
- Several waste management techniques such as landfill and composting need wide areas for putting in practice. This fact complicated the applicability of the management technique. Because of this, land requirement is appears as an important criterion.
- The employed waste management technique must be in accordance with Turkey's and the European Union's legal arrangements on environment.
- Public acceptance criterion denotes the acceptance level of the local inhabitants.

7.2 Application of the Hierarchical Fuzzy MCDM Method

The importance weights of various criteria and the ratings of qualitative criteria are considered as linguistic variables. These linguistic variables can be expressed by triangular fuzzy numbers as represented in Figure 7.2.

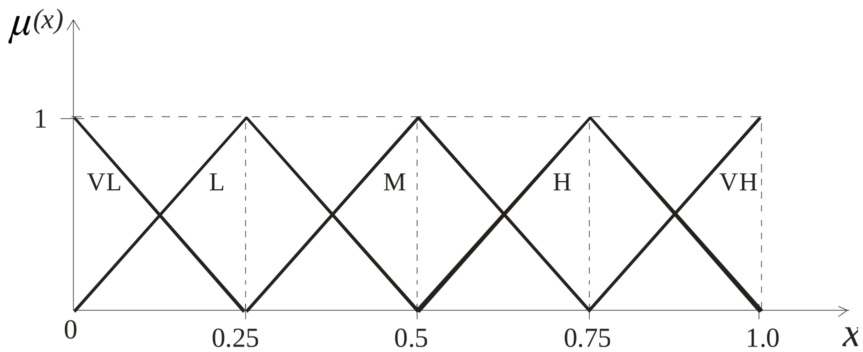


Figure 7.2 A linguistic term set where VL = (0, 0, 0.25), L = (0, 0.25, 0.5), M = (0.25, 0.5, 0.75), H = (0.5, 0.75, 1), VH = (0.75, 1, 1)

***Step* 1.** The expert used the linguistic variables "very low (VL)", "low (L)", "moderate (M)", "high (H)" and "very high (VH)" to evaluate the importance of the criteria and sub-criteria, and also the ratings of alternatives with respect to various subjective criteria and sub-criteria [115]. The evaluations are represented in Table 7.1, Table 7.2 and Table 7.3, respectively.

Table 7.1 Fuzzy importance weights of criteria

Criteria	**Importance weight**
Economic	M
Technical	M
Environmental	VH
Social	H

Table 7.2 Fuzzy importance weights of sub-criteria

Sub-Criteria	**Importance weight**
Net cost per ton	VH
Revenue	H
Process feasibility	VH
Operating experience	M
Release with health effects	H
CO_2 emission	H
CH_4 emission	VH
NO_x emission	H
SO_2 emission	H
Surface water disperses releases	VH
Aesthetic pollution and odor	L
Release to land	H
Land requirement	VH
Adaptability to environmental policy	VH
Public acceptance	H

Table 7.3 Data related to SWM problem

Sub-Criteria	S_1	S_2	S_3	S_4
Net cost per ton	(25,30,40)	(27,33,43)	(30.5,37.5,48)	(46.5,58.5,71)
Revenue	VL	L	L	VH
Process feasibility	VH	VH	VH	VH
Operating experience	M	H	H	H
Release with health effects	VL	VL	VL	VL
CO_2 emission	(65,90,120)	(52,72,96)	(45.5,63,84)	(6.5,9,12)
CH_4 emission	(80,120,150)	(64,96,120)	(56,84,105)	(8,12,15)
NO_x emission	(0,0,0)	(0,0,0)	(0,0,0)	(0,0,0)
SO_2 emission	(0,0,0)	(0,0,0)	(0,0,0)	(0,0,0)
Surface water disperses releases	VH	H	H	M
Aesthetic pollution and odor	VH	H	H	M
Release to land	VH	H	H	M
Land requirement	VH	H	H	L
Adaptability to environmental policy	H	H	H	VH
Public acceptance	H	H	H	H

Table 7.3 Data related to SWM problem (cont.)

Sub-Criteria	S_5	S_6	S_7
Net cost per ton	(49.5,60,72)	(184.5,222,246)	(200.75,241.65,267.5)
Revenue	L	H	VH
Process feasibility	VH	VL	VL
Operating experience	H	H	H
Release with health effects	L	H	VH
CO_2 emission	(45.5,63,84)	(6.5,9,12)	(3.25,4.5,6)
CH_4 emission	(56,84,105)	(8,12,15)	(4,6,7.5)
NO_x emission	(15,27,40)	(105,189,280)	(112.5,202.5,300)
SO_2 emission	(20,55,80)	(140,385,560)	(150,412.5,600)
Surface water disperses releases	H	L	L
Aesthetic pollution and odor	H	L	L
Release to land	H	L	L
Land requirement	H	M	M
Adaptability to environmental policy	M	VH	VH
Public acceptance	M	M	L

In the following steps, we will only show the calculations related to S_1. The remaining computations are performed in a similar way.

***Step* 2.** By using equation (12), the crisp data is normalized as given below.

Net cost per ton is a cost criterion, and $y_{11}^{*} = \max_i y_{i11} = 267.5$ and $y_{11}^{-} = \min_i y_{i11} = 25$. Then, we obtain

$$\tilde{y}_{111} = (y'_{a111}, y'_{b111}, y'_{c111}) = \left(\frac{267.5-40}{267.5-25}, \frac{267.5-30}{267.5-25}, \frac{267.5-25}{267.5-25}\right) = (0.94, 0.98, 1)$$

CO_2 emission is a cost criterion, and $y_{32}^{*} = \max_i y_{i32} = 120$ and $y_{32}^{-} = \min_i y_{i32} = 3.25$. Then, we find

$$\tilde{y}_{132} = (y'_{a132}, y'_{b132}, y'_{c132}) = \left(\frac{120-120}{120-3.25}, \frac{120-90}{120-3.25}, \frac{120-65}{120-3.25}\right) = (0,0.26,0.47),$$

CH_4 emission is a cost criterion, and $y^*_{33} = \max_i y_{i33} = 150$ and $y^-_{33} = \min_i y_{i33} = 4$. Then, we obtain

$$\tilde{y}_{133} = (y'_{a133}, y'_{b133}, y'_{c133}) = \left(\frac{150-150}{150-4}, \frac{150-120}{150-4}, \frac{150-80}{150-4}\right) = (0,0.21,0.48),$$

NO_x emission is a cost criterion, and $y^*_{34} = \max_i y_{i34} = 300$ and $y^-_{34} = \min_i y_{i34} = 0$. Then, we find

$$\tilde{y}_{134} = (y'_{a134}, y'_{b134}, y'_{c134}) = \left(\frac{300-0}{300-0}, \frac{300-0}{300-0}, \frac{300-0}{300-0}\right) = (1,1,1),$$

SO_2 emission is a cost criterion, and $y^*_{35} = \max_i y_{i35} = 600$ and $y^-_{35} = \min_i y_{i35} = 0$. Then, we obtain

$$\tilde{y}_{135} = (y'_{a135}, y'_{b135}, y'_{c135}) = \left(\frac{600-0}{600-0}, \frac{600-0}{600-0}, \frac{600-0}{600-0}\right) = (1,1,1),$$

The normalized data related to SWM problem are shown in Table 7.4

Table 7.4 Normalized data related to SWM problem

Sub-Criteria	S_1	S_2	S_3	S_4
Net cost per ton	(0.94,0.98,1)	(0.93,0.97,0.99)	(0.91,0.95.0.98)	(0.81,0.86.0.91)
Revenue	(0,0,0.25)	(0,0.25,0.50)	(0,0.25,0.50)	(0.75,1,1)
Process feasibility	(0.75,1,1)	(0.75,1,1)	(0.75,1,1)	(0.75,1,1)
Operating experience	(0.25,0.50,0.75)	(0.50,0.75,1)	(0.50,0.75,1)	(0.50,0.75,1)
Release with health effects	(0,0,0.25)	(0,0,0.25)	(0,0,0.25)	(0,0,0.25)
CO_2 emission	(0,0.26,0.47)	(0.21,0.41,0.58)	(0.31,0.49,0.64)	(0.93,0.95,0.97)
CH_4 emission	(0,0.21,0.48)	(0.21,0.37,0.59)	(0.31,0.45,0.64)	(0.92,0.95,0.97)
NO_x emission	(1,1,1)	(1,1,1)	(1,1,1)	(1,1,1)
SO_2 emission	(1,1,1)	(1,1,1)	(1,1,1)	(1,1,1)
Surface water disperses releases	(0.75,1,1)	(0.50,0.75,1)	(0.50,0.75,1)	(0.25,0.50,0.75)
Aesthetic pollution and odor	(0.75,1,1)	(0.50,0.75,1)	(0.50,0.75,1)	(0.25,0.50,0.75)
Release to land	(0.75,1,1)	(0.50,0.75,1)	(0.50,0.75,1)	(0.25,0.50,0.75)
Land requirement	(0.75,1,1)	(0.50,0.75,1)	(0.50,0.75,1)	(0,0.25,0.50)
Adaptability to environmental policy	(0.50,0.75,1)	(0.50,0.75,1)	(0.50,0.75,1)	(0.75,1,1)
Public acceptance	(0.50,0.75,1)	(0.50,0.75,1)	(0.50,0.75,1)	(0.50,0.75,1)

Table 7.4 Normalized data related to SWM problem (cont.)

Sub-Criteria	S_5	S_6	S_7
Net cost per ton	(0.81,0.86.0.90)	(0.09,0.19.0.34)	(0,0.11.0.28)
Revenue	(0,0.25,0.50)	(0.50,0.75,1)	(0.75,1,1)
Process feasibility	(0.75,1,1)	(0,0,0.25)	(0,0,0.25)
Operating experience	(0.50,0.75,1)	(0.50,0.75,1)	(0.50,0.75,1)
Release with health effects	(0,0.25,0.50)	(0.50,0.75,1)	(0.75,1,1)
CO_2 emission	(0.31,0.49,0.64)	(0.93,0.95,0.97)	(0.98,0.99,1)
CH_4 emission	(0.31,0.45,0.64)	(0.92,0.95,0.97)	(0.98,0.99,1)
NO_x emission	(0.87,0.91,0.95)	(0.07,0.37,0.65)	(0,0.33,0.63)
SO_2 emission	(0.87,0.91,0.97)	(0.07,0.36,0.77)	(0,0.31,0.75)
Surface water disperses releases	(0.50,0.75,1)	(0,0.25,0.50)	(0,0.25,0.50)
Aesthetic pollution and odor	(0.50,0.75,1)	(0,0.25,0.50)	(0,0.25,0.50)
Release to land	(0.50,0.75,1)	(0,0.25,0.50)	(0,0.25,0.50)
Land requirement	(0.50,0.75,1)	(0.25,0.50,0.75)	(0.25,0.50,0.75)
Adaptability to environmental policy	(0.25,0.50,0.75)	(0.75,1,1)	(0.75,1,1)
Public acceptance	(0.25,0.50,0.75)	(0.25,0.50,0.75)	(0,0.25,0.50)

***Step* 3.** Sub-criteria values are aggregated to criteria level using equation (13), and are represented in Table 7.5

$$\tilde{x}_{11} = (x_{a11}, x_{b11}, x_{c11}) = \frac{((0.75,1,1) \otimes (0.94,0.98,1)) \oplus ((0.50,0.75,1) \otimes (0,0,0.25))}{(0.75,1,1) \oplus (0.50,0.75,1)}$$

$$= (0.56,0.56,0.63),$$

$$\tilde{x}_{12} = (x_{a12}, x_{b12}, x_{c12}) = \frac{((0.75,1,1) \otimes (0.75,1,1)) \oplus ((0.25,0.50,0.75) \otimes (0.25,0.50,0.75))}{(0.75,1,1) \oplus (0.25,0.50,0.75)}$$

$$= (0.63,0.83,0.89),$$

$$\tilde{x}_{13} = (x_{a13}, x_{b13}, x_{c13}) =$$

$$\frac{((0.50,0.75,1) \otimes (0,0,0.25)) \oplus ((0.50,0.75,1) \otimes (0,0.26,0.47)) \oplus ((0.75,1,1) \otimes (0,0.21,0.48)) \oplus ((0.50,0.75,1) \otimes (1,1,1))}{(0.50,0.75,1) \oplus (0.50,0.75,1) \oplus (0.75,1,1) \oplus (0.50,0.75,1) \oplus (0.50,0.75,1) \oplus (0.75,1,1) \oplus (0,0.25,0.50) \oplus (0.50,0.75,1)}$$

$$\oplus \frac{((0.50,0.75,1) \otimes (1,1,1)) \oplus ((0.75,1,1) \otimes (0.75,1,1)) \oplus ((0,0.25,0.50) \otimes (0.75,1,1)) \oplus ((0.50,0,75,1) \otimes (0.75,1,1))}{(0.50,0.75,1) \oplus (0.50,0.75,1) \oplus (0.75,1,1) \oplus (0.50,0.75,1) \oplus (0.50,0.75,1) \oplus (0.75,1,1) \oplus (0,0.25,0.50) \oplus (0.50,0.75,1)}$$

$$= (0.48,0.65,0.76),$$

$$\tilde{x}_{14} = (x_{a14}, x_{b14}, x_{c14})$$

$$= \frac{((0.75,1,1) \otimes (0.75,1,1)) \oplus ((0.75,1,1) \otimes (0.50,0.75,1)) \oplus ((0.50,0.75,1) \otimes (0.50,0.75,1))}{(0.75,1,1) \oplus (0.75,1,1) \oplus (0.50,0.75,1)}$$

$$= (0.59,0.84,1),$$

Table 7.5 Criteria level aggregated values

Criteria	S_1	S_2	S_3	S_4
Economic	(0.56,0.56,0.63)	(0.56,0.66,0.75)	(0.54,0.65,0.74)	(0.79,0.92,0.96)
Technical	(0.63,0.83,0.89)	(0.69,0.92,1)	(0.69,0.92,1)	(0.69,0.92,1)
Environmental	(0.48,0.65,0.76)	(0.47,0.61,0.79)	(0.50,0.64,0.80)	(0.62,0.69,0.81)
Social	(0.59,0.84,1)	(0.50,0.75,1)	(0.50,0.75,1)	(0.41,0.66,0.83)

Table 7.5 Criteria level aggregated values (cont.)

Criteria	S_5	S_6	S_7
Economic	(0.48,0.60,0.70)	(0.25,0.43,0.67)	(0.30,0.49,0.64)
Technical	(0.69,0.92,1)	(0.13,0.25,0.57)	(0.13,0.25,0.57)
Environmental	(0.47,0.64,0.83)	(0.37,0.54,0.75)	(0.40,0.58,0.75)
Social	(0.34,0.59,0.83)	(0.44,0.68,0.83)	(0.38,0.61,0.75)

***Step* 4.** The normalized values of these aggregate performance ratings are computed using equation (14) and are represented in Table 7.6, where 0 indicates the worst value and 1 indicates the best value.

$x_{c1}^{*} = \max_{i} x_{ci1} = 0.96$ and $x_{a1}^{-} = \min_{i} x_{ai1} = 0.25$, then we find

$$\tilde{r}_{11} = (r_{a11}, r_{b11}, r_{c11}) = \left(\frac{0.56-0.25}{0{,}96-0.25}, \frac{0.56-0.25}{0{,}96-0.25}, \frac{0.63-0.25}{0{,}96-0.25} \right) = (0.44, 0.44, 0.53)$$

$x_{c2}^{*} = \max_{i} x_{ci2} = 1$ and $x_{a2}^{-} = \min_{i} x_{ai2} = 0.13$, then we obtain

$$\tilde{r}_{12} = (r_{a12}, r_{b12}, r_{c12}) = \left(\frac{0.63-0.13}{1-0.13}, \frac{0.83-0.13}{1-0.13}, \frac{0.89-0.13}{1-0.13} \right) = (0.57, 0.81, 0.88)$$

$x_{c3}^{*} = \max_{i} x_{ci3} = 0.83$ and $x_{a3}^{-} = \min_{i} x_{ai3} = 0.37$, then we find

$$\tilde{r}_{13} = (r_{a13}, r_{b13}, r_{c13}) = \left(\frac{0.48-0.37}{0.83-0.37}, \frac{0.65-0.37}{0.83-0.37}, \frac{0.76-0.37}{0.83-0.37} \right) = (0.25, 0.61, 0.86)$$

$x_{c4}^{*} = \max_{i} x_{ci4} = 1$ and $x_{a4}^{-} = \min_{i} x_{ai4} = 0.34$, then we obtain

$$\tilde{r}_{14} = (r_{a14}, r_{b14}, r_{c14}) = \left(\frac{0.59-0.34}{1-0.34}, \frac{0.84-0.34}{1-0.34}, \frac{1-0.34}{1-0.34} \right) = (0.38, 0.76, 1)$$

Table 7.6 Normalized values of aggregate performance ratings

Criteria	S_1	S_2	S_3	S_4
Economic	(0.44,0.44,0.53)	(0.43,0.58,0.70)	(0.41,0.56,0.69)	(0.76,0.95,1)
Technical	(0.57,0.81,0.88)	(0.64,0.90,1)	(0.64,0.90,1)	(0.64,0.90,1)
Environmental	(0.25,0.61,0.86)	(0.22,0.53,0.92)	(0.29,0.59,0.95)	(0.54,0.71,0.96)
Social	(0.38,0.76,1)	(0.24,0.62,1)	(0.24,0.62,1)	(0.10,0.48,0.75)

Table 7.6 Normalized values of aggregate performance ratings (cont.)

Criteria	S_5	S_6	S_7
Economic	(0.33,0.49,0.64)	(0,0.25,0.59)	(0.07,0.34,0.55)
Technical	(0.64,0.90,1)	(0,0.14,0.51)	(0,0.14,0.51)
Environmental	(0.22,0.60,1)	(0,0.38,0.83)	(0.07,0.45,0.83)
Social	(0,0.38,0.75)	(0.14,0.52,0.75)	(0.05,0.41,0.62)

***Step* 5.** We define the ideal and the anti-ideal solutions as

$$A^* = ((1,1,1),(1,1,1),(1,1,1),(1,1,1)),$$

$$A^- = ((0,0,0),(0,0,0),(0,0,0),(0,0,0)),$$

***Step* 6.** We calculate the weighted distances from ideal and anti-ideal solutions as follows:

$$\begin{aligned} D_1^* &= 1/2\left\{\max(0.25*|0.44-1|,0.75*|0.53-1|)+0.50*|0.44-1|\right\} \\ &+1/2\left\{\max(0.25*|0.57-1|,0.75*|0.88-1|)+0.50*|0.81-1|\right\} \\ &+1/2\left\{\max(0.75*|0.25-1|,1*|0.86-1|)+1*|0.61-1|\right\} \\ &+1/2\left\{\max(0.50*|0.38-1|,1*|1-1|)+0.75*|0.76-1|\right\} \\ &=1.14 \end{aligned}$$

$$D_2^* = 1.14$$

$$D_3^* = 1.10$$

$$D_4^* = 0.85$$

$$D_5^* = 1.31$$

$$D_6^* = 1.82$$

$$D_7^* = 1.82$$

$$
\begin{aligned}
D_1^- &= 1/2\left\{\max(0.25*|0.44-0|, 0.75*|0.53-0|) + 0.50*|0.44-0|\right\} \\
&\quad + 1/2\left\{\max(0.25*|0.57-0|, 0.75*|0.88-0|) + 0.50*|0.81-0|\right\} \\
&\quad + 1/2\left\{\max(0.75*|0.25-0|, 1*|0.86-0|) + 1*|0.61-0|\right\} \\
&\quad + 1/2\left\{\max(0.50*|0.38-0|, 1*|1-0|) + 0.75*|0.76-0|\right\} \\
&\quad = 2.36
\end{aligned}
$$

$D_2^- = 2.47$

$D_3^- = 2.50$

$D_4^- = 2.60$

$D_5^- = 2.28$

$D_6^- = 1.69$

$D_7^- = 1.62$

***Step* 7.** We calculate the proximity of the alternatives to the ideal solution as follows:

$P_1^* = 2.36/(1.14 + 2.36) = 0.6746$

$P_2^* = 2.47/(1.14 + 2.47) = 0.6834$

$P_3^* = 2.50/(1.10 + 2.50) = 0.6948$

$P_4^* = 2.60/(0.85 + 2.60) = 0.7541$

$P_5^* = 2.28/(1.31 + 2.28) = 0.6353$

$P_6^* = 1.69/(1.82 + 1.69) = 0.4814$

$P_7^* = 1.62/(1.82 + 1.62) = 0.4721$

***Step* 8.** The results are illustrated in Table 7.7.

Table 7.7 Ranking of the SWM scenarios

S_i	P_i^*	Ranking
S_1	0.675	4
S_2	0.683	3
S_3	0.695	2
S_4	0.754	1
S_5	0.635	5
S_6	0.481	6
S_7	0.472	7

Table 7.7 shows that the fourth scenario, S_4, with the highest P_i^* value is the best SWM scenario due to higher percentages of recycling and composting compared with other scenarios. Since landfill is an economic alternative, the scenarios with high landfill percentages rank after scenario 4. As expected, the scenarios with high incineration percentages are found at the lowest ranks because of the high cost and adverse environmental impacts of incineration.

7.3 Application of the Fuzzy Analytic Hierarchy Process to Solid Waste Management Problem in Istanbul

The expert used the triangular fuzzy conversion scale shown in Table 7.8 for the pairwise comparison.

Table 7.8 Triangular fuzzy conversion scale [97]

Linguistic scale	Triangular fuzzy scale	Triangular fuzzy reciprocal scale
Just equal (JE)	(1,1,1)	(1,1,1)
Equally important (EI)	(1/2,1,3/2)	(2/3,1,2)
Weakly important (WI)	(1,3/2,2)	(1/2,2/3,1)
Strongly more important (SMI)	(3/2,2,5/2)	(2/5,1/2,2/3)
Very strongly more important (VSMI)	(2,5/2,3)	(1/3,2/5,1/2)
Absolutely more important (AMI)	(5/2,3,7/2)	(2/7,1/3,2/5)

In the following, we will only show the calculations for determining the weighting vector of the criteria. For the rest, the calculations are performed in the same way and the results given in the tables are obtained.

Determining the weighting vector of the criteria:

Via pairwise comparison of criteria, the fuzzy evaluation matrix is constructed as in Table 7.9.

Table 7.9 Fuzzy evaluation matrix of criteria

	Economic	Technical	Environmental	Social
Economic	JE	WI	1/SMI	1/EI
Technical	1/WI	JE	1/SMI	1/WI
Environmental	SMI	SMI	JE	WI
Social	EI	WI	1/WI	JE

***Step* 1.** By using Eq. 6.8, we find

$$S_E = (3.07, 4, 5.67) \otimes \left(\frac{1}{22.83}, \frac{1}{17.50}, \frac{1}{13.47} \right) = (0.13, 0.23, 0.42)$$

$$S_T = (2.40, 2.83, 3.67) \otimes \left(\frac{1}{22.83}, \frac{1}{17.50}, \frac{1}{13.47} \right) = (0.11, 0.16, 0.27)$$

$$S_{EN} = (5, 6.50, 8) \otimes \left(\frac{1}{22.83}, \frac{1}{17.50}, \frac{1}{13.47} \right) = (0.22, 0.37, 0.59)$$

$$S_S = (3, 4.17, 5.50) \otimes \left(\frac{1}{22.83}, \frac{1}{17.50}, \frac{1}{13.47} \right) = (0.13, 0.24, 0.41)$$

***Step* 2.** Using Eq. 6.9 and 6.10, we obtain

$$V(S_E \geq S_T) = 1$$

$$V(S_E \geq S_{EN}) = \frac{0.22 - 0.42}{0.23 - 0.42 - 0.37 + 0.22} = 0.59$$

$$V(S_E \geq S_S) = \frac{0.13 - 0.42}{0.23 - 0.42 - 0.24 + 0.13} = 0.97$$

$$V(S_T \geq S_E) = \frac{0.13 - 0.27}{0.16 - 0.27 - 0.23 + 0.13} = 0.67$$

$$V(S_T \geq S_{EN}) = \frac{0.22 - 0.27}{0.16 - 0.27 - 0.37 + 0.22} = 0.20$$

$$V(S_T \geq S_S) = \frac{0.13 - 0.27}{0.16 - 0.27 - 0.24 + 0.13} = 0.65$$

$$V(S_{EN} \geq S_E) = 1$$

$$V(S_{EN} \geq S_T) = 1$$

$$V(S_{EN} \geq S_S) = 1$$

$$V(S_S \geq S_E) = 1$$

$$V(S_S \geq S_T) = 1$$

$$V(S_S \geq S_{EN}) = \frac{0.22 - 0.41}{0.24 - 0.41 - 0.37 + 0.22} = 0.59$$

***Step* 3.** Finally, by using Eq. 6.11, 6.12, and 6.13, we find

$$d'(E) = V(S_E \geq S_T, S_{EN}, S_S) = \min(1, 0.59, 0.97) = 0.59$$

$$d'(T) = V(S_T \geq S_E, S_{EN}, S_S) = \min(0.67, 0.20, 0.65) = 0.20$$

$$d'(EN) = V(S_{EN} \geq S_E, S_T, S_S) = \min(1,1,1) = 1$$

$$d'(S) = V(S_S \geq S_E, S_T, S_{EN}) = \min(1,1,0.59) = 0.59$$

Therefore,

$$W' = (0.59, 0.20, 1, 0.59)^T .$$

***Step* 4.** Via normalization, the normalized weight vectors with respect to the criteria have been obtained as

$$W = (0.25, 0.08, 0.42, 0.25)^T$$

Determining the weighting vector of the sub-criteria related to economic criterion:

Through pairwise comparison of sub-criteria related to economic criterion, the fuzzy evaluation matrix is constructed as in Table 7.10.

Table 7.10 Fuzzy evaluation matrix of sub-criteria related to economic criterion

	Net cost per ton	Revenue
Net cost per ton	JE	SMI
Revenue	1/SMI	JE

Therefore, we have

$$W' = (1,0)^T$$

Using the normalization procedure, the normalized weight vectors of the sub-criteria with respect to the economic criterion have been obtained:

$$W = (1,0)^T$$

Determining the weighting vector of the sub-criteria related to technical criterion:

Employing pairwise comparison of criteria, the fuzzy evaluation matrix is constructed as in Table 7.11.

Table 7.11 Fuzzy evaluation matrix of sub-criteria related to technical criterion

	Process feasibility	Operating experience
Process feasibility	JE	WI
Operating experience	1/WI	JE

Thus, we find

$$W^{'} = (1,0.46)^T$$

Via normalization, the normalized weight vectors of the sub-criteria with respect to the technical criterion have been obtained:

$$W = (0.68,0.32)^T$$

Determining the weighting vector of the sub-criteria related to environmental criterion:

Using pairwise comparison of criteria, the fuzzy evaluation matrix is constructed as in Table 7.12.

Table 7.12 Fuzzy evaluation matrix of sub-criteria related to environmental criterion

	Release with health effects	CO_2 emission	CH_4 emission	NO_x emission
Release with health effects	JE	1/WI	1/WI	1/WI
CO_2 emission	WI	JE	1/EI	WI
CH_4 emission	WI	EI	JE	WI
NO_x emission	WI	1/WI	1/WI	JE
SO_2 emission	WI	1/WI	1/WI	1/EI
Surface water disperses releases	SMI	1/SMI	1/SMI	1/WI
Aesthetic pollution and odor	WI	1/SMI	1/SMI	1/SMI
Release to land	VSMI	1/SMI	1/SMI	1/WI

Table 7.12 Fuzzy evaluation matrix of sub-criteria related to environmental criterion (cont.)

	SO_2 emission	Surface water disperses releases	Aesthetic pollution and odor	Release to land
Release with health effects	1/WI	1/SMI	1/WI	1/VSMI
CO_2 emission	WI	SMI	SMI	SMI
CH_4 emission	WI	SMI	SMI	SMI
NO_x emission	EI	WI	SMI	WI
SO_2 emission	JE	WI	SMI	WI
Surface water disperses releases	1/WI	JE	SMI	1/EI
Aesthetic pollution and odor	1/SMI	1/SMI	JE	1/SMI
Release to land	1/WI	EI	SMI	JE

Thus, we have

$$W^{'} = (0.27,1,1,0.80,0.81,0.66,0.26,0.69)^T$$

Employing the normalization procedure, the normalized weight vectors of the sub-criteria with respect to the environmental criterion have been obtained:

$$W = (0.05,0.18,0.18,0.15,0.15,0.12,0.04,0.13)^T$$

Determining the weighting vector of the sub-criteria related to social criterion:

Employing pairwise comparison of criteria, the fuzzy evaluation matrix is constructed as in Table 7.13.

Table 7.13 Fuzzy evaluation matrix of sub-criteria related to social criterion

	Land requirement	Adaptability to environmental policy	Public acceptance
Land requirement	JE	1/WI	1/SMI
Adaptability to environmental policy	WI	JE	1/EI
Public acceptance	SMI	EI	JE

Therefore, we find

$$W^{'} = (0.38, 0.89, 1)^{T}$$

Using the normalization procedure, the normalized weight vectors of the sub-criteria with respect to the social criterion have been calculated as

$$W = (0.17, 0.39, 0.44)^{T}$$

Determining the weighting vector of the scenarios with respect to net cost per ton criterion:

Via pairwise comparison of criteria, the fuzzy evaluation matrix is constructed as in Table 7.14.

Table 7.14 Fuzzy evaluation matrix of scenarios related to net cost per ton sub-criterion

Net cost per ton	S_1	S_2	S_3	S_4	S_5	S_6	S_7
S_1	JE	EI	SMI	VSMI	SMI	AMI	AMI
S_2	1/EI	JE	EI	SMI	WI	AMI	AMI
S_3	1/SMI	1/EI	JE	SMI	WI	AMI	AMI
S_4	1/VSMI	1/SMI	1/SMI	JE	1/EI	VSMI	VSMI
S_5	1/SMI	1/WI	1/WI	EI	JE	VSMI	VSMI
S_6	1/AMI	1/AMI	1/AMI	1/VSMI	1/VSMI	JE	EI
S_7	1/AMI	1/AMI	1/AMI	1/VSMI	1/VSMI	1/EI	JE

Therefore, we have

$$W^{'} = (1,0.85,0.80,0.43,0.47,0,0)^T$$

Employing the normalization procedure, the normalized weight vectors with respect to the criterion have been obtained:

$$W = (0.28,0.24,0.23,0.12,0.13,0,0)^T$$

Determining the weighting vector of the scenarios with respect to revenue criterion:

Using pairwise comparison of criteria, the fuzzy evaluation matrix is constructed as in Table 7.15.

Table 7.15 Fuzzy evaluation matrix of scenarios related to revenue sub-criterion

Revenue	S_1	S_2	S_3	S_4	S_5	S_6	S_7
S_1	JE	1/WI	1/WI	1/AMI	1/SMI	1/VSMI	1/VSMI
S_2	WI	JE	1/EI	1/VSMI	1/WI	1/SMI	1/SMI
S_3	WI	EI	JE	1/VSMI	1/WI	1/SMI	1/SMI
S_4	AMI	VSMI	VSMI	JE	SMI	1/EI	1/EI
S_5	SMI	WI	WI	1/SMI	JE	1/VSMI	1/VSMI
S_6	VSMI	SMI	SMI	EI	VSMI	JE	1/EI
S_7	VSMI	SMI	SMI	EI	VSMI	EI	JE

Therefore, we have

$$W^{'} = (0,0.23,0.17,1,0.41,0.92,0.92)^T$$

Employing the normalization procedure, the normalized weight vectors with respect to the criterion have been computed as

$$W = (0,0.06,0.05,0.28,0.11,0.25,0.25)^T$$

Determining the weighting vector of the scenarios with respect to process feasibility criterion:

Via pairwise comparison of criteria, the fuzzy evaluation matrix is constructed as in Table 7.16.

Table 7.16 Fuzzy evaluation matrix of scenarios related to process feasibility sub-criterion

Process feasibility	S_1	S_2	S_3	S_4	S_5	S_6	S_7
S_1	JE	1/WI	1/WI	1/AMI	1/WI	VSMI	VSMI
S_2	WI	JE	1/EI	1/AMI	1/WI	VSMI	VSMI
S_3	WI	EI	JE	1/AMI	1/WI	VSMI	VSMI
S_4	AMI	AMI	AMI	JE	EI	EI	EI
S_5	WI	WI	WI	1/EI	JE	VSMI	VSMI
S_6	1/VSMI	1/VSMI	1/VSMI	1/EI	1/VSMI	JE	1/EI
S_7	1/VSMI	1/VSMI	1/VSMI	1/EI	1/VSMI	EI	JE

Thus, we have

$$W^{'} = (0.55,0.70,0.69,1,0.89,0.14,0.07)^T$$

Using the normalization procedure, the normalized weight vectors with respect to the criterion have been obtained:

$$W = (0.14,0.17,0.17,0.25,0.22,0.03,0.02)^T$$

Determining the weighting vector of the scenarios with respect to operating experience criterion:

Employing pairwise comparison of criteria, the fuzzy evaluation matrix is constructed as in Table 7.17.

Table 7.17 Fuzzy evaluation matrix of scenarios related to operating experience sub-criterion

Operating experience	S_1	S_2	S_3	S_4	S_5	S_6	S_7
S_1	JE	1/WI	1/WI	1/AMI	SMI	1/AMI	1/AMI
S_2	WI	JE	1/EI	1/VSMI	1/WI	1/VSMI	1/VSMI
S_3	WI	EI	JE	1/VSMI	1/EI	1/VSMI	1/VSMI
S_4	AMI	VSMI	VSMI	JE	SMI	EI	EI
S_5	SMI	WI	EI	SMI	JE	1/SMI	1/SMI
S_6	AMI	VSMI	VSMI	1/EI	SMI	JE	EI
S_7	AMI	VSMI	VSMI	1/EI	SMI	1/EI	JE

Therefore, we obtain

$$W^{'} = (0.08,0.18,0.24,1,0.57,1,1)^{T}$$

Via normalization, the normalized weight vectors with respect to the criterion have been computed as

$$W = (0.02,0.04,0.06,0.24,0.14,0.25,0.25)^{T}$$

Determining the weighting vector of the scenarios with respect to release with health effects criterion:

Using pairwise comparison of criteria, the fuzzy evaluation matrix is constructed as in Table 7.18.

Table 7.18 Fuzzy evaluation matrix of scenarios related to health effects sub-criterion

Release with health effects	S_1	S_2	S_3	S_4	S_5	S_6	S_7
S_1	JE	1/WI	1/SMI	1/SMI	EI	VSMI	VSMI
S_2	WI	JE	1/EI	1/WI	EI	SMI	VSMI
S_3	SMI	EI	JE	1/SMI	WI	VSMI	VSMI
S_4	SMI	WI	SMI	JE	WI	VSMI	AMI
S_5	1/EI	1/EI	1/WI	1/WI	JE	VSMI	SMI
S_6	1/VSMI	1/SMI	1/VSMI	1/VSMI	1/VSMI	JE	WI
S_7	1/VSMI	1/VSMI	1/VSMI	1/AMI	1/SMI	1/WI	JE

Thus, we have

$$W^{'} = (0.54, 0.69, 0.79, 1, 0.63, 0, 0)^T$$

Employing the normalization procedure, the normalized weight vectors with respect to the criterion have been obtained:

$$W = (0.15, 0.19, 0.22, 0.27, 0.17, 0, 0)^T$$

Determining the weighting vector of the scenarios with respect to CO_2 emission criterion:

Via pairwise comparison of criteria, the fuzzy evaluation matrix is constructed as in Table 7.19.

Table 7.19 Fuzzy evaluation matrix of scenarios related to CO_2 emission sub-criterion

CO_2 emission	S_1	S_2	S_3	S_4	S_5	S_6	S_7
S_1	JE	1/WI	1/SMI	1/VSMI	1/SMI	1/AMI	1/AMI
S_2	WI	JE	1/WI	1/VSMI	1/WI	1/VSMI	1/AMI
S_3	SMI	WI	JE	1/VSMI	1/EI	1/VSMI	1/VSMI
S_4	VSMI	VSMI	VSMI	JE	VSMI	EI	1/EI
S_5	SMI	WI	EI	1/VSMI	JE	1/VSMI	1/VSMI
S_6	AMI	VSMI	VSMI	1/EI	VSMI	JE	1/WI
S_7	AMI	AMI	VSMI	EI	VSMI	WI	JE

Therefore, we have

$$W^{'} = (0, 0, 0.22, 0.89, 0.17, 0.90, 1)^T$$

Using the normalization procedure, the normalized weight vectors with respect to the criterion have been obtained:

$$W = (0, 0, 0.07, 0.28, 0.05, 0.28, 0.32)^T$$

Determining the weighting vector of the scenarios with respect to CH_4 emission criterion:

Employing pairwise comparison of criteria, the fuzzy evaluation matrix is constructed as in Table 7.20.

Table 7.20 Fuzzy evaluation matrix of scenarios related to CH_4 emission sub-criterion

CH_4 emission	S_1	S_2	S_3	S_4	S_5	S_6	S_7
S_1	JE	1/WI	1/SMI	1/VSMI	1/SMI	1/AMI	1/AMI
S_2	WI	JE	1/WI	1/VSMI	1/WI	1/VSMI	1/AMI
S_3	SMI	WI	JE	1/VSMI	1/EI	1/VSMI	1/VSMI
S_4	VSMI	VSMI	VSMI	JE	VSMI	EI	1/EI
S_5	SMI	WI	EI	1/VSMI	JE	1/VSMI	1/VSMI
S_6	AMI	VSMI	VSMI	1/EI	VSMI	JE	1/WI
S_7	AMI	AMI	VSMI	EI	VSMI	WI	JE

Therefore, we obtain

$$W' = (0,0,0.22,0.89,0.17,0.90,1)^T$$

Using the normalization procedure, the normalized weight vectors with respect to the criterion have been computed as

$$W = (0,0,0.07,0.28,0.05,0.28,0.32)^T$$

Determining the weighting vector of the scenarios with respect to NO_X emission criterion:

Employing pairwise comparison of criteria, the fuzzy evaluation matrix is constructed as in Table 7.21.

Table 7.21 Fuzzy evaluation matrix of scenarios related to NO_x emission sub-criterion

NO_X emission	S_1	S_2	S_3	S_4	S_5	S_6	S_7
S_1	JE	1/JE	1/JE	1/JE	WI	AMI	AMI
S_2	JE	JE	1/JE	1/JE	WI	AMI	AMI
S_3	JE	JE	JE	1/JE	WI	AMI	AMI
S_4	JE	JE	JE	JE	WI	AMI	AMI
S_5	1/WI	1/WI	1/WI	1/WI	JE	VSMI	VSMI
S_6	1/AMI	1/AMI	1/AMI	1/AMI	1/VSMI	JE	WI
S_7	1/AMI	1/AMI	1/AMI	1/AMI	1/VSMI	1/WI	JE

Thus, we have

$$W^{'} = (1,1,1,1,0.60,0,0)^T$$

Using the normalization procedure, the normalized weight vectors with respect to the criterion have been obtained:

$$W = (0.22,0.22,0.22,0.22,0.12,0,0)^T$$

Determining the weighting vector of the scenarios with respect to SO_2 emission criterion:

Employing pairwise comparison of criteria, the fuzzy evaluation matrix is constructed as shown in Table 7.22.

Table 7.22 Fuzzy evaluation matrix of scenarios related to SO_2 emission sub-criterion

SO_2 emission	S_1	S_2	S_3	S_4	S_5	S_6	S_7
S_1	JE	1/JE	1/JE	1/JE	WI	AMI	AMI
S_2	JE	JE	1/JE	1/JE	WI	AMI	AMI
S_3	JE	JE	JE	1/JE	WI	AMI	AMI
S_4	JE	JE	JE	JE	WI	AMI	AMI
S_5	1/WI	1/WI	1/WI	1/WI	JE	VSMI	VSMI
S_6	1/AMI	1/AMI	1/AMI	1/AMI	1/VSMI	JE	WI
S_7	1/AMI	1/AMI	1/AMI	1/AMI	1/VSMI	1/WI	JE

Therefore, we have

$$W' = (1,1,1,1,0.60,0,0)^T$$

Using the normalization procedure, the normalized weight vectors with respect to the criterion have been calculated as

$$W = (0.22,0.22,0.22,0.22,0.12,0,0)^T$$

Determining the weighting vector of the scenarios with respect to surface water disperses releases criterion:

Via pairwise comparison of criteria, the fuzzy evaluation matrix is constructed as in Table 7.23.

Table 7.23 Fuzzy evaluation matrix of scenarios related to surface water disperses releases sub-criterion

Surface water disperses releases	S_1	S_2	S_3	S_4	S_5	S_6	S_7
S_1	JE	1/WI	1/SMI	1/SMI	1/SMI	1/AMI	1/VSMI
S_2	WI	JE	1/EI	1/WI	1/WI	1/AMI	1/VSMI
S_3	SMI	EI	JE	1/WI	1/EI	1/VSMI	1/VSMI
S_4	SMI	WI	WI	JE	WI	1/SMI	1/SMI
S_5	SMI	WI	EI	1/WI	JE	1/VSMI	1/VSMI
S_6	AMI	AMI	VSMI	SMI	VSMI	JE	EI
S_7	VSMI	VSMI	VSMI	SMI	VSMI	1/EI	JE

Therefore, we have

$$W' = (0,0.07,0.20,0.41,0.21,1,0.93)^T$$

Employing the normalization procedure, the normalized weight vectors with respect to the criterion have been obtained:

$$W = (0, 0.03, 0.07, 0.15, 0.07, 0.35, 0.33)^T$$

Determining the weighting vector of the scenarios with respect to aesthetic pollution and odor criterion:

Using pairwise comparison of criteria, the fuzzy evaluation matrix is constructed as in Table 7.24.

Table 7.24 Fuzzy evaluation matrix of scenarios related to aesthetic pollution and odor sub-criterion

Aesthetic pollution and odor	S_1	S_2	S_3	S_4	S_5	S_6	S_7
S_1	JE	1/WI	1/SMI	1/SMI	1/WI	1/VSMI	1/SMI
S_2	WI	JE	1/EI	1/WI	1/WI	1/VSMI	1/SMI
S_3	SMI	EI	JE	1/WI	1/EI	1/SMI	1/SMI
S_4	SMI	WI	WI	JE	WI	1/SMI	1/SMI
S_5	WI	WI	EI	1/WI	JE	1/SMI	1/SMI
S_6	VSMI	VSMI	SMI	SMI	SMI	JE	EI
S_7	SMI	SMI	SMI	SMI	SMI	1/EI	JE

Thus, we have

$$W^{'} = (0, 0.30, 0.42, 0.59, 0.38, 1, 0.93)^T$$

Via normalization, the normalized weight vectors with respect to the criterion have been computed as

$$W = (0, 0.08, 0.12, 0.16, 0.11, 0.28, 0.25)^T$$

Determining the weighting vector of the scenarios with respect to release to land criterion:

Via pairwise comparison of criteria, the fuzzy evaluation matrix is constructed as shown in Table 7.25.

Table 7.25 Fuzzy evaluation matrix of scenarios related to release to land sub-criterion

Release to land	S_1	S_2	S_3	S_4	S_5	S_6	S_7
S_1	JE	1/WI	1/SMI	1/SMI	1/SMI	1/AMI	1/VSMI
S_2	WI	JE	1/EI	1/WI	1/WI	1/AMI	1/VSMI
S_3	SMI	EI	JE	1/WI	1/EI	1/VSMI	1/VSMI
S_4	SMI	WI	WI	JE	WI	1/SMI	1/SMI
S_5	SMI	WI	EI	1/WI	JE	1/VSMI	1/VSMI
S_6	AMI	AMI	VSMI	SMI	VSMI	JE	EI
S_7	VSMI	VSMI	VSMI	SMI	VSMI	1/EI	JE

Therefore, we obtain

$$W' = (0,0.07,0.20,0.41,0.21,1,0.93)^T$$

Using the normalization procedure, the normalized weight vectors with respect to the criterion have been calculated as

$$W = (0,0.03,0.07,0.15,0.07,0.35,0.33)^T$$

Determining the weighting vector of the scenarios with respect to Land requirement criterion:

Employing pairwise comparison of criteria, the fuzzy evaluation matrix is constructed as in Table 7.26.

Table 7.26 Fuzzy evaluation matrix of scenarios related to land requirement sub-criterion

Land requirement	S_1	S_2	S_3	S_4	S_5	S_6	S_7
S_1	JE	1/WI	1/WI	1/AMI	1/SMI	1/AMI	1/VSMI
S_2	WI	JE	1/EI	1/VSMI	1/WI	1/VSMI	1/VSMI
S_3	WI	EI	JE	1/VSMI	1/WI	1/VSMI	1/VSMI
S_4	AMI	VSMI	VSMI	JE	SMI	1/WI	1/WI
S_5	SMI	WI	WI	1/SMI	JE	1/SMI	1/SMI
S_6	AMI	VSMI	VSMI	WI	SMI	JE	WI
S_7	VSMI	VSMI	VSMI	WI	SMI	1/WI	JE

Thus, we have

$$W' = (0,0.08,0.01,0.86,0.33,1,0.89)^T$$

Employing the normalization procedure, the normalized weight vectors with respect to the criterion have been obtained:

$$W = (0,0.02,0,0.27,0.11,0.32,0.28)^T$$

Determining the weighting vector of the scenarios with respect to adaptability to environmental policy criterion:

Using pairwise comparison of criteria, the fuzzy evaluation matrix is constructed as given in Table 7.27.

Table 7.27 Fuzzy evaluation matrix of scenarios related to adaptability to environmental policy sub-criterion

Adaptability to environmental policy	S_1	S_2	S_3	S_4	S_5	S_6	S_7
S_1	JE	1/EI	1/EI	1/AMI	WI	1/EI	1/EI
S_2	EI	JE	1/EI	1/VSMI	WI	1/EI	1/EI
S_3	EI	EI	JE	1/VSMI	EI	1/EI	1/EI
S_4	AMI	VSMI	VSMI	JE	VSMI	SMI	SMI
S_5	1/WI	1/WI	1/EI	1/VSMI	JE	1/EI	1/EI
S_6	EI	EI	EI	1/SMI	EI	JE	EI
S_7	EI	EI	EI	1/SMI	EI	1/EI	JE

Therefore, we have

$$W' = (0.46,0.44,0.37,1,0.33,0.32,0.36)^T$$

Via normalization, the normalized weight vectors with respect to the criterion have been obtained:

$$W = (0.14, 0.14, 0.11, 0.30, 0.10, 0.10, 0.11)^T$$

Determining the weighting vector of the scenarios with respect to public acceptance criterion:

Via pairwise comparison of criteria, the fuzzy evaluation matrix is constructed as shown in Table 7.28.

Table 7.28 Fuzzy evaluation matrix of scenarios related to public acceptance sub-criterion

Public acceptance	S_1	S_2	S_3	S_4	S_5	S_6	S_7
S_1	JE	1/WI	1/WI	1/VSMI	EI	SMI	VSMI
S_2	WI	JE	1/EI	1/SMI	WI	VSMI	VSMI
S_3	WI	EI	JE	1/SMI	WI	VSMI	VSMI
S_4	VSMI	SMI	SMI	JE	SMI	AMI	AMI
S_5	1/EI	1/WI	1/WI	1/SMI	JE	AMI	AMI
S_6	1/SMI	1/VSMI	1/VSMI	1/AMI	1/AMI	JE	EI
S_7	1/VSMI	1/VSMI	1/VSMI	1/AMI	1/AMI	1/EI	JE

Therefore, we have

$$W' = (0.32, 0.60, 0.58, 1, 0.52, 0, 0)^T$$

Employing the normalization procedure, the normalized weight vectors with respect to the criterion have been obtained:

$$W = (0.11, 0.20, 0.19, 0.33, 0.17, 0, 0)^T$$

All priority weights calculated above are shown in Table 7.29.

Table 7.29 Calculated priority weights

Scenarios	E		T		EN								S		
	0.25		0.08		0.42								0.25		
	C	R	P	O	H	CO	CH	NO	SO	W	A	L	LR	EP	PA
	1	0	0.68	0.32	0.05	0.18	0.18	0.15	0.15	0.12	0.04	0.13	0.17	0.39	0.44
1	0.28	0	0.14	0.02	0.15	0	0	0.22	0.22	0	0	0	0	0.14	0.11
2	0.24	0.06	0.17	0.04	0.19	0	0	0.22	0.22	0.03	0.08	0.03	0.02	0.14	0.20
3	0.23	0.05	0.17	0.06	0.22	0.07	0.07	0.22	0.22	0.07	0.12	0.07	0	0.11	0.19
4	0.12	0.28	0.25	0.24	0.27	0.28	0.28	0.22	0.22	0.15	0.16	0.15	0.27	0.30	0.33
5	0.13	0.11	0.22	0.14	0.17	0.05	0.05	0.12	0.12	0.07	0.11	0.07	0.11	0.10	0.17
6	0	0.25	0.03	0.25	0	0.28	0.28	0	0	0.35	0.28	0.35	0.32	0.10	0
7	0	0.25	0.02	0.25	0	0.32	0.32	0	0	0.33	0.25	0.33	0.28	0.11	0

Finally, we obtain the final weights and ranking of the alternatives as in Table 7.30.

Table 7.30 Ranking of SWM scenarios

S_i	Weight	Ranking
S_1	0.1331	4
S_2	0.1410	3
S_3	0.1510	2
S_4	0.2212	1
S_5	0.1196	5
S_6	0.1168	7
S_7	0.1174	6

Table 7.30 shows that the results of the fuzzy AHP method for the solid waste management problem in Istanbul are approximately the same as the results obtained using the hierarchical fuzzy MCDM method. The fourth scenario, S_4, with the highest weight, is the best SWM scenario. The scenarios with high landfill percentages rank after scenario 4, and the scenarios with high incineration percentages are found at the lowest ranks.

8. CONCLUSION

Recently, due to the rise in the environmental problems caused by the solid wastes, it is necessary to construct an efficient waste management system, which considers numerous factors including environmental, economic and social aspects. Some of these factors can be quantified, while others are qualitative at most. Thus, especially in metropolitans, choosing the adequate waste management system appears as a multi-criteria decision making problem with a hierarchical nature. A robust MCDM procedure used for evaluating SWM scenarios should be able to consider both qualitative and quantitative data. Fuzzy set theory appears as an effective way to express factors such as process feasibility and health effects, which can be assessed by neither crisp values nor random processes.

In this study, the hierarchical fuzzy MCDM algorithm proposed by Karsak and Ahiska [102] and the fuzzy AHP method proposed by Chang [111] have been employed for addressing the solid waste management problem in Istanbul.

In classical 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. Besides having the capability of considering numerous attributes that are structured in a multi-level hierarchy, the proposed decision frameworks enable the decision-makers to use linguistic terms. These approach are able to incorporate both crisp data and fuzzy data represented as linguistic variables or fuzzy numbers into the analysis. The decision-makers' importance assessment of evaluation criteria is incorporated into the analysis via linguistic variables [106].

Considering the fact that an alternative with the shortest distance from the ideal alternative may not have the farthest distance from the anti-ideal, Karsak and Ahiska's decision algorithm takes into account the weighted distances from both the ideal and anti-ideal simultaneously. Furthermore, Karsak and Ahıska's approach does not require the use of fuzzy number ranking methods, which may yield different results according to the ranking method selected for application purposes.

In conclusion, the decision frameworks presented in this study appear to be robust decision tools due to their effectiveness in quantifying the imprecision inherent in decision-maker's assessments.

After the evaluation of different SWM scenarios for Istanbul using two fuzzy multiple criteria decision making methods, the rankings are obtained. The ranking obtained according to the hierarchical fuzzy MCDM algorithm proposed by Karsak and Ahıska is $S_4 \succ S_3 \succ S_2 \succ S_1 \succ S_5 \succ S_6 \succ S_7$, whereas the ranking found using the fuzzy AHP is as $S_4 \succ S_3 \succ S_2 \succ S_1 \succ S_5 \succ S_7 \succ S_6$. The rankings obtained from two MCDM methods appear to be very close. Using both of the methods, we obtained the fourth scenario as the best alternative for Istanbul due to higher percentages of recycling and composting. Thus, we can conclude that the Turkish Government and Municipalities have to put special emphasis on waste recovery techniques. With the legal arrangement, they have to compel the producers to fabricate their products by recoverable materials. Furthermore, they have to encourage the citizens to use recoverable materials. Although landfill has several drawbacks for the environment, the scenarios with high landfill percentages rank after scenario four since landfill is a highly economic alternative compared with incineration. Finally, the scenarios with high incineration percentages are found at the lowest ranks because of the high cost and adverse environmental impacts of incineration.

For further study, extensions of the proposed methodology can be developed employing both subjective and objective weight assessments of the criteria and related sub-criteria. Moreover, the results can be compared with those of other fuzzy MCDM methods reported in the literature.

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