



A bi-objective Model for the Capacity and Location of Landfills for Municipal Solid Wastes

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ABSTRACT

This paper considers a bi-objective mathematical model for locations of landfills, transfer stations, and material recovery facilities in order to serve the entire regions and simultaneously identify the capacities of landfills. This is a mixed-integer programming (MIP) model whose objectives are to minimize the total cost and pollution simultaneously. To validate the model, a numerical example was solved by an augmented ϵ -constraint method, and the associated computational results were presented to show the number of solid waste facilities and location of sites for solid waste facilities.

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1. Introduction

In recent decades, many industrialized and developing countries plan and try to reduce human pollution and hazardous waste and increase recycling materials simultaneously. The aim is to improve the quality of urban life and protect the country environment. For example, urban transportation usually produces air pollution and noise pollution or hazard of igniting flammable materials and spreading radioactive radiance threat healthiness. So, choosing locations for waste disposal and optimal routes to reduce environmental pollution have been the agenda of these countries.

This paper is related to an undesirable location problem in which an undesirable facility is harmful to the welfare and health of employees or restriction of the existing facilities. We consider a

mixed-integer linear programming (MILP) model to locate landfills or sites for waste and hazardous materials and identify their capacities; besides, the model specifies the location of transfer stations and material recovery facilities (MRFs). The waste flow system is shown in Fig. 1. First, the waste flow starts from the population centers (i.e., waste producers) and transfers either to the transfer station, MRF or landfill. At a transfer station, depending on problem optimization, waste transfers to an MRF or landfill. At the MRF, recycling operations are performed on waste in order to recover materials and residual wastes for disposing transfers to landfill.

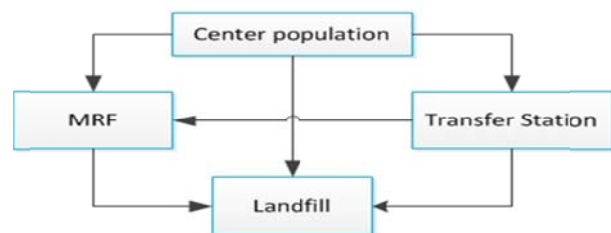


Fig. 1. Waste flow system

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This problem usually faces the conflicting objectives that minimize the cost and pollution. Thus, we consider a bi-objective mathematical model and obtain Pareto-optimal solutions to this problem.

The rest of the paper is organized as follows. In Section 2, we present the related studies in this field. In Section 3, we introduce detailed description of our research and mathematical formulations. In Section 4, we explain the augmented ε -constraint method. Section 5 presents our computational results for a numerical example. Conclusion and suggestions for further research are given in Section 6.

2. Literature Review

In 1960s, the initial step was taken by Anderson [1] who introduced economical optimization for the planning of waste management systems, which was then developed by other researchers [2-10]. Some review articles in the recent years have been written by [11] and [12].

Cheng et al. [13] Integrated multi-criteria decision analysis (MCDA) and inexact mixed integer linear programming (IMILP). The IMILP method obtains the minimum total cost for each landfill site, and then uses the MCDA factor to rank this landfill according to their total gained weight.

Beskese et al. [14] surveyed a landfill site selection problem with fuzzy AHP and fuzzy TOPSIS for the city of Istanbul. Also, Kharat et al. [15] studied this problem with MCDA techniques using a hybrid fuzzy Delphi, fuzzy AHP, and DEMATEL methods. Li and Huang [16] proposed an interval-parameter two-stage mixed-integer linear programming (ITMILP) model for long-term solid waste management (SWM) planning in Regina, Canada. Their objective is to minimize the total cost considering three scenarios based on different waste management policies.

Yeomans et al. [17] presented grey linear-programming (GLP) and a genetic algorithm with simulation (GAS) under uncertainty to solve the municipal waste flow Hamilton-Wentworth in the province of Ontario. In a municipal SWM problem, in uncertain environment, Cai et al. [18] developed an interval-valued fuzzy robust programming (I-VFRP) model.

Wu et al. [19] proposed an interval nonlinear programming model with a linear constraint for optimizing SWM by considering effect of economies-of-scale. Minciardi et al. [20] proposed a non-linear multi-objective model for

SWM in Genova, Italy for minimizing four objectives related to economic costs, unrecycled waste, sanitary landfill disposal, and environmental impact.

Caruso et al. [21] proposed a multi-objective location-allocation model that contains three objectives (i.e., economical cost, waste of resource, and environmental impact). They used a weighting method combining these objectives into a single objective. Rakas et al. [22] developed a multi-objective model for determining the number and location of landfills for waste materials so that the total cost and political opposition are minimized simultaneously. For minimizing the municipal SWM cost in Port Said in Egypt, Badran and El-Haggar [23] presented a MIP model determining the best collection site among the candidate locations. Because of determining the number, size, and location of SWM facilities with the aim of minimizing the total cost, Mitropoulos [24] proposed an MIP model for the problem. For large-scale problems, they proposed an interchange heuristic algorithm.

Erkut et al. [25] presented a new multi-criteria mixed-integer linear programming model related to greenhouse effects for locating municipal solid waste management facilities in North Greece. They considered five objectives that are to minimize the greenhouse effect, minimize the final disposal to the landfill, maximize the energy recovery, maximize the material recovery, and minimize the total cost. They proposed the lexicographic minimax approach to obtain non-dominated solutions.

For finding the optimal location and allocation in a SWM system in Duisburg city in Germany, Noche [26] proposed a multi-objective model for minimizing total cost and considered the economic and environmental aspects. Eiselt and Marianov [27] proposed a bi-objective MIP model in order to present the locations of landfills and transfer stations and simultaneously determine the sizes of the landfills that are to be established under cost and pollution minimization as objective functions. Yadav et al. [28] proposed an approach for a SWM problem with geographical information system tools and a model including on-road measurements of distances and strategic allocation of transfer stations in Nashik, India.

Our paper is different as given in the literature (e.g., [27]), in which the contribution of our model is to consider MRFs alongside landfills and transfer stations in a SWM problem. These

MRFs can recycle materials or recover energy; therefore, we determine the locations of landfills, MRFs and transfer stations. Also, we specify the capacity of landfills in a bi-objective mathematical model that minimizes the total cost and pollution.

3. Mathematical Model

3-1. Indices

- l Index of customers ($i=1, \dots, m$)
- j Index of landfills ($j=1, \dots, l$)
- k Index of transfer stations ($k=1, \dots, t$)
- q Index of MRFs ($q=1, \dots, r$)

3-2. Parameters

- f_j^L Fixed annual cost for installing and operating a landfill at location j
- Δf_j^L Capacity-dependent annual cost (\$/ton) after installing and operating a landfill at location j
- f_k^T Annualized fixed cost for installing and operating a transfer station at location k
- Δf_k^T Capacity-dependent annual cost(\$/ton) after installing and operating a transfer station at location k
- f_q^R Annualized fixed cost for installing and operating a MRF at location q
- Δf_q^R Capacity-dependent annual cost (\$/ton) after installing and operating a MRF at location q
- $(\underline{T}_k, \overline{T}_k)$ Lower and upper limit capacities of a transfer station at location k
- $(\underline{R}_q, \overline{R}_q)$ Lower and upper limit capacities of MRF q
- η_L, η_T, η_R Polluted factors considered for landfill, transfer station, and MRF (kilometers²/ton)
- $\frac{\eta_R}{P_c}$ Maximum allowable pollution for all populated centers
- $\theta_{ij}, \theta_{ik}, \theta_{iq}$ Unit transportation cost (\$/ton) from customer i to landfill j , from customer i to a transfer station k , from customer i to MRF q
- $\hat{\theta}_{kj}$ Unit transportation cost (\$/ton) from a

- $\hat{\theta}_{qj}, \hat{\theta}_{kq}$ transfer station k to landfill j , from MRF q to a landfill l , and from transfer station k to MRF q
- d_{ij}, d_{ik}, d_{iq} Euclidean distance between customer i , landfill j , transfer station k , and MRF q . These distances just are used for pollution at customer sites
- φ Capacity-dependent annual profit (\$/ton) to install and operate a MRF
- λ Average tons of garbage that each people generates per year
- α (output garbage) / (input garbage) in MRF
- w_i The number of customers in population center i

3-3. Decision variables

- Q_j This continues variable measures the capacity (ton) of landfill at location j
- Y_j Equals 1 if install a landfill at location j ; otherwise, equals 0
- V_k Equals 1 if install a transfer station at location k ; otherwise, equals 0
- R_q Equals 1 if install a MRF at location q ; otherwise, equals 0
- Z_{ij} If all garbage from customer i is shipped to landfill j equal 1; otherwise, 0
- X_{ik} Equals 1 if all garbage from customer i is shipped to transfer station k ; otherwise, 0
- g_{iq} Equals 1 if all garbage from customer i is shipped to MRF q ; otherwise, 0
- u_{kj} The continuous variable that measures the amount of garbage shipped from transfer station k to landfill j
- o_{kq} The continuous variable that measures the amount of garbage shipped from to transfer station k to MRF q
- b_{qj} The continuous variable that measures the amount of garbage shipped from MRF q to landfill j

We formulate the mathematical model consisting of two objective functions for (1) installation and garbage transportation costs and (2) pollution.

3-4. Objective functions

$$\begin{aligned}
 \text{Min } z_1 = & \sum_j (f'_j + \Delta f'_j Q_j) Y_j \\
 & + \sum_q \left(f_q^R R_q + (\Delta f_q^R - \varphi) \left[\left(\sum_i \lambda W_{iq} g_{iq} \right) + \left(\sum_k o_{kq} \right) \right] \right) \\
 & + \sum_k \left(f_k^T V_k + \Delta f_k^T \left(\sum_i \lambda W_{ik} x_{ik} \right) \right) \\
 & + \sum_i \sum_k \theta_{ik} \lambda W_{ik} x_{ik} + \sum_i \sum_j \theta_{ij} \lambda W_{ij} z_{ij} \\
 & \quad + \sum_i \sum_q \theta_{iq} \lambda W_{iq} g_{iq} \\
 & + \sum_k \sum_q \hat{\theta}_{kq} o_{kq} + \sum_k \sum_j \hat{\theta}_{kj} u_{kj} + \sum_q \sum_j \hat{\theta}_{qj} b_{qj}
 \end{aligned} \tag{1}$$

$$\begin{aligned}
 \text{Min } z_2 = & \sum_i^m W_i \left[\sum_j \frac{\eta_L (\sum_i \lambda W_{ij} z_{ij} + \sum_k u_{kj} + \sum_l c)}{(d_{ij} + \varepsilon)^2} \right. \\
 & \left. + \sum_k \frac{\eta_T (\sum_i \lambda W_{ik} x_{ik})}{(d_{ik} + \varepsilon)^2} + \sum_q \frac{\eta_R (\sum_i \lambda W_{iq} g_{iq} + \sum_k o_{kq})}{(d_{iq} + \varepsilon)^2} \right]
 \end{aligned} \tag{2}$$

In the first objective function, we introduce the first objective function of the total cost including the installation cost and garbage transportation cost with nine terms. In the first three terms, we refer to the annual cost in order to install and operate landfills, transfer stations, and material recoveries. These three terms contain two components that the first one is the fixed cost and the second one is the capacity-dependent cost. The second six terms refer to the garbage transportation cost between landfills, transfer stations, and material recoveries.

The second objective expresses pollution quantity. By following Eiselt and Marianov [27], we assume that the ill effects of pollution increase linearly when the amounts of waste increase, while decreasing by the square of the distance to the polluting facility. This paper only considers the part of the pollution at customer site i derived from the landfills, transfer stations, and material recoveries because the customers feel pollution and live in urban areas. Therefore, the aim of this paper is to decrease the pollution in customer areas, in which the customers feel lower pollution from these sites of solid wastes. The total pollution in the world needs a collaboration between all countries and industries.

3-5. Constraints

$$\begin{aligned}
 & \sum_j \frac{\eta_L (\sum_i \lambda W_{ij} z_{ij} + \sum_k u_{kj} + \sum_q b_{qj})}{(d_{ij} + \varepsilon)^2} + \sum_k \frac{\eta_T (\sum_i \lambda W_{ik} x_{ik})}{(d_{ik} + \varepsilon)^2} + \sum_q \frac{\eta_R (\sum_i \lambda W_{iq} g_{iq} + \sum_k o_{kq})}{(d_{iq} + \varepsilon)^2} \leq P_c \\
 & \forall i \\
 & z_{ij} \leq Y_j \quad \forall i, j \\
 & x_{ik} \leq V_k \quad \forall i, k \\
 & g_{iq} \leq R_q \quad \forall i, q \\
 & \sum_j z_{ij} + \sum_k x_{ik} + \sum_q g_{iq} = 1 \quad \forall i \\
 & \sum_j u_{kj} + \sum_q o_{kq} = \sum_i \lambda W_{ik} x_{ik} \quad \forall k \\
 & \underline{T} \leq \sum_i \lambda W_{ik} x_{ik} \leq \bar{T} \quad \text{or} \quad \sum_i \lambda W_{ik} x_{ik} = 0 \\
 & \forall k \\
 & \sum_j b_{qj} = \alpha \left[\sum_i \lambda W_{iq} g_{iq} + \sum_k o_{kq} \right] \quad \forall q \\
 & \underline{R} \leq \sum_i \lambda W_{iq} g_{iq} + \sum_k o_{kq} \leq \bar{R} \quad \text{or} \quad \sum_i \lambda W_{iq} g_{iq} + \sum_k o_{kq} = 1 \\
 & \forall q \\
 & Y_j + V_j + R_j \leq 1 \quad \forall j \\
 & \sum_i \lambda W_{ij} z_{ij} + \sum_k u_{kj} + \sum_q b_{qj} \leq Q_j Y_j \quad \forall j \\
 & Y_j, V_k, R_q, z_{ij}, x_{ik}, g_{iq} \in \{0, 1\}; \quad Q_j, u_{kj}, o_{kq}, b_{qj} \geq 0 \quad \forall i, j, k, q
 \end{aligned} \tag{1-12}$$

Constraint (3) shows that the pollution at any populated center i must not exceed the maximum allowable pollution. Constraints (4) to (6) ensure that the garbage transportations are shipped to the facilities if these facilities exist. Constraint (7) shows that customer i allows choosing one route to the landfills, transfer stations, and material recoveries. Constraint (8) indicates that the amount of input garbage from all customers to the transfer station k is equal to the output garbage to the landfill and MRF. Constraint (9) shows that the amount of input garbage from all customers to transfer station k is between lower and upper limit capacities of transfer station k . Constraint (10) shows that the output garbage from material recoveries equals α percent of input garbage from all customers and transfers stations to material recoveries. Constraint (11) indicates that the amount of input garbage from all customers to MRF q is between lower and

upper limit capacities of MRF q . Constraint (12) shows that at each candidate location j , we have up to one landfill or transfer station or MRF. Constraint (13) shows that the total input garbage to landfill j from customer i , transfer station k , and MRF q cannot exceed Q_j capacity of landfill at location j . Constraint (14) defines a domain of the decision variables.

At last, we change nonlinear expression in the first objective function and Constraint (13) to linear expression by replacing this with the following five equations (15) to (19).

$$Q Y_j = h_j \tag{1}$$

$$h_j \geq Q_j - M(1 - Y_j) \tag{2}$$

$$h_j \leq Q_j + M(1 - Y_j) \tag{3}$$

$$h_j \geq 0 \tag{4}$$

$$h_j \leq M Y_j \tag{5}$$

Also, we change nonlinear expression in constraint (9) to linear expression by replacing this with the following four equations (20) to (23); in the same way, the nonlinearity of Constraint (11) is eliminated.

$$\sum_i \lambda w_i g_{iq} + \sum_k o_{kq} \leq Ma \tag{1}$$

$$\sum_i \lambda w_i g_{iq} + \sum_k o_{kq} \geq \underline{T} - M(1 - a) \tag{2}$$

$$\sum_i \lambda w_i g_{iq} + \sum_k o_{kq} \leq \bar{T} \tag{3}$$

$$a \in \{0, 1\} \tag{4}$$

4. The Augmented ϵ -Constraint Method

One of the best known techniques, in comparison with traditional weighting approaches, to solve multi-objective problems is the augmented ϵ -constraint method that has two advantages in contrast to the ϵ -constraint method. The first is to use lexicographic optimization for every objective function that makes a pay-off table with only efficient solutions. The second is to overcome weakly efficient solutions by incorporating the appropriate slack or surplus variables to objective function constraints [29]. For this problem, the augmented ϵ -constraint is modeled as follows:

$$\text{Min } (f_1(x) - \delta s_2)$$

s.t.

$$f_2(x) + s_2 = e_2$$

$$f_2(x_2^*) \leq e_2 \leq f_2(x_1^*)$$

$$s_2 \in R^+$$

where δ is a small number (e.g., between 10^{-3} and 10^{-6}) and $f_2(x_1^*)$ is obtained from lexicographic optimization for the second objective function.

5. Computational Results

The model is applied to the location of landfills, material recoveries, and transfer stations for serving the land, whose size is around 300 kilometers by 300 kilometers square. In this region, there are 8 cities with a population larger than 100000 inhabitants, in which we consider as the population to be served. To find good candidates for the location of the landfills, transfer stations, and material recoveries, we consider points, scattered across the region. Daily per capita waste generation λ is about 0.275 kg per day, which is about 0.1 ton annually. The capacities of each city are 700000, 450000, 300000, 800000, 1200000, 650000, 850000, and 1000000 sequential.

There are two candidate landfill locations, three transfer station locations, which are uniformly distributed within the range of 150000 to 500000 tons and three MRFs, uniformly distributed within the range of 150000 to 500000 tons with the assumption that one location between transfer station and MRF is common. The Euclidean distances between pairs of customer i , landfill j , transfer station k , and MRF q are shown in Tables 1 to 6. The transportation cost per ton per km from customers to transfer stations is \$0.2 and from customers to landfills or material recoveries is \$0.4, while the transportation cost from the transfer stations to landfills or material recoveries (per ton per km) is \$0.15. Furthermore, the transportation cost from material recoveries to landfills (per ton per km) is \$0.1. Also, we suppose that unit transportation costs θ between pairs of two sites can be obtained by multiplication of the mentioned costs by Euclidean distances.

The annualized fixed cost of establishing and operating a transfer station is \$100,000, while the variable cost per annual ton is \$10. The fixed cost per landfill is \$300,000, while the variable cost per annual ton is \$5. The fixed cost per material recoveries is \$2,000,000, while the variable cost

per annual ton is \$20. Polluted factors considering landfill, transfer station, and MRF are 0.1, 0.025, and 0.5, respectively. Also, the maximum allowable pollution, P_c , is 1000. The output garbage percent in MRF is 0.3 and

capacity-dependent annual profit for installing and operating a MRF is \$40 (\$/ton).

Tab. 1. Euclidean distances between customer and landfill

Landfill-Customer	1	2	3	4	5	6	7	8
1	50	30	100	160	140	40	210	70
2	60	110	90	50	160	200	30	170

Tab. 2. Euclidean distances between Transfer station and customer

Transfer station-Customer	1	2	3	4	5	6	7	8
1	40	65	90	50	65	70	20	40
2	60	95	100	75	45	30	25	40
3 (common with MRF)	70	30	55	80	45	130	110	75

Tab. 3. Euclidean distances between MRF and customer

MRF-Customer	1	2	3	4	5	6	7	8
1	60	30	20	25	65	80	40	130
2	90	60	10	70	150	50	65	40
3 (common with MRF)	70	30	55	80	45	130	110	75

Tab. 4. Euclidean distances between transfer station and landfill

Transfer station-Landfill	1	2
1	65	40
2	30	70
3 (common with MRF)	45	55

Tab. 5. Euclidean distances between transfer station and MRF

Transfer station-MRF	1	2	3
1	170	50	50
2	65	130	130
3 (common with MRF)	80	140	-

Tab. 6. Euclidean distances between MRF and landfill

MRF-Landfill	1	2
1	50	120
2	60	110
3 (common with MRF)	45	55

Tab. 7. Result ($\varphi=40$ \$/ton)

State	e_2	Z_1^* (Total cost)	Z_2^* (Pollution)	The selected Landfills	Capacity of Landfill 1	Capacity of Landfill 2	The selected Transfer Stations	The selected MRF
1	9115879	29065000	9115879	1	595000	0	-	-
2	20000000	16700000	13201770	1,2	360000	235000	1,2,3	-
3	40000000	16700000	13201770	1,2	360000	235000	1,2,3	-
4	60000000	16700000	13201770	1,2	360000	235000	1,2,3	-
5	80000000	16700000	13201770	1,2	360000	235000	1,2,3	-
6	100000000	11547500	97311710	1	280000	0	-	1,2,3
7	117785496	6574750	117785496	1	178500	0	-	1,2,3

Tab. 8. Result ($\varphi=30$ \$/ton)

State	e_2	Z_1^* (Total cost)	Z_2^* (Pollution)	Selected landfills	Capacity of Landfill 1	Capacity of Landfill 2	Selected transfer stations	Selected MRF
1	9115879	29065000	9115879	1	595000	0	-	-
2	20000000	16700000	13201770	1,2	360000	235000	1,2,3	-
3	40000000	16700000	13201770	1,2	360000	235000	1,2,3	-
4	60000000	16700000	13201770	1,2	360000	235000	1,2,3	-
5	80000000	16700000	13201770	1,2	360000	235000	1,2,3	-
6	100000000	16047500	97311710	1	280000	0	-	1,2,3
7	117785496	12524750	117785496	1	178500	0	-	1,2,3

Tab. 9. Result ($\varphi=20$ \$/ton, equals to variable capacity-dependent annual cost of MRFs, Δf_q^R)

State	e_2	Z_1^* (Total cost)	Z_2^* (Pollution)	Selected landfills	Capacity of Landfill 1	Capacity of Landfill 2	Selected transfer stations	Selected MRF
1	9115879	29065000	9115879	1	595000	0	-	-
2	10000000	19775000	9308466	1,2	400000	195000	-	-
3	11000000	19775000	9308466	1,2	400000	195000	-	-
4	12000000	19775000	9308466	1,2	400000	195000	-	-
5	13000000	17887500	12978460	1,2	445000	150000	-	-
6	13201770	16700000	13201770	1,2	360000	235000	1,2,3	-

We solved the model by an augmented ϵ -constraint method and different capacity-dependent annual profit (φ). The related results (e.g., the selected landfills, selected transfer stations, selected MRFs, capacity of each selected landfills, and the values of objective functions in each state) are shown in Tables 7 to 9. We realized that there is a struggle between the total cost and amount of pollution. In other words, if we want to lower the cost, the pollution increases, and vice versa.

We investigated the model for different capacity-dependent annual profit (φ), and found that if φ is

high and the recycling operations are profitable, the model decides two scenarios dependent on the pollution quantity. If the pollution function is more important, the model does not install MRFs; if the cost function is more important, the model install all candidate MRFs.

In Table 9, we consider $\varphi=20$ \$/ton that is equal to variable capacity-dependent annual cost of MRFs. The results show that we do not have any MRFs for transfer stations, in which the model just selects them at the sixth term (when the cost function is more important), because the recovery

operations are not profitable, and the model does not install any MRFs.

6. Conclusion

This paper has proposed a mixed-integer linear programming (MILP) model to locate landfills or sites for waste and hazardous materials and identify their capacities. Additionally, the presented model has specified the location of transfer stations and material recovery facilities (MRFs). Two objectives have been considered to minimize the total cost and minimize the total pollution simultaneously. The numerical example has been solved by an augmented ε -constraint method to find a fair non-dominated solution. Moreover, we presented the results of model when we have different amounts of Capacity-dependent annual profit (φ) to install and operate a MRF. The results show that there is a struggle between total cost and amount of pollution; if we want to lower the cost, the pollution increases, and vice versa.

To extend this research, political opposition, as another objective function, can be considered. Political opposition means that no community wants to store the solid waste produced by others close to its zone. For another future research, pollution of transportation routes can also be considered as another way of pollution. Also, the parameters (e.g., the average generated garbage of people and recycling ratio in MRFs) can be stochastic.

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