Modeling landfill site selection using an integrated fuzzy MCDM approach

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Abstract Landfill site selection is a complex process, which requires the evaluation of multiple criteria. Decision-makers often face difficulties in taking the right decision in a multiple attribute environment. In this paper, an integrated fuzzy-analytical hierarchy process (AHP)–the technique for order preference by similarity to ideal solution (TOPSIS)-based methodology was applied to the municipal solid waste (MSW) landfill site selection problem. To demonstrate the approach taken, a real case of Mumbai city is taken. The model was developed to suit the socio-economic and regulatory set-up. The fuzzy-analytic hierarchy process was used to make pairwise comparisons of criteria to assign weights and rank them, while F-TOPSIS was employed to rank the alternatives. It was found that the fuzzy-AHP–TOPSIS-based methodology can be a powerful guiding tool for MSW management planners. With this modeling approach, the accuracy of landfill site selection procedure can be significantly enhanced as compared to the traditional methods, thereby reducing the cost and time required. The developed methodology helps in representing and analyzing the uncertainty and error in the decision making process of landfill site selection.

Keywords Municipal solid waste management · Landfill siting · MCDM · Fuzzy logic · Fuzzy-AHP · Fuzzy-TOPSIS

Introduction

Landfill site selection is a complex problem and requires an extensive evaluation process that has to be carried out taking into account the environmental, economic, socio-political, and legislative aspects. Landfill sites are considered as undesirable or obnoxious facilities and are usually opposed socially (Rodriguez et al. 2006; Colebrook and Sicilia 2007). Due to the scarcity of land and increasing amount of waste, it is vital that the available land resources are used with proper planning.

During the siting process, the challenge is to make an environment friendly and financially sound selection. Siting a suitable landfill location involves the consideration of a wide array of points, taking into account different criteria and verifying a given set of limitations to ultimately provide an optimal solution. The inability to properly site landfills has led to a great deal of controversy and negative effects. Public awareness of environmental impacts, and distrust for scientific studies to determine proper siting locations certainly leave waste managers with little room for error.

Until recently, there were no engineered landfill sites in India. As construction and management of landfills are quite expensive and need professional management, scientific location of landfills has not been actively considered in India. Most of the Indian cities, including the populated metros Mumbai and Delhi, do not have scientifically identified landfill sites. Indian metro cities generate an enormous amount of waste, containing 50–70 % of

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biodegradables, 5–10 % of inert materials and 10–20 % recyclable waste. More than 90 % of the municipal solid waste (MSW) generated in India is directly disposed of by dumping in low-lying areas or the land designated for this purpose within or outside the city, in an unscientific and unsatisfactory manner (Das et al. 1998). The selected disposal sites are mostly close to the collection area, and less attention is given to the siting of new sites. In several municipalities, existing landfill sites have already been exhausted and the respective local bodies do not have the resources and expertise to acquire new land. This significantly decreases their MSW collection efficiency. Also, in the existing sites, there is no provision for leachate and gas control, and soil cover is rarely provided except at the time of closure of the site. As a result, the landfills create severely unhygienic conditions and cause the degradation of environmental quality.

It is difficult to find suitable land to develop a landfill site that is close to the waste source. Economic concerns play an important role when the waste is to be transported at a distant site. Furthermore, from an economic perspective, the available land must be accessible through road networks. However, the location of landfill sites on or too close to existing road and rail networks can also hinder transportation and may have an impact on land price and tourism in the area. Thus, the landfill site should be located at an adequate distance for economic feasibility; contrastingly, they must be sufficiently far from the waste source to avoid social conflict.

Siting, design, construction, operation, and maintenance of an MSW landfill site need a financial plan for its long-term workability. Further, the location of a site should be such that it is possible to make technological changes in the landfill design and operation, and support post-closure care monitoring. In selecting a landfill site, many potential criteria and factors should be carefully identified, evaluated and analyzed; these include the distance from residential areas, selection of the optimal transportation routes, environmentally sensitive areas, geological features, and the cost of land. Thus, landfill site selection involves multiple criteria and can be viewed as a multiple criteria decision making (MCDM) problem.

Due to uncertainty and impreciseness of available information, apart from the ambiguity of human preferences, it is difficult to get accurate numerical values for the evaluation criteria. Therefore, most of the selection factors cannot be given correctly; this may hamper the evaluation process for decision-makers. In the current study, an integrated fuzzy analytical hierarchy process (AHP)–the technique for order preference by similarity to ideal solution (TOPSIS) methodology has been used to identify an optimal landfill site for MSW disposal. To demonstrate the approach taken, a real case of Mumbai city is taken. The

evaluation criteria are determined based on international standards used in landfill siting. The fuzzy-AHP procedure is used to incorporate the decision-maker's opinions on the relative importance of the selection criteria. TOPSIS provides the advantage of simultaneous consideration of various criteria with different units. In this study, fuzzy-TOPSIS is used to convert qualitative data to fuzzy numbers, which are then used in the calculations to rank the best alternative site. The study identifies a minimal optimal set of criteria for landfill site selection, which reduces the time taken in the decision making process. The developed methodology effectively takes into account the uncertain, subjective and linguistic data from expert opinions, providing more logical and precise results. Significantly, a literature survey revealed that no Indian study had made use of fuzzy MCDM methods considering uncertainty for landfill site selection.

The structure of the paper is as follows: “[Introduction](#)” of the paper introduces the landfill siting problem and accentuates the need of MCDM tools. In “[Literature review](#)”, a brief literature review of previous papers reporting the use of any kind of MCDM technique in a landfill location-related problem has been presented. In “[Materials and methods](#)” a short description of the underlying theories has been presented; this has been followed by the main siting criteria used in this study. Finally, the results from the analysis are discussed in “[Results and discussion](#)” and conclusions are outlined in “[Conclusion](#)”.

Literature review

The disposal facility siting problem in waste management has been studied by many researchers globally using MCDM techniques alone or in combination with other techniques. Many authors have applied multiple objective techniques in the waste facility location analysis (Stowers and Palekar 1993; Erkut and Verter 1995; Current and Ratick 1995). Also, facility location models have been widely used for locating waste landfill sites to minimize exposure to the public and ecosystem.

Cheng et al. (2002) addressed the need for using MCDM methodologies in solid waste management systems because these systems can have complex and conflicting impacts on different stakeholders. Harvey and O’Flaherty (1973) developed a model, which determines the optimal locations of the landfill sites as well as the locations of the transfer stations. They applied their model on a 14 district problem that had 5 alternative sites for the transfer stations and 3 possible landfill sites.

In another study by Erkut and Moran (1991), the researchers developed an AHP-based decision modeling procedure that can be used by decision-makers to locate

obnoxious facilities. They also demonstrated the applicability of the procedure in an analysis of recent decisions to locate a landfill site for the city of Edmonton, Alberta, Canada. A model to locate a treatment facility for hazardous wastes was developed by Stowers and Palekar (1993). Ramu and Kennedy (1994) applied a heuristic algorithm for locating a solid waste disposal site. A mixed-integer programming model was proposed by Kao and Lin (1996) to obtain a suitable landfill site. Siddiqui et al. (1996) used geographical information system (GIS) in combination with AHP for determining the suitability of land for a landfill site. In another study, fuzzy set theory was combined with GIS by Charnpratheep et al. (1997) for the screening of landfill sites in Thailand. Giannikos (1998) proposed a multiple objective model based on goal programming technique for locating disposal and treatment facilities for hazardous waste. In Portugal, Antunes (1999) developed a mixed integer optimization model combining the elements of a p-median model and a capacitated location model for locating the landfill sites. The developed model was used by decision-makers during the actual locating process in the Portuguese Centro region for minimizing the cost objective problem. Nema and Gupta (1999) developed a model using a multi-objective integer programming method to determine the optimal configuration of a hazardous waste management system. Chang and Wei (2000) developed a model for optimal features that should be considered in the solid waste collection network and landfill location, using fuzzy multi-objective nonlinear integer programming. Mahler and De Lima (2003) proposed a value analysis and fuzzy logic-based methodology for the selection of ideal landfill sites by assessing and ranking a predefined pool of objects. Vasiloglou (2004) presented a decision making process for the potential location of new suitable landfill sites with wide community participation. This study proposed a comprehensive set of criteria for the potential sites. Rakas et al. (2004) developed a multiple objective programming model utilizing the fuzzy linear programming approach for identifying unwanted facility locations. Al-Jarrah and Abu-Qdais (2006) proposed a methodology based on fuzzy sets for ideal MSW landfill sites. Şener et al. (2006) used integrated GIS and MCDM method, providing an efficient tool to solve the landfill site selection problem; here, GIS provided effective manipulation and presentation of the data and MCDM supplied consistent ranking of the potential landfill areas based on a variety of criteria.

In addition to these studies, Hung et al. (2006) and Cram et al. (2006) provided a viewpoint for the use of multi-criteria decision making techniques in the related research area. Önüt and Soner (2008) applied a fuzzy TOPSIS methodology to solve the transshipment site selection problem in Istanbul, Turkey. The criteria weights were

calculated using the AHP procedure. Similarly, Aragonés-Beltrán et al. (2010) in Spain used ANP and AHP for siting of suitable locations for a landfill. Geneletti (2010) applied the MCDM technique of simple additive weighting for landfill locations in Italy. Babalola and Busu (2011) attempted to determine a suitable landfill location through multi-criteria decision such as ANP. Aydi et al. (2013) employed fuzzy AHP, ELECTRE and the weighted linear combination method with GIS for landfill site selection; GIS was used for the screening of sites. More recently, Makan et al. (2012, 2013) applied PROMETHEE for suitable waste disposal site selection. AHP in combination with GIS was used by Alavi et al. (2013) for landfill site selection.

The following section of paper surveys and summarizes the work done world-wide in locating landfill sites using MCDM techniques in chronological order. Table 1 outlines the trend in the use of MCDM techniques in landfill siting. Table 1 highlights the main aspects and the contributions. The selected studies are segregated on the basis of the study area, techniques used, criteria used, and objective of the study. The survey does not include the studies that dealt with the collection and transportation problems, and hazardous waste. Most of the studies surveyed includes the combination of multi-criteria decision making tools. The studies consist of multiple criteria which are generalized mainly into four dimensions as social, technical, economic and environmental criteria in Table 1.

The major focus of survey table was on the evolution of the landfill siting problem and the trend in using MCDM tools for it. In the past, the studies mainly used single objective linear, dynamic, mixed-integer programming techniques and vector optimization. In the early 1990s, the focus was on using multi-criteria decision making techniques such as AHP and outranking methods. In the mid-1990s the trend moved to the use of GISs. In the late 1990s, most of the studies used the MCDM tools in combination with GISs which dealt with more complex problems with different types of constraints, allowing suitable and highly visual sensitivity analysis. At the dawn of the new century the researchers concentrated more on the fuzzy programming, which allows to translate qualitative assessment into quantitative data. Most of the earlier models were region specific, focusing only on the location of a single landfill site. But recently the trend changed with the improvements in modelling and increased computational power.

An overview of the above-mentioned studies amply accentuates that the multi-criteria decision-making methods such as AHP and fuzzy model have been introduced as applied and current models during the recent years and tangible results of the calculations of these models has been revealed. However, some of these studies did not take into account the supply of imprecise data and the uncertainty

Table 1 Literature review of studies related to the location of landfills sites

References	Study area	Technique	Criteria	Objectives
Harvey and O'Flaherty (1973)	USA	Mixed integer programming	Minimizing the present worth and total cost of solid waste transportation and disposal	Optimal locations of the landfill sites
Fuertes et al. (1974)	Boston, MA, USA	MILP (discrete)	Cost minimization, i.e., limit on ton-mileage shipped and that shipped across boundaries	Landfills and treatment sites
Jenkins (1982)	Toronto	Mixed integer linear programming	Land suitability and cost	Landfill sites
Wirasinghe and Waters (1983)	Calgary, AB, Canada	Location-allocation method (continuous)	Cost minimization	Landfill site and transfer stations
Gottinger (1988)	Munich, Germany	MILP (discrete)	Cost minimization (operating, transportation, and fixed)	Landfill sites and incinerators
Erkut and Moran (1991)	Edmonton, AB, Canada	AHP (discrete)	Various environmental, social, and economic factors and minimizing their negative impacts	Landfill site
Shekdar et al. (1991)	Delhi, India	LP (route and transportation problem)	Cost minimization, i.e., min. discounted transportation costs	5 new landfill sites in addition to 3 existing facilities
Vuk et al. (1991)	Yugoslavia	PROMETHEE with GAIA	General standard concerns and social, economic and environmental criteria	A single landfill site (evaluation and ranking)
Caruso et al. (1993)	Lombardy, Italy	Vector MILP (discrete), weighting method	Minimizing annualized fixed and transport cost, landfill waste, environmental impacts (air pollution, leachates, public opposition)	Landfill site and processing plants (incinerator, composting, recycling)
Wichelms et al. (1993)	Rhode Island, USA	Utility functions (discrete model)	Logit model and a linear approximation based on a regression, maximum the number of votes a site would receive in a referendum	Landfill sites
Frantzis (1993)	Athens, Greece	Computation of trade off curve of environmental index and total cost	Cost reduction and social, economic and environmental criteria	2 landfill sites
Rey et al. (1995)	France	ELETRE-I	Technical and socio-political aspects	Landfill site
Barlischen and Baetz (1996)	Winnipeg, MB, Canada	DSS, optimization, simulation, excel spreadsheets	Cost minimization	Landfill sites and recycling facilities
Chang and Wang (1996)	Taiwan	Vector optimization, MILP, compromise programming	Minimizing net cost, rote optimization, minimum traffic congestion, noise impact and air pollution	Expansion or addition of landfills and transfer stations including ranking for best option
Mutiah et al. (1996)	Indiana, USA	GIS and simulated annealing	Reducing risk to environment and humans, cost minimization	Landfill site
Siddiqui and Everett (1996)	Oklahoma, USA	Spatial GIS and AHP	Social, economic and environmental criteria, aggregate raster cells to design landfill blocks	Ranking land suitability for landfill sites
Kao and Lin (1996)	Taiwan	Mixed integer programming and GIS	Social, economic and environmental criteria, minimizing impacts	Landfill site and land suitability
Hokkanen and Salminen (1997)	Finland	PROMETHEE I and II	Social, economic and environmental criteria	A single landfill site (taking into account the expansion of the existing landfill site)

Table 1 continued

References	Study area	Technique	Criteria	Objectives
Lin and Kao (1998)	Taiwan	MILP	Maximum suitability of location site and its “compactness”	Landfill sites
Nema and Modak (1998)	India	Integer linear programming	Optimization of regional waste management systems	Landfill site evaluation
Antunes (1999)	Portugal	MILP (discrete)	Cost minimization, transportation and transfer station opening (landfill costs are assumed to be proportional to capacity)	Landfill sites and transfer stations
Herzog (1999)	Larimer Co., Colorado	GIS, compromise programming and PROMETHEE	Economic and environmental criteria	Landfill site
Miranda et al. (2000)	Orange Co., NC	MCDM	Social, economic and environmental criteria	Landfill site
Leao et al. (2001)	Porto Alegre, Brazil	MCDM and GIS	General criteria and complicated parameters such as population growth, location of expanding populations	Assessing the lifespan of an existing landfill and the optimal location for siting of a landfill site
Lahdelma et al. (2002)	Lappeenranta, Finland	Stochastic multi-criteria acceptability analysis	Economic and environmental criteria	Suitable waste treatment facility among four alternatives
Natesan and Suresh (2002)	Chennai, India	GIS based decision support system. MCE models: AHP, FIC, ANN and Delphi	Social, economic and environmental criteria	Landfill site
Chambal et al. (2003)	Alaska AFB	MCDM: value-focused thinking	Cost and environment, compliance with state, federal, and other regulations	Landfill site
Cheng et al. (2003)	Regina, SK, Canada	MCDM, MILP, Game theory, ELECTRE	Cost minimization, Impacts on environment, humans	Landfill site
Kontos et al. (2003)	Lesvos, Greece	AHP	Social, economic and environmental criteria	Landfill site
Mahler and De Lima (2003)	Brazil	Value analysis and fuzzy logic	Technical, social, economic, political and environmental criteria	Comparative appraisal of group of elements for landfill siting
Şener (2004)	Ankara, Turkey	Simple weighted addition and AHP	Social, economic and environmental criteria	Landfill site
Vasiloglou (2004)	West Thessaly, Greece	MCD method with outranking and AHP	Social, economic and environmental criteria	Landfill site
Chau (2005)	Hong Kong	DSS, expert system and ANN	Risk minimization (targets at risk, waste composition)	Landfill site
Kontos et al. (2005)	Lemnos, Greece	GIS and AHP	Economic and environmental criteria, transportation cost not included	Developing site suitability indexes for landfill site
Hatzichristos and Giacuzzi (2006)	Greece	Fuzzy logic, Delphi and GIS	Cost minimization, reducing risk	Landfill site and suitability
Al-Jarrah and Abu-Qdais (2006)	Amman, Jordan	Fuzzy logic in an “intelligent” inference system, based on expert evaluations	Social, economic and environmental criteria	A single landfill

Table 1 continued

References	Study area	Technique	Criteria	Objectives
Eiselt (2006)	Alberta, Canada	MILP (discrete)	Minimizing transportation costs	Landfill sites and transfer stations
Javaheri et al. (2006)	Iran	AHP	Social, economic and environmental criteria	Landfill site
Mahini and Gholamalifard (2006)	Iran	Multi-criteria evaluation (MCE)-weighted linear combination (WLC), GIS, AHP	Social concern, economic and environmental criteria	Landfill site
Li and Huang (2006)	Regina, SK, Canada	MILP (discrete) with interval data	Cost minimization	Ranking landfill sites, waste treatment facilities
Melo et al. (2006)	Brazil	GIS and Fuzzy AHP	Social, economic and environmental criteria	Ranking and rating of landfill sites
Norese (2006)	Turin, Italy	ELECTRE III	Social, economic and environmental criteria	Single landfill site and single incinerator
Sadek et al. (2006)	Lebanon	GIS and simple weighted average method	Social and environmental criteria, transportation costs not included	Land suitability for landfill sites
Vuppala et al. (2006)	Hyderabad, India	GIS and AHP	The usual exclusionary and non-exclusionary criteria	Ranking and categorization of sites regarding suitability for landfills
Banar et al. (2007)	Turkey	AHP and ANP	Risk minimization considering social, economic and environmental criteria	Rating and ranking of four potential sites for landfill
Ojha et al. (2007)	India	Fuzzy sets, point count system	Cost and risk minimization	Landfill site
Eiselt (2007)	New Brunswick, Canada	MILP (discrete)	Transportation cost minimization	Landfill sites and transfer stations
Gemitzi, et al. (2007)	North-eastern Greece	Fuzzy logic with AHP, simple weighted average method and GIS	Social, economic and environmental criteria	Landfill site
Padmaja et al. (2007)	Medak, India	GIS and AHP	Module that calculates site sensitivity index (SSI), and selection criteria for disposal site evaluation	Land suitability for landfill site
Chang et al. (2008)	South Texas, USA	Fuzzy MCDM with expert opinion and GIS	Social concern, economic and environmental criteria	A single landfill site
Delgado et al. (2008)	Mexico	MCDM and GIS	Social, economic and environmental criteria, proximity cost consideration	Land suitability landfill site
Erkut et al. (2008)	Central Macedonia, Greece	Lexico-minimax	Cost minimization, reducing global warming impact and landfill waste, energy and material recovery and minimum total cost	Landfill sites, transfer stations and processing facilities
Önit and Soner (2008)	Istanbul, Turkey	Fuzzy-TOPSIS and AHP	Proximity to household area and industrial waste generators, ease of transportation	A single transfer station among five options
Tuzkaya et al. (2008)	Turkey	ANP	Benefits, opportunities, cost and risks reduction	Landfill site
Sumathi et al. (2008)	Pondicherry, India	GIS based system, MCDA, overlay, AHP	Social, economic and environmental criteria	Landfill site

Table 1 continued

References	Study area	Technique	Criteria	Objectives
Guqin et al. (2009)	Peking, China	GIS and AHP with simple weighted average	Social, economic and environmental criteria	Landfill ranking, grouped w.r.t. size
Mitropoulos et al. (2009)	Western Greece	MILP	Minimizing operating, transportation, opening cost	Landfill sites and other waste facilities
Adamides et al. (2009)	Western Greece	MILP within systems approach	Transportation cost minimization and social acceptability	Landfill sites, transfer stations
Aragónés-Beltrán et al. (2010)	Valencia, Spain	AHP and ANP	Social, economic and environmental criteria	Waste treatment plant
Ekmekçiöğlu et al. (2010)	Istanbul, Turkey	Fuzzy-AHP and Fuzzy-TOPSIS	Social, economic and environmental criteria	Landfill site and preferred suitable technology
Geneletti (2010)	Northern Italy	MCDM, simple additive weighting	Social, economic and environmental criteria	Landfill site
Moeinaddini et al. (2010)	Karaj, Iran	GIS, cluster analysis, AHP	Social, economic and environmental criteria	Landfill site
Xi et al. (2010)	Peking, China	Fuzzy MCDM using MILP with interval data	Minimizing transportation and expansion cost, societal resistance	Landfill sites and incinerators, composting plants
Eskandari et al. (2012)	Iran	AHP for weights, GIS, simple additive weighting	Social, economic and environmental criteria	Landfill site
Gorsevski et al. (2012)	Macedonia	MCDM: AHP and ordered weighted average	Economic and environmental criteria	Landfill site
Yildirim (2012)	Turkey	AHP for weights	Social, economic and environmental criteria	Landfill site
Eiselt and Marianov (2014)	Chile	MILP (discrete)	Cost minimization and reducing environmental impacts	Landfill sites and transfer stations

Source adopted and modified from Eiselt and Marianov (2015)

involved in the decision making process, apart from lacking logical interpretation. Importantly, none of the studies applied a fuzzy TOPSIS-based methodology in their studies. Therefore, to overcome these shortcomings, we combined fuzzy logic-based AHP and TOPSIS model to give more precise valuing of the subjective data and also to achieve results in a logical and scientific manner. Finally, the main objective was to locate an appropriate landfill site for the disposal of MSW. To demonstrate the approach taken, a real case of Mumbai city is taken.

Materials and methods

Introduction of study area

Mumbai, the financial capital of India, is located on the western coast and is a rapidly developing city. It is mainly a peninsula with geographical restrictions and enormous population pressure, leading to high land demand and land prices. In addition, Mumbai generates around 14,500 metric tonnes of MSW per day, 90 % of which is dumped into landfills (MPCB 2014). It has three existing landfill sites, out of which two are already on the verge of closure. The existing landfill sites were identified merely according to convenience, with no scientific backing. They even violated legislations such as the coastal regulation zone notification (CRZ 2011). As a result, the selection and usage of these sites resulted in many politico-legal, socio-economic and environmental problems. Also, being close to mangroves, they posed a serious threat to the fragile mangrove ecosystem.

The Mumbai city is divided into 24 wards with municipal boundaries. The city has a temperate continental climate influenced by the wet monsoon. The average annual rainfall is around 1,100 mm. MCDM techniques have been applied in the study for identifying suitable landfill locations in Mumbai, considering the diverse features of the city and taking into account the requirements of minimizing error, reducing uncertainties and avoiding the violation of existing legislation.

Analytic hierarchy process

The AHP, developed by Saaty (1977) (Saaty 1980; Saaty and Vargas 2000), is a process designed for solving complex multiple criteria problems. AHP is a flexible decision making process to help decision-makers set priorities and make the best decision when both qualitative and quantitative aspects of a decision need to be taken into account.

Many researchers have concluded that AHP is a systematic method for ranking as it reduces complex decisions to a series of one-on-one comparisons, and then synthesizes

the obtained results (Ting and Cho 2008). However, in many cases, the human preference model is uncertain and decision-makers might not be able to assign exact numerical values to the comparison judgments. For instance, when identifying different suitable locations, the decision-makers are unsure about their level of choice due to incomplete, imprecise and uncertain information about possible locations and their performances. Also, due to subjective and qualitative site evaluation criteria, it is very difficult for the decision-makers to express the strength of their preferences, and to provide exact pairwise comparison judgments. For this reason, a methodology based on fuzzy-AHP can help one reach an effective decision and the uncertainty and ambiguity involved in the decision making process can be dealt with.

AHP is also a popular method to determine the appropriate weights of the selected criteria, which is one of the problems faced during multi-criteria decision analysis. The AHP decomposes the decision process into a hierarchical structure and also deals with quantifiable and intangible criteria by using the pairwise comparison matrices. The breaking down of the decision problem into composite steps through AHP has been described in Table 2 (Chamodrakas et al. 2010; Raut et al. 2011).

Steps involved in the AHP method:

1. Define an objective of the problem and determine its goal.
2. Structure the hierarchy from the top (objectives from a decision-makers viewpoint) through intermediate levels (criteria, sub-criteria if any) to the lowest level, which contains a list of alternatives.
3. Employ a pairwise comparison approach.

Saaty (2000) developed the fundamental scale for pairwise comparisons, as shown in Table 2. The pairwise comparison matrix A , in which the element a_{ij} of the matrix is the relative importance of the i th factor with respect to the j th factor, can be calculated as

Table 2 Scale for pairwise comparisons (Saaty 1980)

Numerical rate	Judgment
1	Factor i and j are equal important
3	Factor i is weak important
5	Factor i is strong important
7	Factor i is demonstrated important
9	Factor i is absolute important
2, 4, 6, 8	Intermediate values between the two adjacent judgments
Reciprocal	If the important rate of factor i to j is R_{xy} , then the important rate of factor j to i is $R_{yx} = 1/R_{xy}$

$$A = [a_{ij}] = \begin{bmatrix} 1 & a_{12} & \cdots & a_{1n} \\ 1/a_{12} & 1 & \cdots & a_{2n} \\ \vdots & \vdots & \cdots & \vdots \\ 1/a_{1n} & 1/a_{2n} & \cdots & 1 \end{bmatrix} \quad (1)$$

4. There are $n(n - 1)$ judgments required for developing the set of matrices in step 3. Reciprocals are automatically assigned to each pairwise comparison, where n is the matrix size.
5. Utilizing the hierarchical synthesis to weigh the eigenvectors according to the weights of criteria. The sum is for all weighted eigenvectors corresponding to those in the next lower hierarchy level.
6. Having made all pairwise comparisons, consistency is identified by using the eigenvalue. To calculate the consistency index (CI), Saaty (1990) proposed that the largest eigenvalue, $\lambda_{\max}$ will be

$$\lambda_{\max} = \sum_{j=1}^n a_{ij} \frac{W_j}{W_i} \quad (2)$$

where $\lambda_{\max}$ is the principal or largest eigenvalue of positive real values in a judgment matrix, W_j the weight of j th factor, W_i is the weight of i th factor.

7. Conducting consistency test. Each pairwise comparison contains numerous decision elements for the CI, which measures the entire consistency judgment for each comparison matrix and the hierarchy structure. Saaty (1990) utilized the CI and consistency ratio (CR) to assess the consistency of the comparison matrix. The CI and CR are defined as

$$CI = \frac{\lambda_{\max} - n}{n - 1} \quad (3)$$

where n is the matrix size.

$$CR = \frac{CI}{RI} \quad (4)$$

The judgment consistency can be checked by taking the CR of CI with the appropriate value, as shown in Table 3. The CR is acceptable if it does not exceed 0.10. If the value of CR is >0.10 , the judgment matrix is inconsistent. To acquire a consistent matrix, judgments should be reviewed and improved.

The AHP methodology has been demonstrated by applying it to a landfill site selection problem in this study.

Fuzzy-analytic hierarchy process (F-AHP)

In this study, the framework of the feasible regions of relative weights was adopted. Firstly, allowing the feasible region to include tolerance deviations of the fuzzy ratios, we defined fuzzy consistency as the existence of relative weights within the region. Secondly, we devised a maximum/minimum set ranking method to derive a crisp ranking from the global fuzzy weights. There are two main characteristics of fuzzy systems that allow them to give better performance for specific applications: (1) fuzzy systems are suitable for uncertain or approximate reasoning, especially for the system with a mathematical model that is difficult to derive; and (2) fuzzy logic allows decision making with estimated values under incomplete, imprecise or uncertain information. Hence, fuzzy logic was combined and used along with AHP, and resulted in a fuzzy-AHP methodology for reviewing and weighting the landfill site selection criteria.

The following steps of fuzzy-AHP proposed by Chang (1996) were utilized for selecting and ranking the criteria in the multi-period phase. According to the method of Chang's extent analysis, each object is taken and extent analysis for each goal is performed, respectively. Therefore, m extent analysis values for each object can be obtained, with the following signs:

$$M_{g^i}^1, M_{g^i}^2, \dots, M_{g^i}^m, \quad i = 1, 2, \dots, n.$$

Where $M_{g^i}^j$ ($j = 1, 2, \dots, m$) all are triangular fuzzy numbers (TFNs).

The steps of Chang's extent analysis (Chang 1996) are as follows:

1. The value of fuzzy synthetic extent with respect to the i th object is defined as

$$S_i = \sum_{j=1}^m M_{g^i}^j \otimes \left[\sum_{i=1}^n \sum_{j=1}^m M_{g^i}^j \right]^{-1} \quad (5)$$

To obtain $\sum_{j=1}^m M_{g^i}^j$, the fuzzy addition operation of m extent analysis values for a particular matrix is performed as

$$\sum_{j=1}^m M_{g^i}^j = \left(\sum_{j=1}^m l_j, \sum_{j=1}^m m_j, \sum_{j=1}^m u_j \right) \quad (6)$$

Table 3 Average random consistency (RI)

Size of matrix	1	2	3	4	5	6	7	8	9	10
Random consistency	0	0	0.58	0.9	1.12	1.24	1.32	1.41	1.45	1.49

and to obtain $[\sum_{i=1}^n \sum_{j=1}^m M_{g^i}^j]$, the fuzzy addition operation of $M_{g^i}^j$ ($j = 1, 2, \dots, m$) values is performed such that,

$$\left[\sum_{i=1}^n \sum_{j=1}^m M_{g^i}^j \right] = \left(\sum_{i=1}^n l_i, \sum_{i=1}^n m_i, \sum_{i=1}^n u_i \right) \quad (7)$$

and $\sum_{i=1}^n \sum_{j=1}^m M_{g^i}^j$ can be calculated by the inverse of Eq. (7), as follows:

$$\left[\sum_{i=1}^n \sum_{j=1}^m M_{g^i}^j \right]^{-1} = \left(\frac{1}{\sum_{i=1}^n u_i}, \frac{1}{\sum_{i=1}^n m_i}, \frac{1}{\sum_{i=1}^n l_i} \right) \quad (8)$$

2. As $M_1 = (l_1, m_1, u_1)$ and $M_2 = (l_2, m_2, u_2)$ are two TFNs, the degree of possibility of $M_2 = (l_2, m_2, u_2) \geq M_1 = (l_1, m_1, u_1)$ is defined as

$$V(M_2 \geq M_1) = \sup[\min(\mu_{M_1}(x), \mu_{M_2}(y))] \quad (9)$$

$$y \geq x$$

and can be equally expressed as follows:

$$V(M_2 \geq M_1) = hgt(M_1 \cap M_2) = \mu_{M_2}(d) \quad (10)$$

$$= \begin{cases} 1 & \text{if } m_2 \geq m_1 \\ 0 & \text{if } l_1 \geq u_2 \\ \frac{(l_1 - u_2)}{(m_2 - u_2) - (m_1 - l_1)} & \text{otherwise} \end{cases} \quad (11)$$

Figure 1 (Chang 1996) shown below illustrates Eq. (10) where d is the ordinate of the highest intersection point D between μ_{M_1} and μ_{M_2} . To compare $M_1 = (l_1, m_1, u_1)$ and $M_2 = (l_2, m_2, u_2)$, we need both the values of $V(M_1 \geq M_2)$ and $V(M_2 \geq M_1)$.

3. The degree possibility for a convex fuzzy number to be greater than k convex fuzzy M_i ($i = 1, 2, \dots, k$) numbers can be defined by

$$V(M \geq M_1, M_2, \dots, M_k) = V[(M \geq M_2) \text{ and } (M \geq M_2) \text{ and } \dots \text{ and } (M \geq M_k)] \\ = \min V(M \geq M_i), i = 1, 2, \dots, k \quad (12)$$

Fig. 1 Intersection between M_1 and M_2 (Kahraman et al. 2004)

Assume that

$$d(A_i) = \min V(S_i \geq S_k) \text{ for } k = 1, 2, \dots, n; k \neq i. \quad (13)$$

Then the weight vector is given by

$$W' = (d'(A_1), d'(A_2), \dots, d'(A_n))^T \quad (14)$$

where A_i ($i = 1, 2, \dots, n$) are the n elements.

4. After normalization, the normalized weight vectors are

$$W = (d(A_1), d(A_2), \dots, d(A_n))^T \quad (15)$$

where W is a non-fuzzy number.

Fuzzy-TOPSIS

The technique for order preference by similarity to ideal solution was developed for solving the MCDM problems by Hwang and Yoon (1981), based on the concept that the chosen/improved alternatives should be the shortest distance from the positive ideal solution (PIS) and the farthest from the negative-ideal solution (NIS) (Wu et al. 2009). After calculating the importance weights and ranking of criteria, a modified fuzzy-TOPSIS approach has been applied for conducting the ranking process of alternatives (Shih et al. 2007). The rationale of the fuzzy method is to defuzzify imprecise values at the end of the process, not from the beginning (Wang and Elhag 2006). Wang and Elhag (2006) developed a fuzzy TOPSIS method based on alpha-level sets to perform defuzzification at the very end of the decision analysis process.

To avoid complicated calculations and to improve the applicability of the proposed approach, we used the graded mean integration representation (GMIR) method proposed by Chen and Hsieh (2000) to obtain the final closeness coefficient of each alternative. The formulation of the F-TOPSIS was adopted from Jolai et al. (2011). In order to establish the fuzzy decision matrix, each decision-maker employed the linguistic variables shown in Table 4.

The step-by-step procedure of using the fuzzy-TOPSIS is listed as follows.

1. Establish the normalized performance matrix.

The purpose of normalizing the performance matrix is to merge the unit of matrix entries. Assume that the original performance matrix is

Table 4 Linguistic variables for ratings of alternatives with respect to each criterion

Very low	(0, 1, 2)
Low	(2, 3, 4)
Medium	(4, 5, 6)
High	(6, 7, 8)
Very high	(8, 9, 10)

$$x = (x_{ij}) \quad \forall_{i,j} \quad (16)$$

where x_{ij} is the performance of alternative i to criterion j .

2. Create the weighted normalized performance matrix.

TOPSIS defines the weighted normalized performance matrix as:

$$\begin{aligned} V &= (V_{ij}) \quad \forall_{i,j} \\ V_{ij} &= w_{ij} \times r_{ij} \quad \forall_{i,j} \end{aligned} \quad (17)$$

where w_j is the weight of criterion j .

3. Determine the PIS and NIS.

The ideal solution is computed based on the following equations:

$$\begin{aligned} A^+ &= \{(\max V_{ij}/j \in J), (\min V_{ij}/j \in J'), i \\ &= 1, 2, \dots, m\} \end{aligned} \quad (18a)$$

$$\begin{aligned} A^- &= \{(\min V_{ij}/j), (\min V_{ij}/j \in J'), i = 1, 2, \dots, m\} \\ & \end{aligned} \quad (18b)$$

where

$j = \{j = 1, 2, \dots, n/j \text{ belongs to benefit criteria}\};$
 $j = \{j = 1, 2, \dots, n/j \text{ belongs to cost criteria}\};$

4. Calculate the distance between PIS and NIS for each alternative:

$$S_i^+ = \sqrt{\sum_{j=1}^n w_j \cdot (V_{ij} - V_j^+)^2} \quad i = 1, 2, \dots, m \quad (19)$$

$$S_i^- = \sqrt{\sum_{j=1}^n w_j \cdot (V_{ij} - V_j^-)^2} \quad i = 1, 2, \dots, m \quad (20)$$

5. Calculate the relative closeness to the ideal solution of each alternative:

$$C_i^+ = \frac{S_i^-}{S_i^+ + S_i^-} \quad i = 1, 2, \dots, m \quad (21)$$

where $0 \leq C_i^+ \leq 1$ that is, an alternative i is closer to A_i^* as C_i^+ approaches to 1.

6. Rank the preference order.

Using the GMIR method we can calculate the closeness coefficient of each alternative A_i , $i = 1, 2, \dots, m$ as follows:

$$CC_i^+ = \frac{Ci1 + 4Ci2 + Ci3}{6} \quad i = 1, 2, \dots, m. \quad (22)$$

Questionnaire development, validity and reliability

In order to prioritize the landfill siting process in an Indian context, the siting criteria were obtained from the existing

Table 5 F-AHP scale

Definition	Intensity of importance
Equal	(1, 1, 1)
Weak	(2/3, 1, 3/2)
Fairly strong	(3/2, 2, 5/2)
Very strong	(5/2, 3, 7/2)
Absolute	(7/2, 4, 9/2)

literature and relevant standards. Using a fuzzy approach, the numerical value of each linguistic term used in the questionnaire was determined based on the fuzzy-AHP scale shown in Table 5 (Lin et al. 2006). Fuzzy logic ensures a precise mathematical approach to deal with the vagueness associated with the importance of a criterion or relative judgment of people. Fuzzy set theory acts as a very useful tool to address the uncertainty and imprecision issue, which affects the landfill site selection. As observed from Table 5, the solid 5 scale linguistic term has been transformed to equal fuzzy intervals.

Selection of evaluation criteria

Based on a review of the literature, evaluation criteria related to landfill site selection were identified. Then, expert questionnaires were used for screening the indexes fit for the landfill site selection process. Twelve siting indexes were selected by the committee of experts. The expert committee consisted of ten professionals from practice and five from the academia. The siting criteria (i.e., 12 indexes) used in the landfill site selection are shown in Table 6.

On the basis of the hierarchical framework of the siting indexes, the F-AHP questionnaire using fuzzy triangular numbers (FTN) was distributed among the experts for soliciting their professional opinions. The relative importance (fuzzy weight) of each criteria analysed by F-AHP is listed in Table 7.

Results and discussion

Three alternative sites A1, A2 and A3, were taken as an illustrative example and were evaluated by the experts based on the screened evaluation criteria. Since there are differences of subjective judgments between the ways in which experts view each evaluation criterion, the overall evaluation of the fuzzy judgment was employed to synthesize the opinions of the various experts in order to achieve a reasonable and objective evaluation.

Each decision-maker establishes the fuzzy decision matrix in which each alternative is evaluated with respect

Table 6 Criteria identified and used in the study

Criteria	Abbr.	Definition
Public acceptance	PA	The location identified should be accepted socially
Hydrology	HY	Pollution of surface and ground water resources by leachate is a prime concern
Climate	CL	Wind and rain are common climatic factors influencing site selection, especially in the coastal areas. If the site is exposed to strong winds, coastal disasters are a distinct possibility, and adequate coastal protection is a must. Also, for high rainfall areas as in the case of Mumbai, to minimize leachate production, effective storm water diversion is essential
Soil and topography	SAT	A suitable site will have a sufficient grade to provide drainage of surface runoff and adequate level areas to enable excavation of trenches and associated earthworks and the construction of service facilities avoiding potential ground water problems, soil erosion risk, access, and providing site visibility and protection from prevailing winds. Sites with slopes exceeding 1:5 are generally not suitable because of the soil erosion risk
Fracture and faults	FNF	Faulted zone locations should be avoided if possible
Adjacent land use	ALU	Existing and possible future developments adjacent to the site should be considered. Locations with higher potential for nature conservation, agriculture and residential development should not be considered, e.g. wetlands, etc
Sensitive areas	SA	Presence of airports, nuclear sites, electrical supply lines, oil ducts, petrochemical industries, etc. in the nearby areas is not desirable
Habitat, flora and fauna	HAF	Sites having natural flora and fauna and habitation are unsuitable as the landfill can cause major disruption to them. Control of vermin populations, bird, rodents and other animal pests is an important factor in maintaining both public health and environmental stability
Inter-municipality	INM	More than one municipality may use the facility, sharing building and maintenance costs
Site capacity	SC	Identified sites should have enough capacity
Cost	COS	Each location has its own cost value
Road network/access	RNA	Direct access to the site so that waste is not dumped before getting to the landfill, and to minimize waste spillage, traffic congestion and fuel usage of vehicles

Table 7 Fuzzy weights of performance evaluation index by F-AHP

Criteria	α	β	γ	Best non-fuzzy performance		
				[[$(U - L) + (M - L)]/3 + L$		Ranking
Hydrology (HY)	0.078273034	0.101978808	0.12886248	0.103038107	10.30381074	2
Sensitive areas (SA)	0.073189279	0.090645393	0.108895491	0.090910054	9.091005435	5
Soil and topography (SAT)	0.087195632	0.094615897	0.100205011	0.094005514	9.400551354	4
Habitat and flora & fauna (HAF)	0.088215792	0.0956239	0.099016338	0.094285343	9.428534335	3
Climate (CL)	0.093057903	0.104275293	0.112047935	0.103127043	10.31270435	1
Fracture and faults (FNF)	0.070969262	0.07419064	0.078402389	0.074520764	7.4520764	9
Public acceptance (PA)	0.082237151	0.07526837	0.067493175	0.074999565	7.499956538	7
Adjacent land use (ALU)	0.073684553	0.070555984	0.067542988	0.070594508	7.059450843	12
Intra-municipality (INM)	0.080829767	0.073455331	0.063869715	0.072718271	7.271827108	10
Cost of site (COS)	0.08143124	0.071331433	0.060944339	0.071235671	7.123567057	11
Road network/access (RNA)	0.094282332	0.073268209	0.057220789	0.074923777	7.492377651	8
Site capacity (SC)	0.096634053	0.074790742	0.05549935	0.075641382	7.564138189	6

to each criterion. Decision-makers use the linguistic variables shown in Table 4 to perform these evaluations. The ranking of these three alternatives by the decision-makers under each criterion, and the aggregated fuzzy decision matrix of the group is presented in Table 8.

In this study, the five linguistic variables, “very low”, “low”, “medium” “high” and “very high”, were used to measure the alternatives with respect to the evaluation

criteria. As shown in Table 4, each linguistic variable is represented by a TFN in the range of 1–10. The average fuzzy judgment values of each criterion of the three alternatives, integrated by various experts, calculated through Eqs. (12)–(15), are summarized in Table 8. The final fuzzy synthetic judgment of the three locations is derived from the fuzzy criteria weight (Table 7) and the fuzzy judgment values are calculated by Eqs. (15)–(20).

Table 8 Final ranking of landfill locations

Si+	Si−				Ci = Si−/Si+(+)Si−				CCI = Si1 + 4Si2 + Si3/6		Ranking
	α		γ		α	β	γ	γ	Normalized		
	α	β	γ	γ							
0.04	0.02741	0.01823	0.225962348	0.113552982	0.07253772	0.821743533	0.805498468	0.79912659	4.176925169	0.88924689	2
0.027	0.01147	0.00720	0.228392219	0.120465654	0.075552886	0.892832975	0.913041393	0.91290272	4.697149002	1	1
0.290	0.14713	0.09312	0.013506158	0.007839705	0.00541702	0.044449577	0.05058729	0.05497160	0.25596068	0.05449277	3

Table 8 presents the final fuzzy synthetic judgment of the three locations based on the evaluation criteria. Consequently, based on the fuzzy weights of the evaluation criteria calculated by F-AHP, the MCDM analytical tool F-TOPSIS is adopted to rank the alternative locations (Table 8). The fuzzy weights of the performance evaluation indexes, as calculated by F-AHP, have been shown in Table 7. The weighted normalized performance matrices are calculated by Eq. (17) and both PIS and NISs for the evaluation criteria are obtained through Eqs. (18a and 18b).

Table 8 lists the separations of the PIS $Si+$ and the negative-ideal solution $Si-$ for the three alternatives calculated by Eqs. (19 and 20). The relative closeness $Ci+$ to the ideal solution and preference evaluation results derived from F-TOPSIS calculated by Eqs. (21 and 22) are presented in Table 8. The relative closeness coefficient $CCi+$ values for the three alternatives are $A1 = (4.17)$, $A2 = (4.69)$, and $A3 = (0.25)$. The normalized values for the three ideal locations are $A1 = (0.88)$, $A2 = (1.00)$, and $A3 = (0.05)$. This implies that location A2 has the smallest gap for achieving the aspired/desired level among the three locations, whereas A3 has the largest gap. Thus, A2 is the ideal location followed by A1 and A3.

The methodology used in this study is superior since it has the capability of representing vague data. In multi-criteria problems, a decision-maker may encounter enormous difficulty in quantifying imprecise and fuzzy data. Our proposed methodology easily quantifies these types of data. It includes an effective method to weigh the criteria and rank the alternatives to find the optimal solution. Thus, the proposed method presented in this paper can be applied to landfill site selection for MSW.

Conclusion

Management of MSW is a public issue, which requires efficient planning and operation. Landfill site selection is the crucial element of MSW management. Landfills have a direct bearing on the environmental health of the locality. The complexity involved in the landfill site selection process due to various parameters to be considered makes it necessary to apply sophisticated mathematical modeling for the decision making process.

This study provides a systematic decision making process for selecting an alternative MSW disposal location in the city of Mumbai, considering all aspects of MSW management in a holistic way. At present, there is no standard method of site evaluation due to diverse, complex factors and parameters and the proposed MCDM-based methodology for best-suited landfill site selection fills a gap.

1. In this study, the integrated fuzzy-AHP–TOPSIS methodology was employed. We first listed the criteria as per the standard procedures and compared the possible alternatives of waste disposal sites.
2. Three alternative locations were compared and the site that was optimal for the location was found. The integrated methodology was found to be advantageous compared to the existing methods since it reduced the uncertainty in decision making by taking care of incomplete information and qualitative variables along with managerial preferences.
3. The modeled integrated approach reduces the possibility of errors and uncertainty in the decision making and ranking process, and makes landfill site selection less time consuming.

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