

ENHANCED SPATIAL MODEL FOR LANDFILL SITING ANALYSIS

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ABSTRACT: A landfill siting analysis typically requires evaluating various rules, factors, constraints, and numerous spatial data. A modern geographical information system, although capable of rapidly processing a massive amount of spatial data, lacks the ability to locate an optimal site when compactness and other factors are simultaneously evaluated. A previously developed grid-based model could not be applied to resolve this inability for irregularly shaped spatial data. Therefore, an enhanced spatial siting model is proposed herein for general spatial data. A compactness index is applied to ensure the integrity of selected sites. Two case studies are presented to demonstrate the applicability of the proposed model. The proposed model and two models developed previously are compared in the first case study based on the single factor of land cost. A single factor model is perhaps quite unacceptable with respect to other factors. The second case study is thus presented to demonstrate the flexibility of the model for considering additional factors, land slope, and road network accessibility. Moreover, results obtained from various models and siting factors are compared and discussed.

INTRODUCTION

Siting a landfill or other waste facility requires consideration of numerous criteria, factors, and regulations. Massive amounts of spatial data are therefore processed for waste facility siting. Such difficulties are exacerbated even further when siting hazardous waste landfills, owing to their rigid environmental restrictions. Manual analysis of spatial data is, however, time consuming and tedious. Furthermore, the public consensus of "Not In My Back Yard" (Lindquist 1991) poses yet another major obstacle in the siting process. A candidate landfill or waste facility site is often abandoned owing to public opposition. The siting process may thus need to be repeated several times until an appropriate site is located. Other factors hindering waste facility siting include limited land resources and increasing amounts of waste generation, particularly in a densely populated country such as Taiwan. In addition, the local waste authority lacks manpower and qualified experts to implement a comprehensive siting analysis, leading to improper evaluation of crucial factors. An inappropriate waste facility site may thus be selected and, consequently, may adversely affect the surrounding environment and other economic and sociocultural aspects. In light of such circumstances, an enhanced technique is presented in this study to facilitate the siting analysis.

With the assistance of modern computer technology, tremendous amounts of data and complex rules can be rapidly processed. Michaels (1988), Lindquist (1991), and Kao et al. (1996) used a geographical information system (GIS) to facilitate their siting of a landfill. Lindquist (1991) pointed out that a GIS is objective, flexible, and capable of processing large amounts of spatial data in a relatively short time. However, a typical GIS cannot implement an optimization model. When a siting area is large, a GIS without an optimizing function can offer only limited assistance. Therefore, in this study, an optimization model is developed for use with a GIS.

A landfill site is normally larger than a geographical land unit expressed by a GIS parcel, and a candidate site must con-

sist of at least a few parcels that are tightly integrated together. Herein, a compactness measure is thus adopted to ensure the continuity and integrity of a chosen candidate site. Various definitions for compactness have been proposed (Wright et al. 1983; Gilbert et al. 1985; Diamond and Wright 1989). Wright et al. (1983) used the ratio of perimeter to the area of a site as a measure for compactness. According to their definition, the associated compactness value is increased when the perimeter of an area decreases. The appropriateness of this definition for use with a mixed-integer programming (MIP) model accounts for why previous investigations (Wright et al. 1983; Benabdallah and Wright 1992; Minor and Jacobs 1994; Kao and Lin 1996) and this study have adopted it.

Regarding the aspect of compactness when developing an optimization model, Wright et al. (1983) proposed an MIP model and demonstrated its effectiveness with several tiny grid-based cases. Diamond and Wright (1989) developed a nonlinear model for land allocation problems with a different compactness definition. Minor and Jacobs (1994) proposed an MIP model for solid- and hazardous-waste landfill siting. Kao and Lin (1996) developed an improved MIP model. This model is primarily aimed at grid-based data, for which geo-referenced units are expressed by grids of the same size. However, that grid-based model could not effectively resolve a general spatial problem, in which geo-referenced units are expressed as polygons (parcels) of irregular shape and size.

The MIP model for general spatial data is more difficult to construct than the grid-based one because of the irregular structure of spatial data. A preliminary model based on previous work (Kao and Lin 1996) was developed (Lin and Kao 1998) for a simple hypothetical case. The effectiveness of applying the proposed model to two real cases is presented herein. In addition, the results are compared with those using two other models. As in a previous grid-based model (Kao and Lin 1996), the proposed model can simultaneously consider multiple factors.

The rest of this paper is organized as follows. The proposed model is introduced and compared with two other models for general spatial data type. A comparison of models based on grid-based data type can be found in a previous study (Kao and Lin 1996). A case study of the landfill siting problem for Orange County, N.C. (Minor and Jacobs 1994), is used to demonstrate the applicability of the proposed model. This case study considers only the single factor of land cost. Land cost, although important, is not the only factor for making an appropriate siting decision. Therefore, a multifactor problem for Shihu County, Taiwan, is illustrated. Results obtained by using different models and various sets of siting factor weights are presented and discussed.

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COMPACTNESS MODELS

Compactness refers to the extent to which the shape or boundaries of a site can be regarded as tightly integrated. The lower the level of compactness implies less of a likelihood that it can satisfy the siting requirements, such as those illustrated in Fig. 1. Therefore, a proper compactness model is prerequisite to ensure the integrity of a candidate site. The following MIP model was developed to satisfy this requirement:

$$\text{Minimize } \sum_{i=1}^{i=n} u_i \cdot A_i \left(\sum_{k=1}^{k=m} W_k \cdot C_{ik} \right) \quad (1a)$$

Subject to

$$\sum_{j \in E_i} S_{ij} \cdot u_j - ST_i \cdot u_i + v_i \geq 0, \quad \forall i \in \{1, \dots, n\} \quad (1b)$$

$$\sum_{i=1}^{i=n} u_i \cdot A_i \geq A_r, \quad \forall i \in \{1, \dots, n\} \quad (1c)$$

$$\sum_{i=1}^{i=n} v_i - \lambda \cdot \sum_{i=1}^{i=n} u_i \cdot A_i \leq 0, \quad \forall i \in \{1, \dots, n\} \quad (1d)$$

where n = number of land parcels in a siting area; m = number of siting factors considered; u_i = $[0, 1]$ integer variable to represent whether parcel i was included in the selected candidate site; A_i = area of parcel i ; W_k = relative weight for siting factor k ; C_{ik} = suitability score for constructing a landfill on parcel i for factor k ; ST_i = total length of the perimeter of parcel i ; v_i = variable for calculating the compactness index; E_i = set of parcels adjacent to parcel i , as illustrated in Fig. 2; S_{ij} = length of the common boundary between parcels i and j ; A_r = minimum size required for a suitable landfill; and λ = maximally acceptable value of the compactness index for constructing a landfill (Minor and Jacobs 1994).

Eq. (1a) defines the objective of the proposed model. It denotes the suitability score of the selected candidate site for the considered siting factors. The score of each factor for each parcel is multiplied by its own relative weight. The accumulation of all the scores of parcels in the selected candidate site represents its appropriateness as a landfill site. Eq. (1b) is the constraint used for calculating the valid perimeter of a land parcel for the selected candidate site. The value of u_i can be either 0 or 1. If u_i equals 0, parcel i is not part of the selected candidate site and the value of v_i is 0 as well. If u_i equals 1, v_i may be a positive value depending on the sum of the other

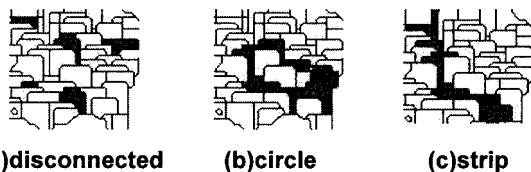


FIG. 1. Unsuitable Shapes for Constructing Landfill

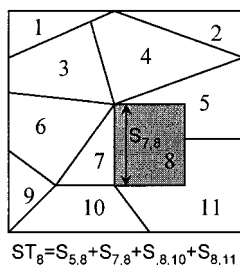


FIG. 2. Perimeters and Borders

terms in (1b); and the positive value is the length of the valid perimeter of parcel i of the selected candidate site. Then, the summation of v_i equals the perimeter of the selected candidate site. Eq. (1c) ensures that the size of the selected candidate site is more than a minimally required size. Eq. (1d) is used to ensure that all the parcels included in the selected site are tightly integrated. The compaction index λ was adopted from the model proposed by Minor and Jacobs (1994) and is equal to the ratio of the perimeter to the area of a site. If the area is constant, the smaller the index value implies the better the integrity of the site. Although it is hard to determine which good value (or the shape of a site) is the best, a small value of the index is necessary to avoid locating a site with irregular shape or disconnected land cells, as illustrated in Fig. 1.

Two previous models developed by Minor and Jacobs (1994) and Wright et al. (1983) are compared with the model proposed in this study. Both models are briefly described as follows.

The formulation of the model developed by Wright et al. (1983) is listed as follows.

Minimize

$$\sum_{i=1}^n \sum_{j \in T_i} S_{ij} (P_{ij} + N_{ij}) \quad (2a)$$

Subject to

$$x_i - x_j - P_{ij} + N_{ij} = 0,$$

$$\forall i, j \in T_i \quad (\text{other constraints or bounds}) \quad (2b)$$

where x_i and x_j = $[0, 1]$ integer variable that determine whether cells i and j are part of the selected candidate site, respectively; T_i = set of cell number of cells adjacent to cell i ; S_{ij} = length of the side shared by cells i and j ; and P_{ij} and N_{ij} = $[0, 1]$ integers that determine whether the associated S_{ij} is part of the perimeter.

The model developed by Minor and Jacobs (1994) is presented as follows:

Minimize

$$\sum_{i=1}^N c_i x_i \quad (3a)$$

Subject to

$$x_i - x_j \leq B_{ij}, \quad \forall i, j \in \{i + 1, \dots, N\} \quad (3b)$$

$$x_j - x_i \leq B_{ij}, \quad \forall i, j \in \{i + 1, \dots, N\} \quad (3c)$$

$$x_i + x_j + B_{ij} \leq 2, \quad \forall i, j \in \{i + 1, \dots, N\} \quad (3d)$$

$$B_{ij} - x_i - x_j \leq 1, \quad \forall i, j \in \{i + 1, \dots, N\} \quad (3e)$$

$$\left(\sum_{i=1}^N \sum_{j=i+1}^N S_{ij} (B_{ij}) + \sum_{i=1}^N S_{ei} x_i \right) \leq \lambda \left(\sum_{i=1}^N a_i x_i \right),$$

$$\forall i, j \in \{i + 1, \dots, N\} \quad (\text{other constraints or bounds}) \quad (3f)$$

where N = number of land parcels in the siting area; c_i represents the cost of parcel i ; x_i and x_j = $[0, 1]$ integers that indicate whether parcels i and j are selected, respectively; B_{ij} = $[0, 1]$ integer that determines whether the common boundary of parcels i and j is included in the perimeter of the selected candidate site or not; S_{ij} represents the length of the common boundary of parcels i and j ; S_{ei} = boundary length of parcel i that resides on the border of the siting area; λ = upper bound of compactness; and a_i = area of parcel i .

Detailed information regarding the above two models can be found in Wright et al. (1983) and Minor and Jacobs (1994),

TABLE 1. Comparison of Spatial Compactness Models for Required Number of Variables and Constraints for Siting Problem with General Spatial Data

Model (1)	Number of integer/noninteger variables (2)	Number of constraints (3)
Wright et al. (1983)	$n + 2m/0$	m
Minor and Jacobs (1994)	$n + m/0$	$4m$
Proposed model	n/n	n

Note: n = number of land parcels; m = number of all borders in siting area.

respectively. Table 1 lists the constraints and variables required for a problem with irregular land parcels. According to this table, the number of land parcels n is less than the number of borders m because each parcel has at least three borders and each border can be shared by two parcels at most. For the model developed by Wright et al. (1983) the number of required constraints approximately equals the number of all borders in the entire siting area if the equality constraint is regarded as one constraint rather than two inequalities. Notably, the number of required binary integer variables equals the sum of the number of parcels and twice the number of borders. The model developed by Minor and Jacobs (1994) reduces the number of required integer variables. In that model, the number of required integer variables is the sum of the number of land parcels and the number of borders. However, the number of constraints increases three times as compared to that for the model developed by Wright et al. (1983). For the proposed model, the number of constraints and integer variables is significantly lower, as shown in Table 1, although for each land parcel a general variable is added. Increasing the number of integer variables significantly increases the difficulty of solving an MIP problem, whereas increasing the number of general variables is less significant.

CASE STUDY I—ORANGE COUNTY, N.C.

The case demonstrated herein was originally presented by Minor and Jacobs (1994). The siting area, located in Orange County in North Carolina, includes 66 land parcels. This landfill siting analysis considered only one siting factor—land cost. LP_SOLVE (Berkelaar 1997), an LP and MLP problem solver, was used to implement the models. For this case, 23 different values of the compactness index value λ varying from 0.008 to 0.030 (1/ft) were tested, as used by Minor and Jacobs (1994). The larger value of λ implies a worsening compactness of the obtained candidate site. The minimally required area constraint of 350 acres was used to provide an adequate landfill volume at the candidate site.

Each model was tested for 23 subcases (each subcase having a different λ -constraint) on a Pentium-Pro 233 personal computer. Table 2 lists the total CPU solving time for each model for the 23 subcases. Among the three models, the CPU time used by the proposed model is significantly less than that used by the other two. Because all three models are using the same definition of compactness with corresponding λ values, the outputs of the three models are the same. Fig. 3 depicts the land costs versus compactness index values of solutions for this Orange County siting problem. Notably, increasing the value of the compactness index λ decreases the total cost of the parcels of the selected candidate site. However, if a site with tightly integrated land parcels is desired, the compactness index must decrease and the total cost would increase as a result. A decision-making process for evaluating the trade-off between the compactness and the land cost is required to obtain a compromise decision.

TABLE 2. Comparison of CPU Time Used for Resolving Problem in Case Study I

Model (1)	Total CPU time for 23 tested cases (s) (2)
Minor and Jacobs (1994)	3,214.03
Wright et al. (1983)	2,137.93
Proposed model	85.39

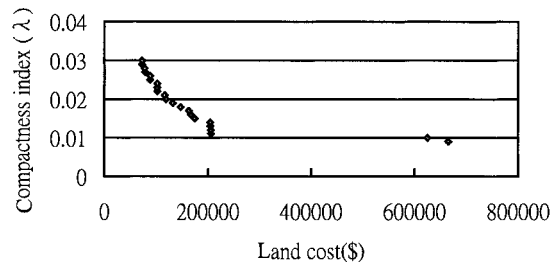


FIG. 3. Compactness Index versus Land Cost for Solutions Obtained for Case Study I

CASE STUDY II—SHIHU COUNTY, TAIWAN

The proposed model was further applied to a landfill siting problem in Shihu County in the middle part of Taiwan. In Case I, only the single factor of land cost is considered. Land cost, although important, is not the only factor considered when making an appropriate siting decision. Therefore, in this case, multiple criteria and factors are examined. The landfill siting procedure described in the following subsections for this problem was implemented in two major stages. First, various factors/regulations/rules for landfill siting were evaluated to define the siting criteria. According to the criteria, those areas not satisfying the criteria were prescreened out by map-layer analysis functions provided by a GIS. The proposed model was then utilized to obtain the candidate sites. A different set of factors and associated weights in the objective function would lead to a different candidate site. Various candidate sites obtained by using varied sets of factors and weights were compared and discussed.

Siting Criteria

Before applying the proposed model for landfill siting, siting criteria were defined to screen out the inappropriate parcels. Most of the criteria were extracted from regulation, legislation, and expertise (Kao and Lin 1996). The criteria were set to prohibit the landfill site from being placed in an inappropriate area that may be in conflict with regulations/legislation and/or induce a significant environmental impact. These criteria are categorized into environmental, sociocultural, and engineering-economic issues.

Environmental Issues

- **Water resources:** The landfill site should not be placed in the proximity of ground water or water resources protection areas.
- **Surface water:** A landfill should be placed an appropriate distance away from a surface water body to prevent the possible leachate of the landfill from polluting the water body. In this work, 180 m (Lindquist 1991) constitute the appropriate distance.
- **Floodplain:** The landfill site should not be placed within a floodplain, to reduce the risk of contaminating overland drainage.

- Urban development: The landfill site should not be placed near a residential or an urban area, to avoid adversely affecting land value and future development and to protect the general public from possible environmental hazards released from landfill sites. In this work, a landfill site is prohibited from being placed within 150 m (Lindquist 1991) of a residential or urban area.
- Historical or cultural sites: The landfill site should not be placed near historical or cultural scenic spots. In this study, a landfill site must be at least 500 m (Lin 1985) away from such a spot.

Engineering-Cost Issues

- Fault zones: Fault zones can lead to instability for engineering construction, thereby increasing the possibility of damage and contamination. To satisfy this criterion, a landfill site cannot be placed within 80 m of any fault zone.
- Land slope: An area with a large land slope may be unstable, thereby making construction and maintenance difficult. Land parcels with a land slope more than 40% (Lin 1985) are therefore screened out in this work.
- Road network accessibility: The landfill site should not be placed too far away from existing road networks, to avoid the expensive cost of constructing connecting roads. Land parcels more than 1,000 m (Lin 1985) away from existing road networks are therefore screened out.
- Land cost: A greater area is fundamental for constructing

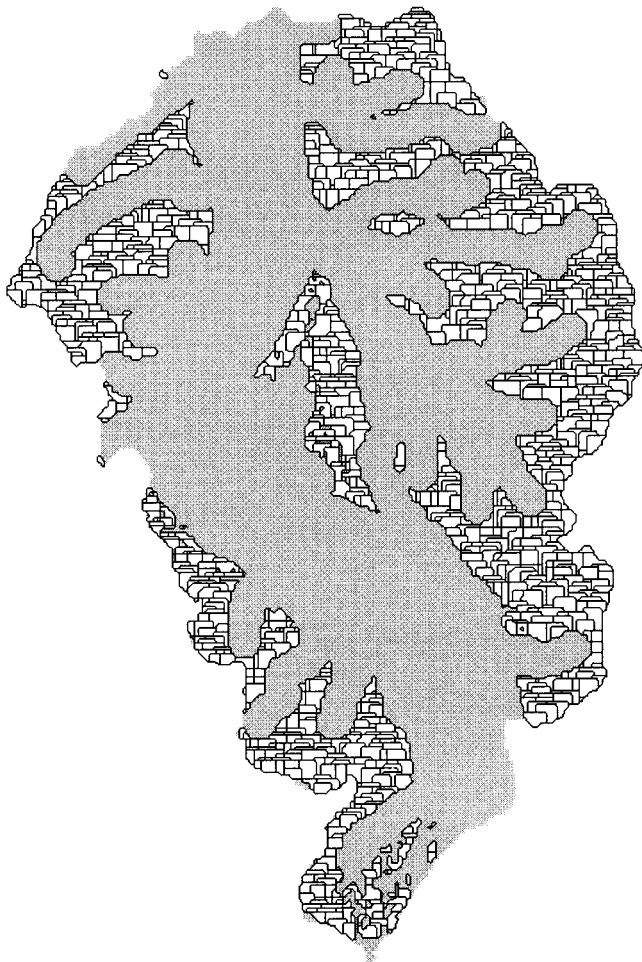


FIG. 4. Land Parcels in Shihu County

the landfill site. There is no need to purchase a land with a highly expensive unit price. Hereby, land parcels with a unit price higher than half the maximum unit price of the entire candidate area were screened out.

GRASS (GRASS4.1 1993), a GIS software, was used to implement the prescreening stage based on the above criteria. The area of Shihu County is 413.75 km². After the prescreening stage, the area remaining is 14.45 km² and consists of 1,245 land parcels. Fig. 4 illustrates the land parcels left after the prescreening. This prescreening stage can eliminate inappropriate areas as well as conserve the computational time required for solving the proposed model. Without the prescreening, the problem would be more difficult or perhaps impossible to resolve by a personal computer within an acceptable computational time.

Siting Factors and Associated Suitability Scores

Three siting factors were considered: (1) Land slope; (2) land cost; and (3) road network accessibility. Depending on the value of each factor, a score was assigned to express its appropriateness for becoming a landfill site. Suitability scores of the three siting factors of each land parcel were assigned according to the figures in Fig. 5. A higher score implies a lower suitability. The figures in Fig. 5 are drawn based on the recommendations of Lin (1985), described as follows:

- Land slope (S): The appropriate slope for constructing a landfill is about 8–12% because too steep of a slope would make it difficult to construct and maintain and too flat of a slope would affect the runoff drainage. Fig. 5(a) displays the suitability scores assigned for various land slopes.
- Land cost (C): The cost for purchasing land parcels is directly added into the total cost. Parcels with unit land cost less than half of the maximum unit cost are assigned

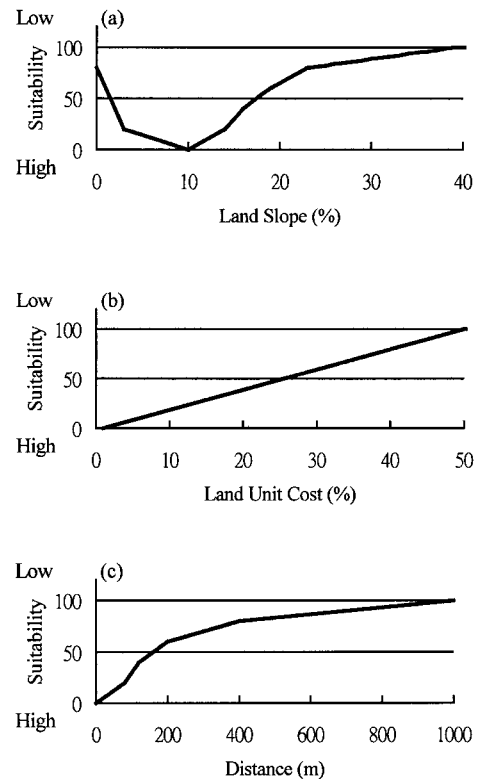


FIG. 5. Suitability Scores for: (a) Land Slope; (b) Land Cost; (c) Road Network Accessibility

with different scores. Fig. 5(b) depicts the relation between the suitability scores and land cost.

- Road network accessibility (R): Placing a landfill site distant from the existing road network would increase the cost for constructing the necessary connection road. Therefore, the distance between the landfill site and any accessible road should be <1 km. Fig. 5(c) illustrates the suitability scores assigned for various distances between the landfill site and a road network.

Siting Analysis with Multiple Factors

Similar to a previous study (Kao and Lin 1996), a weight is assigned for each siting factor to express its relative importance to other factors. Table 3 lists the weight sets used for this case study. Cumulatively, there are 2 sets and 14 scenarios (where S stands for slope; C stands for land cost; and R stands for road accessibility), and the number for the value of λ is 0.016 in Set 1 and 0.045 in Set 2. For instance, SC1 indicates the scenario with the two factors of slope and land cost being considered and λ being set equal to 0.016. The original weights assigned for slope, land cost, and road network ac-

TABLE 3. Compactness Index Value and Considered Siting Factors with Associated Weights of Each Scenario for Case Study II

Scenario (1)	Weight of Factors			Compactness index λ (1/m) (5)
	Land slope (2)	Land cost (3)	Road accessibility (4)	
S1	1 (3.8)	—	—	0.016
C1	—	1 (3.2)	—	0.016
R1	—	—	1 (4.4)	0.016
SC1	0.55 (3.8)	0.45 (3.2)	—	0.016
CR1	—	0.42 (3.2)	0.58 (4.4)	0.016
SR1	0.46 (3.8)	—	0.54 (4.4)	0.016
SCR1	0.33 (3.8)	0.28 (3.2)	0.39 (4.4)	0.016
S2	1 (3.8)	—	—	0.045
C2	—	1 (3.2)	—	0.045
R2	—	—	1 (4.4)	0.045
SC2	0.55 (3.8)	0.45 (3.2)	—	0.045
CR2	—	0.42 (3.2)	0.58 (4.4)	0.045
SR2	0.46 (3.8)	—	0.54 (4.4)	0.045
SCR2	0.33 (3.8)	0.28 (3.2)	0.39 (4.4)	0.045

Note: Numbers in parentheses represent weight originally suggested by Lin (1985); — Indicates that associated factor is not included in objective function of model.

cessibility were suggested by Lin (1985). The weights of each scenario are normalized to be added to 1 for computation and comparison convenience. Determining the weights is quite controversial and occasionally subjective. Although the appropriateness and sensitivity of the weights and other information such as utility functions can be systematically evaluated by decision-making methods described by Cohon (1978) and Zeleny (1982), they are beyond the current scope of this study. These weight sets are heuristically assigned to examine how different weight sets affect the final siting solution. These scenarios were tested on a computer with Intel PII-233 CPU and 64 megabit RAM. CPLEX (*Using* 1997) was used to solve the scenarios because of its numeric stability.

The compactness index λ is equal to the ratio of the perimeter to the area of a site. Therefore, in addition to the shape of a site, increasing the area of a site would also decrease the value of λ . The best compact shape is a circle and therefore the minimum value of λ is equal to $2\pi R/\pi R^2$, where R denotes the radius of the circle. In the Shihu County landfill siting problem, the area desired for the landfill is at least 16,000 m². The minimum λ value for this minimal area is about 0.028. However, determining which shape (circle, square, rectangle, or any other shape) with good integrity is the best for a landfill site is difficult. Furthermore, the area of a candidate site is not necessary to be exactly equal to the minimally acceptable area of 16,000 m². In general, a small λ is necessary to ensure the selected site with good integrity but not necessary to be set to a specific value. To examine how the λ value influences the siting solution, λ was set to 0.016 and 0.045 for scenarios in Set 1 (S1, C1, R1, SC1, SR1, CR1, and SCR1) and Set 2 (S2, C2, R2, SC2, SR2, CR2, and SCR2), respectively.

RESULTS AND DISCUSSION

Tables 4 and 5 summarize the results of all scenarios. Table 4 lists the scores of siting factors for each solution, the objective value, CPU solving time, area, perimeter, and compactness index value. Table 5 displays the number and continuity of parcels in selected candidate sites. Fig. 6 depicts the locations of the candidate sites, with some of them sharing common parcels and four of Set 2 disconnected (parcels are not tightly integrated together). Fig. 7 illustrates the shape of the candidate sites with good integrity.

The average area of selected sites for scenarios in Set 1 is 69,000 m², whereas that for Set 2 is 17,220 m². Because the limitation on the value of the compactness index λ for scenarios in Set 1 is only 0.016 and a small site cannot satisfy

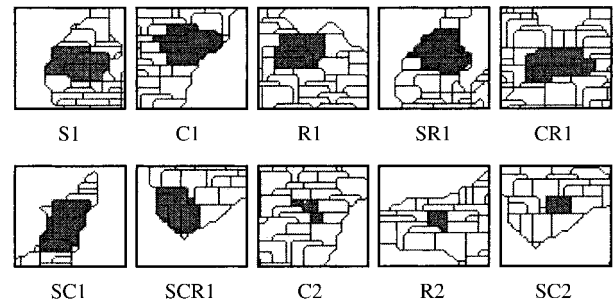
TABLE 4. Optimal Solution of Each Scenario for Case Study II

Scenario (1)	Land slope (2)	Land cost (3)	Road accessibility (4)	Objective value (5)	CPU time (s) (6)	Area (m ²) (7)	Perimeter (m) (8)	Compactness index λ (1/m) (9)
S1	873	(3,820)	(790)	873	764.67	76,765	1,228.24	0.016
C1	(4,898)	54	(3,850)	54	134.11	85,961	1,375.37	0.016
R1	(3,136)	(4,000)	480	480	13,962.18	70,568	1,129.09	0.016
SR1	890	(5,200)	560	694	1,695.44	82,762	1,324.19	0.016
CR1	(4,323)	938	790	835	16,476.94	83,362	1,333.79	0.016
SC1	2,148	413	(2,530)	1,329	14,901.16	81,163	1,298.61	0.016
SCR1	875	2,455	880	1,300	36,795.65	69,768	1,116.29	0.016
S2	110	(447)	(210)	110	1.05	17,192	752.92	0.044
C2	(824)	10	(771)	10	0.63	16,193	708.14	0.044
R2	(761)	(555)	100	100	94.86	16,193	548.15	0.034
SR2	140	(1,070)	110	120	2.16	17,592	752.99	0.043
CR2	(1,090)	130	130	127	3.18	17,192	752.99	0.044
SC2	200	97	(520)	148	1.09	18,991	548.17	0.029
SCR2	120	495	150	233	9.8	17,192	752.92	0.044

Note: Numbers in parentheses indicate that associated factor is not included in objective function of model.

TABLE 5. Number of Parcels and Connectivity of Optimal Solution of Each Case for Case Study II

Case identification (1)	Number of parcels (2)	Connected (3)
S1	6	Yes
C1	6	Yes
R1	6	Yes
SR1	9	Yes
CR1	6	Yes
SC1	5	Yes
SCR1	6	Yes
S2	2	No
C2	2	Yes
R2	1	Yes
SR2	2	No
CR2	3	No
SC2	1	Yes
SCR2	2	No

**FIG. 7. Shapes of Selected Sites**

siting factors for the sites selected for scenarios in Set 2 are better than those of scenarios in Set 1. An iterative procedure can be applied for locating a solution to find the desired compactness and suitability by setting various compactness index values, as in the previous case study.

Selected candidate sites are sparsely distributed over the entire siting area, as illustrated in Fig. 5. Such sparse results are attributed to that the dominating siting factors of the objective functions if all scenarios differ from each other. Scenarios S1, S2, C1, C2, R1, and R2 that consider only one factor are often found to be with low suitabilities of other factors. Two of the three siting factors are included in the objective functions for scenarios SR1, SR2, CR1, CR2, SC1, and SC2, and all three siting factors are included for scenarios SCR1 and SCR2. Among all solutions, there is no obvious solution with absolutely good suitability scores of siting factors. Obtaining a solution with a better suitability score for one factor, worsens the suitability score of at least one of the other two factors. An iterative decision-making process is generally required to evaluate the trade-offs for making a compromise solution.

According to Table 4, the CPU computational times for resolving scenarios in Set 1 are significantly longer than those in Set 2 because the limitation on the compactness index value of Set 1 is more rigid than that of Set 2, and the solution searching process must be implemented further for exploring sites with more parcels. In general, the computational time for resolving an MIP model rapidly increases with an increase in the number of integers, or parcels, in this study, thereby making many MIP models impractical. However, with the proposed model, the longest computational time for this 1,200-parcel problem is about 10 h, which is acceptable and can be regarded as practical.

CONCLUSIONS

Applying digital spatial data to facilitate landfill siting analyses has been an important technical advance in recent years. A tremendous amount of data and complex rules can be rapidly processed by a modern GIS. However, a typical GIS generally lacks optimizing capability and can offer only limited information for a large siting problem. Therefore, this work presented an enhanced model capable of resolving siting problems for general spatial data. Its capability is also demonstrated with two case studies. Comparing the proposed model with two earlier models used in Case Study I reveals that the computational time to solve the proposed model is significantly less than that for the two models because the proposed model significantly reduces the number of required integer variables that makes the model more practical.

In addition, the proposed model can simultaneously consider various siting factors. A single factor problem may yield a solution that is good for the considered factor, but perhaps unacceptable for other factors. For instance, scenario C2 in Case Study II is a single factor (land cost) scenario. The associated solution listed in Table 4, although good for land cost, is not as good as others for land slope and road accessibility.

**FIG. 6. Location of Site Selected in Each Scenario for Case Study II**

this requirement, large sites with good integrity are therefore selected. On the other hand, the compactness limitation for scenarios in Set 2 is released to 0.045 and smaller sites are thus selected. Solutions with an unacceptable integrity can be observed for the sites selected for scenarios S2, SR2, CR2, and SCR2, whose land parcels are not closely connected.

Owing to the rigid limitation on the compactness index value for scenarios in Set 1, sites that satisfy this limitation may not have good suitability. Therefore, suitability scores of

Therefore, multiple factors must be simultaneously analyzed. With a predefined compactness index value and a set of weights for siting factors, the model can locate the optimal site within a siting area, as demonstrated in Case Study II for Shihu County. However, with different compactness index values or siting factor weights, different candidate sites may be selected. If only one solution dominates all other solutions for the compactness index value and considered siting factors, then further decision-making analysis is unnecessary. Unfortunately, for a real world problem, such an obvious solution is generally unavailable, and various candidate sites may be obtained for different sets of factors, as the sparsely distributed sites selected for the Shihu County problem. A decision-making process is generally required to further evaluate the trade-offs among compactness, siting factors, and site locations to reach a final decision.

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