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Multi-objective modeling for determining location of undesirable facilities

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Abstract

This paper develops a model for determining locations of undesirable facilities. It is formulated as multi-objective since the problem of locating undesirable facilities faces many conflicting criteria. A method is also proposed to appropriately address uncertainty associated with this class of location problems. The methodology developed in this study is tested using the real-world data.

Keywords: Fuzzy linear programming; Location; Multi-objective programming; Optimization; Undesirable facilities

1. Introduction

During the last three decades, many industrialized and post-industrialized countries have researched planning and operating activities designed to minimize human pollution, improve transport and disposal of waste and hazardous materials, and consequently, to minimize the potential accidental risk. These countries are greatly aware of the need to protect the environment and the quality of urban living, and thus have been continuously involved in various environmental activities. Transportation is critical to efficiently conduct such activities for shipment and disposal of various waste and hazardous materials. Although a social cost of, for example, road

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transportation, caused by increased air and noise pollution, traffic congestion and accidents, can be as high as 5% of Gross Domestic Product in most developing countries (Bielli et al., 1998), benefits of a transportation system far exceed its social cost. Selecting good disposal sites for such waste and hazardous materials, and effectively transporting them with optimal routing, minimizes population exposure, and reduces further pollution of the environment.

An important planning problem in the transportation and environmental engineering field is locating landfills or sites for waste and hazardous materials. This problem usually faces conflicting goals and thus is difficult to formulate and solve. Although these facilities are necessary for society, they usually have a negative impact on property values or the quality of life because of pollution. In addition, the public wants these facilities as far away as possible, but they must also be accessible to the regions of waste production.

Mathematical location models for undesirable facilities are designed to address key questions (Daskin, 1997) encountered in locating landfill sites, such as

- How many facilities should be located?
- How large should each facility be?
- How should demand for facilities' service be allocated to facilities?

These issues are first modeled as a multi-objective problem and then applied to the real-world problem for Prince George's County, Maryland, US. The goal is to simultaneously find the optimal number of landfill facilities, find the optimal location for the calculated number of landfill facilities, and allocate the population of one county to the suggested landfill facilities.

2. Model formulation

2.1. Literature review

Most people consider landfills and sites for waste and hazardous materials 'undesirable facilities' and want them to be located as far as possible from their areas. Typically, such facilities are either noxious posing a serious health risk to people, or obnoxious posing a threat to people's lifestyle.

As Erkut and Neuman (1989) state 'many location models minimize some function of distance to facilities, which is an appropriate objective when locating service facilities. However, if one is locating an obnoxious facility, such as a garbage dump, a chemical plant or a nuclear reactor, closeness is undesirable'.

In general, such problems are multi-objective. For example, in addition to maximizing the demand-weighted total distance between demands and the nearest facilities, we may also want to maximize the minimum demand-weighted distance between a demand node and the nearest facility. Erkut and Neuman (1989) further emphasize the need for multi-objective approaches to the siting of undesirable facilities when they state that 'The multiple constituency, multi-objective nature of the problem severely limits the usefulness of single objective models.'

While people want undesirable facilities far from demand centers, often these centers are served by the undesirable facilities being sited. It is commonly known that large urban areas produce most of the waste transported to landfills. If such facilities are located too far from urban areas, the operating costs of transporting waste tend to increase. As a result there is a need to minimize the transportation costs, which is in conflict with the original objective to locate landfills far from demand centers.

Routing can also be a very important factor in reducing opposition to undesirable facilities. As Daskin (1997) states 'Hazardous materials often travel along paths other than the shortest distance or cost path to avoid large concentrations of population'. These issues are largely addressed by List and Mirchandani (1991), and Re Velle et al. (1991), who jointly considered location and routing models for hazardous wastes.

Quite often, there is a need to take into consideration the fixed costs of locating undesirable facilities. Because the hazardous materials require special treatment and storage, these fixed costs are usually very high. One of the most important considerations in locating undesirable facilities is to be fair to all communities. [1] The waste produced by a whole region should never be closely allocated to only one community. Only if communities are fairly affected by undesirable facilities is there a chance to reduce the opposition of building such a facility at a designated location.

Ratick and White (1988) develop a multi-objective model for the location of undesirable facilities. Their first objective minimizes the facility location costs; the second minimizes opposition to the siting plan. The third objective maximizes equity. As Daskin (1997) comments 'Equity is defined, based on Ratick and White, as a complementary anti-cover model. If a facility is located at candidate site i, the equity index for a candidate site i is defined as the number of other facilities that are sited outside of the coverage distance associated with the facility at site i. If no facility is located at candidate site i, the equity index for the candidate site is set to a very large number. The overall equity index for the location plan is the minimum of the equity indices over all candidate locations. The rational for this is that the location plan is likely to be perceived as more equitable if other communities are also impacted by other undesirable facilities'.

Erkut and Neuman (1992) based their modeling of fixed facility location costs and transportation costs on work developed by Ratick and White. The distance between a population center and the undesirable facilities was the parameter in the decreasing function that characterized equity and opposition; facility sizes were parameters in the increasing function that represented the same equity and opposition. The problem is solved by enumeration of the feasible facility sizes and locations. It is stated that enumeration is appropriate for solving this group of problems since the number of feasible candidate sites and the number of facility sizes could be small.

Wayman and Kuby (1994) also develop a multi-objective location model for undesirable facilities. They consider three objectives: fixed and transport cost minimization, risk minimization, and inequity minimization. They state that 'equity can be modeled by minimizing the maximum demand-weighted distance that material must travel between a generation site and a processing facility'. In contrast, Re Velle et al. (1991) developed a system of storage facilities for spent fuel rods from commercial nuclear reactors. A proposed multi-objective model simultaneously sites the storage facilities, assigns reactors to those facilities and determines routes for the shipment of the fuel.

[1] Re Velle (2000), for instance, analyzes perspectives and challenges in environmental management. It is emphasized that 'equity as well as rationality in cost allocation' should be considered in the analysis of location problems.

Rahman and Kuby (1995) formulated a multi-objective model for locating solid-waste transfer facilities. At these facilities, refuse was transferred from collection trucks to long-haul trucks for more economical shipping to distant landfills. The paper looks at trade-offs between minimizing costs and public opposition, while the expected public opposition was modeled as a decreasing function of distance from the facility.

Giannikos (1998) developed a Goal Programming model for locating disposal and transporting hazardous waste through transportation networks. Besides minimizing the total operating cost and the total perceived risk, he also considered the equitable distribution of risk and disutility among population centers. Berman et al. (2000) investigated the problem of routing and location on a network with hazardous threats seeking to find a route between two nodes on a network that minimizes the hazard along it, as well as the problem of finding a location on a network where the hazard is minimized. Berman and Drezner (2000) developed a model for determining the best location for an obnoxious facility on a network. The model also maximized the least weighted distance to all nodes of the network.

Marianov et al. (2002) developed models for obnoxious material transportation and addressed the problem of designing routes for transportation of hazardous or obnoxious materials. The proposed concept considered population living along these routes. They also emphasized the fact that values of the properties that are close to the roads used for transportation may decrease as a consequence of this activity.

A significant number of people have thus been involved in problems concerning optimization of the number and location of undesirable facilities. Due to the complexity of such problems, multi-objective approaches are often used. This is also done here, but the overall methodology is modified by introducing a compensatory Multiple Attribute Decision Making Technique as a part of a prescreening process used to reduce the number of landfill candidate sites. In addition to the basic model, a model is presented that could be used to treat uncertainties in locating undesirable facilities.

2.2. Multi-objective model for location of undesirable facilities

According to standard landfill siting criteria, landfill sites must be geologically stable and suitable. Hence, the choice between sites might be determined by a number of objectives. First, a site should be as close as possible to the waste generation sites to minimize transportation cost and initial capital investment costs. Second, it is important to limit political opposition across communities. No community wants to store the waste produced by others. As Daskin (1997) argues, this is often an issue 'not only in the location of disposal sites, but also in the routing of materials from generation sites to disposal facilities'. The problem considered here is determining the number and location of landfills for waste materials so that the total cost and political opposition across communities are simultaneously minimized.

Use is made of the following notation: C is cost; TC is transportation cost; IIC is the initial investment cost; i is an index referring to the number of demand nodes (zip-code areas) $i = 1, 2, 3, \dots, M$; j is an index referring to the number of supply nodes (candidate sites) $j = 1, 2, \dots, N$; P_i is the population of the ith zip-code area; C_p is the amount of waste produced per person; d_i is the amount of waste in the ith zip-code area: $(d_i = C_p \times P_i)$; C_j^{Min} is minimum capacity of each candidate site j; C_j^{Max} is the maximum capacity of each candidate site j; L_{ij} is distance between the center of each zip-code i to the center of candidate site j; C_w is unit waste cost per mile when delivering the waste from demand node i to site j; C_{ij} is transportation unit waste cost from i to j ($C_{ij} = C_w \times L_{ij}$); $f_j(k)$ is the cost to build candidate site j with size k ($f_{jk} = \text{constant3} \times k$); V_i is violation in prescreening of the ith zip-code area; O_i is an opposition factor of the ith zip-code area; and S_j is the capacity S of each candidate site j to be built.

There are also binary variables:

$$X_j = \begin{cases} 1, & \text{if candidate site } j \text{ is selected to be built} \\ 0, & \text{otherwise} \end{cases}$$

$$Y_{ij} = \begin{cases} 1, & \text{if zip-code } i \text{ is served by site } j \\ 0, & \text{otherwise} \end{cases}$$

This then gives

$$C = \text{TC} + \text{IIC} \tag{1}$$

$$\text{TC} = d_i \times C_{ij} \times Y_{ij} \tag{2}$$

$$\text{IIC} = (\text{land cost} + \text{building cost}) = f_j(S_j) \times X_j \tag{3}$$

The following objective functions and constraints are formulated:

$$1.\ \text{Min} \quad Z_1 = \sum_{i=1}^{M} \left(\sum_{j=1}^{N} (d_i \times C_{ij} \times Y_{ij}) \right) + \sum_{j=1}^{N} (f_j(S_j) \times X_j) \tag{4}$$

$$2.\ \text{Min} \quad Z_2 = \sum_{i=1}^{M} \sum_{j=1}^{N} (O_i \times Y_{ij}) \tag{5}$$

Subject to

$$\sum_{j=1}^{N} Y_{ij} = 1, \quad \forall i \tag{6}$$

$$Y_{ij} \leqslant X_j, \quad \forall i,\ \forall j \tag{7}$$

$$\sum_{i=1}^{M} (d_i \times Y_{ij}) \leqslant S_j, \quad \forall j \tag{8}$$

$$C_j^{\text{Min}} \leqslant S_j \leqslant C_j^{\text{Max}}, \quad \forall j \tag{9}$$

The first objective function minimizes TC and IIC, while the second minimizes the population opposition to building a landfill within its zip-code area. The first constraint ensures that each zip-code area is served by one landfill (i.e., candidate site), while the second constraint enables each candidate site to be assigned to a certain zip-code area. The third constraint, as a capacity constraint, guarantees that the amount of waste in each zip-code area does not exceed capacity of the candidate site j. The last constraint ensures that a certain capacity range bounds each candidate site. Other specific constraints will be added according to the specific problem.

3. Proposed solution to the problem

There are two objective functions in the above model. To solve the multi-objective problem, the two functions are combined into one objective function. Each objective function is associated with a certain weight, and the objective functions are then summed. In the first step, the two objective functions are solved as separate mixed integer programming problems using CPLEX and optimal solutions $Z_1^{\rm opt}$ and $Z_2^{\rm opt}$ are obtained. Then, the two objectives are combined, which resulted in a new objective function Z_3,

$$\text{Min } Z_3 = \text{weight1} \times \frac{Z_1}{Z_1^{\rm opt}} + \text{weight2} \times \frac{Z_2}{Z_2^{\rm opt}} \tag{10}$$

where $\frac{Z_1}{Z_1^{\rm opt}}$ is weighted by factor 'weight1', and $\frac{Z_2}{Z_2^{\rm opt}}$ is weighted by factor 'weight2', before summation. $\frac{Z_1}{Z_1^{\rm opt}}$ is used to represent the percent deviation from $Z_1^{\rm opt}$, and so is $\frac{Z_2}{Z_2^{\rm opt}}$. This is justified because $\frac{Z_1}{Z_1^{\rm opt}}$ and $\frac{Z_2}{Z_2^{\rm opt}}$ have relative values that can be summed using weights. On the other hand, since $Z_1^{\rm opt}$ and $Z_2^{\rm opt}$ have different units, (that is, cost and opposition measures) they cannot be summed. The problem is converted into a mixed-integer programming problem that can be solved using the CPLEX integer programming tool to obtain $Z_1^{\rm opt}$ and $Z_2^{\rm opt}$.

4. Analysis and solution for Prince George's County, Maryland

Since modeling location problems requires an understanding of the real-world operations that are to be reflected in the model, data was collected and reviewed. [2] This involved once the data was generated, the reduction of candidate sites (prescreening process), and mathematical modeling.

The prescreening process was performed to reduce the number of candidate sites based on the Prince George's County laws. [3] For example, this law states that, at a minimum, 'every landfill shall be located in an area at least 500 acres in size and have a maintained buffer of at least 250 feet between neighboring property lines and the outermost perimeter of the landfill cells.'

Integer programming (as an optimization technique) is used to formulate the problem which simultaneously finds the optimal number of landfill facilities (i.e., sites), finds the optimal location for the calculated number of landfill facilities, and optimally allocates the population of one county to the suggested landfill facilities. Zip-code areas are used to divide Prince George's County and the demand nodes in the problem represent all 36 zip-code areas that produce waste in the County.

4.1. Prescreening process

Following Prince George's Department of Environmental Resources, the criteria used for prescreening sites (e) are: existing housing (e_1), flood plain and wetland areas (e_2), restricted

[2] Sources included, Prince George's County Planning Board, College Park Municipality, Division of Environmental Resources (Waste Management Division), published literature, and the Internet.

[3] Such as subtitle 21–117 of Prince George's County Code (PGCC).

airports ($e_{3,}$), parklands (e_4), Chesapeake Bay Critical Areas (e_5), drinking water reservoir watersheds (e_6), historic sites, resources, and districts (e_7), sensitive use areas (e_8), and unique plant habitat/areas of critical state or county concern (e_9).

The attributes are cost attributes and when these are present, the greater the attribute value, the less its preference. (For example, the larger the number of houses at a desired location, the less attractive the location becomes.). Weights express the relative importance of each attribute. Here it is assumed, without loss of generality, that all chosen criteria are of equal importance.

In prescreening Table 1, the criteria elimination (e) is defined as

$$\text{Criteria elimination}(e) = \begin{cases} O, & \text{if zip-code area violates any criteria} \\ \text{blank}, & \text{otherwise} \end{cases}$$

The total number of violations for one zip-code area is given in the last column of the table, and is represented in the form:

$$Z_e = e_1 + e_2 + e_3 + e_4 + e_5 + e_6 + e_7 + e_8 + c_9 \tag{11}$$

Table 1
Site criteria elimination for zip-code areas

Zip-code	Criteria elimination (c)									Sum Z_e
	e_1	e_2	e_3	e_4	e_5	e_6	e_7	e_8	e_9	
20608	○	○			○					3
20706	○	○		○		○	○	○	○	7
20707	○	○	○	○	○	○	○	○	○	9
20708	○	○	○	○	○	○	○	○	○	9
20710	○	○		○			○	○	○	6
20712	○	○		○		○	○	○	○	7
20715	○									1
20716	○									1
20720	○									1
20721	○									1
20722	○	○		○		○	○	○	○	7
20723	○	○	○	○	○	○	○	○	○	9
20737	○	○	○	○			○	○	○	7
20740	○	○	○	○			○	○	○	7
20743	○	○		○			○	○	○	6
20745		○		○			○	○	○	5
20746	○			○			○	○	○	5
20747	○	○		○			○	○	○	6
20759	○	○	○	○	○	○	○	○	○	9
20770	○	○		○			○	○	○	6
20772										0
20781	○	○	○	○			○	○	○	7
20782	○	○	○	○			○	○	○	7
20783	○	○	○	○			○	○	○	7
20784	○		○	○			○	○	○	6
20785	○	○	○	○		○	○	○	○	8
21046	○	○	○	○	○	○	○	○	○	9

Table 2
Geographic location of zip-code areas and the candidate landfill sites

Zip-code	Landfill site	North	0-W	Latitude	Longitude
20608	1	38.6016808	76.7442780	0.669091772	1.336464873
20715	2	39.0036087	76.7450714	0.680783381	1.336487952
20716	3	38.9130249	76.7664337	0.678148405	1.337109356
20720	4	38.9945755	76.7871780	0.680520616	1.337712783
20721	5	38.9159622	76.7621765	0.678233848	1.336985519
20772	6	38.8421631	76.8219223	0.676087119	1.338723454

The approach presents a Compensatory Multiple Attribute Decision Making Technique, since low scores on one criterion may be compensated by high scores on another.

Table 1 indicates six candidate sites are selected because their total number of criteria violations does not exceed three, which is deemed as the maximum number of acceptable violations established. In the next step, from the official website (www.census.gov), the locations of the candidate sites in the selected zip-code areas are obtained (Table 2) as is the exact center of each zip-code area.

4.2. Model application

Data and conditions for Prince George's County
Based on the available data, the

- amount of waste produced per person: $C_p = 2$ pound/person,
- minimum capacity of each candidate site $j : C_j^{\text{Min}} = 500$ acres, $\forall j$,
- unit waste cost per mile when delivering the waste from demand node i to site $j : C_w = \$0.15/80\,000 = \$0.000001875$,
- transportation cost per unit waste from i to j:

$$C_{ij} = C_w \times L_{ij} \tag{12}$$

L_{ij} is the distance between the center of each zip-code area and the center of each candidate landfill site calculated using trigonometry equations. Because the County covers a relatively small area, the land price for the candidate landfills is uniform. Hence, the cost $f_j(k)$ to build a candidate site j is only proportional to size. In addition, the size of Prince George's County is fixed and therefore the initial investment cost for the landfills has a fixed value. Thus, the initial investment cost can be omitted from the 1st objective function, without affecting the solution to the integer-programming problem. Based on this condition, the 1st objective function is:

$$Z_1 = \sum_{i=1}^{M} \sum_{j=1}^{N} (P_i \times C_p \times C_w \times L_{ij}) \times Y_{ij} \tag{13}$$

The opposition factor of the ith zip-code area O_i is:

$$O_i = \frac{(\text{population weight}) \times P_i}{(\text{average population over zip-code areas})} + \frac{(\text{weight for political violation}) \times V_i}{(\text{average violation in prescreening})} \quad (14)$$

It was found that four candidate sites (zip-code areas 20715, 20716, 20720, 20721) are part of Bowie municipality. To satisfy the fairness criteria, at most one landfill should be built at these four candidate sites. Besides the constraints in the model, the following is added; $X_2 + X_3 + X_4 + X_5 \leqslant 1$.

4.3. Results

The results of the combined integer-programming model Z_3, suggest that, to obtain overall efficiency for landfill locations in the County, three landfills should be built (Table 3):

- landfill 1: in zip-code area 20608—in the northwest side of 20608 area, near St. Charles community
- landfill 2: in zip-code area 20720—Bowie municipality
- landfill 3: in zip-code area 20772—Upper Marlboro municipality

This pattern accords with the existing two landfills that are located in Bowie and Upper Marlboro municipalities. One additional landfill is suggested in the northwest side of 20608 zip-code area, near St. Charles.

The same solution was obtained from the first (Z_1) separate model. However, the second (Z_2) separate model results in a different solution. The optimal value of the second model and the sub-objective function value of the third model are the same. This is because the second separate model has at least two optimal solutions that result in the same optimal objective function value. Because the models have different goals, they suggest different landfill sites in the same municipality, but in different zip-code areas.

Table 3
CPLEX results for 3 integer-programming problems

Objective function	Integer optimal solution	Variable name (solution value = 1)	Landfill site (zip-code)
Z_1	2.9011651000e+001	X_1	20608
		X_4	20720
		X_6	20772
Z_2	3.6000000000e+001	X_1	20608
		X_3	20716
		X_6	20772
Z_3	1.0002832198e+000	X_1	20608
		X_4	20720
		X_6	20772

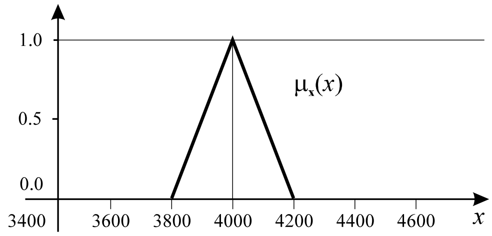

Fig. 1. Fuzzy number X (the amount of waste produced per person at node x).

5. Extensions to the model

In many decision-making problems, input data are not known precisely, or information is not available on some input parameters. There is often uncertainty surrounding specific costs (e.g., the amount of waste produced per person). Linear programming lacks flexibility in dealing with imprecise input data. Therefore, this type of problem is increasingly approached using fuzzy optimization techniques (Bellman and Zadeh, 1970; Zimmermann, 1976, 1978; Teodorovic and Vukadinovic, 1998).

Input data are most commonly obtained by prediction or estimation. A satisfying solution need not imply minimum transportation costs. In fact, in the majority of cases it is sufficient if costs remain within a 'reasonable' range. This type of problem is solved by fuzzy optimization techniques. Most commonly the conventional problem is solved; then, by introducing maximum levels of tolerated violations, fuzziness is described along with the importance of the objectives and constraints. [4]

The amount of waste produced per person C_p is not always known precisely, or the information is not available regarding the input parameter in the mathematical model. It can be assumed, however, that the amount of waste produced per person C_p at any node i can be represented by the triangular fuzzy number $C_{pi} = (c_{1i}, c_{2i}, c_{3i})$.

For example, the amount of waste produced per person at a specific node is 'around 4000 units,' 'between 3800 and 4200 units,' 'approximately 2000 units,' and so on. These approximations can be expressed as triangular fuzzy numbers. Triangular fuzzy numbers could make communication between the analyst and the decision-makers and practitioners because practitioners usually do not have any difficulties accepting approximations. X, for example, can be a fuzzy set for the amount of waste produced per person at node (see Fig. 1).

Using knowledge, experience and intuition, practitioners can determine the 'least possible amount of waste produced' (left boundary of a triangular fuzzy number), or the 'greatest possible amount of waste produced' (right boundary of a triangular fuzzy number). Using fuzzy arithmetic rules (Kaufmann and Gupta, 1985; Teodorovic and Vukadinovic, 1998), the amount of waste in the ith zip-code area $d_i (d_i = C_p \times P_i)$, could be described by an appropriate triangular fuzzy number D_i:

$$D_i = (D_i^* - \delta_D, D_i^*, D_i^* + \delta_D) \tag{15}$$

[4] Waste production can be described through fuzzy numbers. The linguistic expressions 'approximately D tons of waste,' or 'more than D tons of waste' can be used. Costs can also be expressed as 'acceptable.'

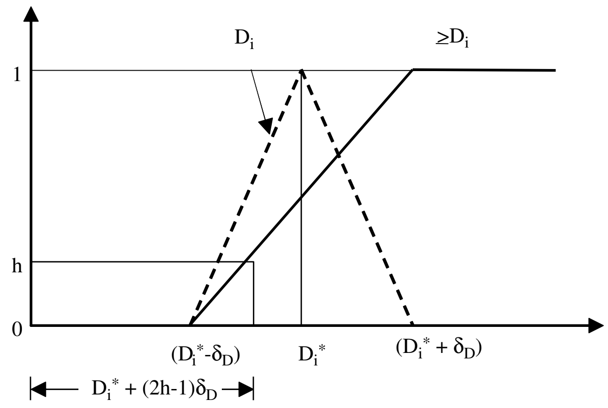

Fig. 2. Fuzzy numbers D_i and $\geqslant D_i$.

where $D_i^* - \delta_D$ is the smallest, and $D_i^* + \delta_D$ is the largest amount of waste in the ith zip-code area. Fuzzy numbers D_i and $\geqslant D_i$ are shown in Fig. 2.

Now consider the following constraint:

$$S_j \geqslant \sum_{i=1}^{M} d_i Y_{ij} \quad \forall j \tag{16}$$

By the similarity of triangles S_j is greater or equal to D_i (and it is greater or equal to $\sum_{i=1}^{M} d_i Y_{ij}$) if the following is satisfied:

$$S_j \geqslant D_i^* + (2h - 1) \times \delta_D. \tag{17}$$

'Acceptable costs' can be introduced by assuming that instead of minimizing costs, one can generate acceptable costs with a level of satisfaction at least equal to h. Acceptable costs are the triangular fuzzy number T in Fig. 3. They could be defined by the decision-maker, and/or by an analyst. The value corresponding to a grade of membership equal to 1 is denoted by $T_{av.}$

The value of δ_T is also arbitrarily defined. Because objective functions and constraints are treated in the same manner in a fuzzy environment, the objective function (minimizing costs) is transformed into the constraint:

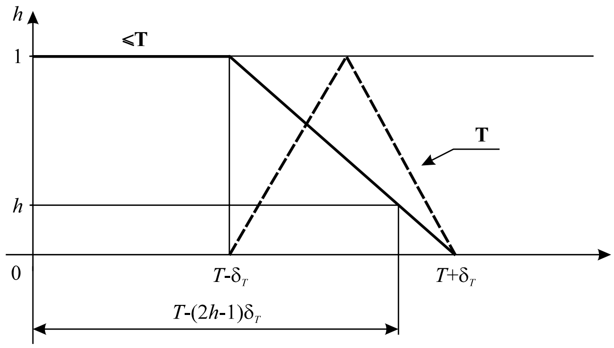

Fig. 3. 'Acceptable costs' (T) and costs equal to or less than 'acceptable costs' ($\leqslant T$).

$$\sum_{i=1}^{M}\left(\sum_{j=1}^{N}(d_i C_{ij} Y_{ij})\right)+\sum_{j=1}^{N}(f_j(S_j)X_j)\leqslant T-(2h-1)\delta_T \tag{18}$$

In the same way, the second objective function $Z_2=\sum_{i=1}^{M}\sum_{j=1}^{N}(O_i\times Y_{ij})$ can be transformed into the appropriate constraint. (In this case the 'acceptable political opposition'.) The objective functions will become constraints, that agree completely with Bellman and Zadeh (1970), whereby both objective functions and constraints in a fuzzy environment are treated in the same way. Since the objective function is transformed into a constraint, a new objective function needs to be defined. The aim is to find a solution that maximizes the level of satisfying the objective function and constraint, h. In another words, to elicit the optimal decision (i.e., to determine the optimal solution that satisfies both the objective and constraints by the maximum possible degree h), a fuzzy optimization principle may be applied by which h is maximized (Zimmermann, 1976):

Maximize h

Subject to

$$\sum_{i=1}^{M}\left(\sum_{j=1}^{N}(d_i C_{ij} Y_{ij})\right)+\sum_{j=1}^{N}(f_j(S_j)X_j)\leqslant T-(2h-1)\delta_T \tag{19}$$

$$\sum_{j=1}^{N} Y_{ij}=1,\quad \forall i \tag{20}$$

$$Y_{ij}\leqslant X_j,\quad \forall i,\ \forall j \tag{21}$$

$$S_j\geqslant D_i^*+(2h-1)\times\delta_D,\quad \forall j \tag{22}$$

$$C_j^{\mathrm{Min}}\leqslant S_j\leqslant C_j^{\mathrm{Max}},\quad \forall j \tag{23}$$

The 'political opposition' factor $Z_2=\sum_{i=1}^{M}\sum_{j=1}^{N}(O_i\times Y_{ij})$ is not included in this formulation, however, it could be incorporated into the analysis in a similar way to the formulation of the cost objective function.

By solving the fuzzy linear programming problem, the locations can be determined, as well as the corresponding level of satisfaction of h. By shifting the 'acceptable costs' and/or 'political opposition' to the left, the level of satisfaction is decreased. Every triplet (h, cost, political opposition) corresponds to a certain decision. In this way, different 'location scenarios' can be generated for a decision maker. The choice of a specific plan is conditioned by the decision maker's willingness to accept that some constraints are not completely satisfied, while still keeping the objective of decreasing total costs and/or political opposition.

6. Conclusion

Many countries are aware of environmental pollution trends, and are responding with continuous research that addresses various environmental issues. One of the major planning challenges is the problem of locating landfills or sites for waste and hazardous materials. Here, a model is developed for solving the problem of locating undesirable facilities. The model is multi-objective, since the problem of locating undesirable facilities faces many conflicting criteria. To optimally locate landfill sites, this paper considers objectives such as minimization of total costs and political opposition. Political opposition is an important issue that occurs when locating undesirable facilities. The methodology is tested using a real-world example (Prince George's County, Maryland).

The amount of waste produced per person is not always known precisely, or in some cases information is not available for input parameters that are part of a mathematical model. This paper also proposes another way to treat uncertainties in locating undesirable facilities, which is based on Fuzzy Mathematical Programming. The model based on Fuzzy Mathematical Programming allows a decision maker to generate a larger number of different 'location scenarios' to better assist them in the decision-making process.

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