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# Subregion Districting Analysis for Municipal Solid Waste Collection Privatization

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## ABSTRACT

Privatization of municipal solid waste (MSW) collection can improve service quality and reduce cost. To reduce the risk of an incapable company serving an entire collection area and to establish a competitive market, a large collection area should be divided into two or more subregions, with each subregion served by a different company. The MSW subregion districting is generally done manually, based on the planner's intuition. Major drawbacks of a manual approach include the creation of a districting plan with poor road network integrity for which it is difficult to design an efficient collection route. The other drawbacks are difficulty in finding the optimal districting plan and the lack of a way to consistently measure the differences among subregions to avoid unfair competition. To determine an MSW collection subregion districting plan, this study presents a mixed-integer optimization model that incorporates factors such as compactness, road network integrity, collection cost, and regional proximity. Two cases are presented to demonstrate the applicability of the proposed model. In both cases, districting plans with good road network integrity and regional proximity have been generated successfully.

## INTRODUCTION

Privatization of municipal solid waste (MSW) collection has become a major environmental policy for years in

many countries. In 1990, more than 80% of waste collection in the United States<sup>1</sup> and the United Kingdom<sup>2</sup> was done by private companies. Similar MSW collection privatization can be observed in other countries.<sup>3</sup> As Fleming<sup>4</sup> indicated, privatization of waste services is nothing new and competition exists among private sectors and between the public and private sectors in some cases. McDavid,<sup>5</sup> after comparing public and private waste collection services for 327 local governments in Canada, stated that contracting-out MSW services is an effective way to reduce cost, especially for communities that use more than one contractor. Steel and Long<sup>6</sup> also pointed out that having fewer bids could result in less competitive outcomes. A proper districting plan that divides the entire area into several subregions is thus essential for promoting privatization of the MSW collection. Dividing a large area into several subregions and allowing more contractors to bid can reduce the investment risk and make it more attractive for companies to bid. Also, a proper districting plan can prevent the domination of the MSW collection market by one large company and can be effective in promoting competition among MSW collection contractors. An approach like this has been reported to be successful in Phoenix,<sup>4</sup> Charlotte,<sup>4</sup> and Seattle.<sup>1</sup> For example, in Phoenix, an area with approximately 60,000 residents was split into six subregions.

The MSW subregion districting is generally done manually, based on the planner's intuition. This manual approach, however, has three major problems. First, a districting plan with poor road network integrity may be generated and that could make the planning of an efficient collection route difficult. Also, many different districting plans are available and it is difficult for the planner to evaluate all of them to find the optimal one. Finally, in the absence of a quantitative procedure, an inappropriate districting plan may be selected and that would make the competition unfair. Thus, a quantitative tool to overcome these problems is explored in this study.

To our knowledge, after a wide search for related literature, no subregion districting model is specifically made available for MSW collection. Most subregion districting models have been constructed for developing voting districts or sales territories.<sup>7-12</sup> Among these studies,

## IMPLICATIONS

Establishing a competitive market is essential when privatizing MSW collection services. Dividing a large area into multiple subregions significantly reduces investment risk, thus attracting a sufficient number of contractors, thereby generating a competitive bidding process. This study developed a districting procedure and optimization model that effectively divides a MSW collection area into a desired number of subregions. Compactness, road network integrity, collection cost, and regional proximity are four major factors evaluated by the proposed model. The procedure was applied to two cases. The analytical results demonstrated that proper subregion districting plans can be obtained based on desired districting decision preferences.

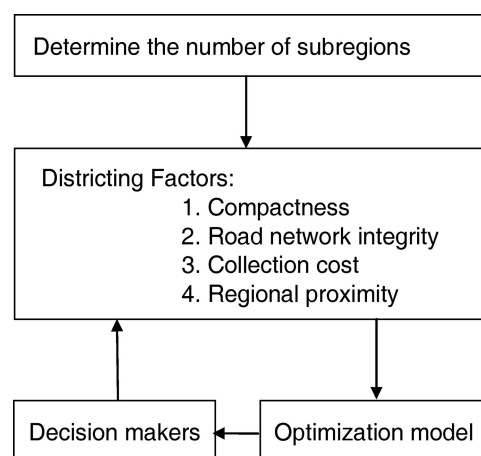
compactness was a primary factor to evaluate. Compactness ensures the integrity of each subregion and eliminates impractical districting plans, such as ring-like or wiggled-band districting. In general, the shape of a compact subregion is close to a square or circle.<sup>10</sup> Districting problems considering compactness are often analyzed with optimization models<sup>9,10,13–15</sup> that require significant computational effort. Compactness can be used also to screen out many inappropriate solutions during the problem-solving process. However, previous definitions of compactness typically evaluated only subregion shapes and are not applicable for a MSW collection problem because MSW collection activities occur along collection routes instead of over the entire region. A new definition for the integrity of a road network in a subregion is thus proposed in this study to overcome this problem.

In addition to compactness and road network integrity, factors such as waste generation, workload, and total length of routes can significantly affect the cost of an MSW collection service. Three factors are thus adopted when evaluating the appropriateness of a MSW collection-districting plan. Similar to previous studies,<sup>13,14</sup> individual values for these factors for all geographical units of a subregion are accumulated to evaluate the suitability of a subregion districting.

This study presents a procedure and an optimization model for dealing with MSW collection subregion districting problems. The subregions obtained using the proposed model are expected to have acceptable spatial compactness, high road network integrity, low collection cost, and good regional proximity. Although, after an extensive literature search, no model is specifically designed for MSW collection, several mixed integer programming (MIP) models are available for other types of districting problems. For instance, Hess et al.<sup>7</sup> proposed an MIP model, probably the first, for voting districting problems. The model partitions a region into a prespecified number of districts that maximizes the sum of the compactness values for all subregions. Several enhancements,<sup>8,10</sup> including heuristic approaches, for solving the same model were also developed. Benedallah et al.<sup>9</sup> proposed an MIP model, a modified version of the model developed by Wright et al.<sup>15</sup> for siting a single subregion to solve a multiple subregion allocation problem. In our previous work,<sup>13</sup> a MIP model was developed for siting a landfill. In this work, the model was revised for MSW collection districting problems. In the following sections, the factors considered for assessing the suitability of a subregion districting are first discussed and followed by an explanation of the optimization model proposed in this work. Two real MSW collection cases in Taiwan are then demonstrated and discussed.

## DISTRICTING PROCEDURE

Figure 1 shows the proposed procedure for MSW collection districting. First, the desired number of subregions to be districted is determined. Then, various districting factors, including subregion compactness, collection cost, and subregion size, are used to evaluate the suitability of candidate districting plans. Finally, the proposed optimization model, which considers road network integrity, is



**Figure 1.** The proposed procedure for MSW collection districting. established and applied to resolve a MSW collection districting problem. The procedure is detailed as follows.

### Numbers of Subregions

One major goal of MSW collection districting is to promote a competitive market. An entrance barrier of the market will occur when the ability required for serving a subregion is beyond a typical company. Generally, the number of companies bidding for MSW collection contracts is correlated with the degree of market competition. However, total cost and management difficulty would likely be high when an area is divided into too many subregions. Determining an appropriate number of subregions is essential for making a districting plan. The recommended procedure for determining the number of subregions is described as follows. First, information on regional characteristics such as the service ability of the candidate companies, the management capability of the public sector, the quantity of waste, difficulties in collection, and the residents' preferences should be collected and carefully evaluated to determine the capacity of a typical contractor. Thereafter, the total MSW quantity of the entire area is estimated. The expected number of subregions is given by the quotient of the total MSW quantity and the capacity of a typical contractor, rounded to an integer value.

### Districting Factors of MSW Collection

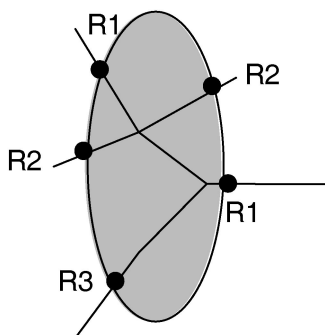
Factors considered for MSW collection subregion districting are compactness, road network integrity, collection cost, and regional proximity. The compactness factor assures that the shapes of divided subregions are as compact as possible. The road network integrity factor ensures the integrity of the interior road network in a subregion. The collection cost factor is evaluated to reduce the cost. The regional proximity factor is examined to reduce the differences among subregions and thereby prompt a competitive market. These factors are explained as follows.

*Compactness.* The compactness factor assures the spatial integrity of subregions. Without this compactness factor, subregions may be in discrete or irregular shapes. Different definitions are available for compactness, and a discussion of them was provided by Kao and Lin<sup>13</sup> for a

landfill siting study. During that landfill siting research, for ease of integration into a landfill siting model, the compactness was defined as the value of the total perimeter over the total landfill site area. This definition is also used for this study to avoid subregions with discrete land parcels.

**Road Network Integrity.** The compactness factor considers only subregion shape that is insufficient for an MSW collection problem because MSW collection occurs along collection routes instead of over the entire region. A new factor for road network integrity was thus defined for an MSW collection districting problem. The number of boundary crossing points (NBCPs), defined as points that roads pass through a subregion boundary, is used to evaluate road network integrity. From the example illustrated in Figure 2, the NBCPs for the region shown in the figure is five. A subregion with few NBCPs on its boundary implies that the interior road network has good integrity, without too many broken roads or roads connecting adjacent subregions. When too many broken roads exist on the boundary, U-turns or multiple trips are necessary and the associated MSW collection routing plan can be inefficient or impractical. To demonstrate the relationship of NBCPs and road network integrity, a simple case is provided in the Appendix.

**Collection Cost.** Although exact cost should be determined based on a detailed routing and collection plan for a subregion, the MSW collection cost for a subregion can be approximated according to three cost factors, described as follows. The total MSW quantity is a typical cost factor generally considered. Local MSW collection services are often contracted out based on cost derived by total MSW quantity multiplied by a unit price. The second cost factor is total road length in a subregion. Residents in a metropolitan area generally dwell in buildings along road networks. Consequently, MSW is typically collected along the road network. When the total length of roads in a subregion is long, the cost to collect MSW will increase. The third cost factor is distance between a subregion and final disposal facility. The collected MSW must be delivered to the final disposal facility, a landfill or an incinerator. Distance to the final disposal facility is positively correlated with collection cost. This study used these three cost factors to compare collection cost differences among varied districting plans.



**Figure 2.** An illustration for NBCPs.

**Regional Proximity.** A competitive market should avoid creating obviously hot subregions that are significantly more attractive for the contractors to bid than other subregions. Generally, because of economies of scale, contractors prefer subregions with a large quantity of MSW. Therefore, the quantity of MSW in subregions should be as close as possible. If two subregions have the same MSW quantity, contractors will prefer the subregion with shorter road length because the associated collection cost will be lower. By considering both MSW quantity and road length, a new factor called the route density index (RDI) is established:

$$RDI = W/L \tag{1}$$

where  $W$  is the total MSW quantity and  $L$  is the total road length for a subregion. A high RDI implies that a subregion is highly populated with a large MSW quantity and short total road length. The MSW collection for such a subregion is generally more cost-effective than a subregion with a low RDI. When a division of subregions with similar RDI values is impossible, the waste authority should apply different price structures to compensate for RDI differences.

**THE OPTIMIZATION MODEL**

The proposed model is described as follows.

$$Min \sum_{k=1}^M u_k + v_k \tag{2a}$$

Subject to

$$\beta_i \cdot t_{ik} - \sum_{j \in E_i} \beta_{ij} \cdot t_{ik} + p t_{ik} \geq 0 \tag{2b}$$

$\forall k \in \{1, \dots, M\}; i \in \{1, \dots, N\}$

$$S_i \cdot t_{ik} - \sum_{j \in E_i} S_{ij} \cdot t_{ik} + p s_{ik} \geq 0 \tag{2c}$$

$\forall k \in \{1, \dots, M\}; i \in \{1, \dots, N\}$

$$\sum_{i=1}^N p t_{ik} \leq P t \quad \forall k \in \{1, \dots, M\} \tag{2d}$$

$$\sum_{i=1}^N p s_{ik} - \gamma \sum_{i=1}^N A_i \cdot t_{ik} \leq 0 \quad \forall k \in \{1, \dots, M\} \tag{2e}$$

$$\sum_{k=1}^M t_{ik} = 1 \quad \forall i \in \{1, \dots, N\} \tag{2f}$$

$$\sum_{i=1}^N C_i \cdot t_{ik} - \alpha \sum_{i=1}^N L_i \cdot t_{ik} + u_k - v_k = 0 \quad \forall k \in \{1, \dots, M\} \quad (2g)$$

$$\sum_{i=1}^N C_i \cdot t_{ik} < C_{up} \quad \forall k \in \{1, \dots, M\} \quad (2h)$$

$$\sum_{i=1}^N C_i \cdot t_{ik} > C_{low} \quad \forall k \in \{1, \dots, M\} \quad (2i)$$

other constraints.

where  $k$  is the index of a subregion;  $M$  is the desired number of subregions;  $i$  is the index of a land parcel, a small MSW collection area;  $N$  is the total number of MSW collection parcels;  $u_k$  and  $v_k$  are positive and negative deviations, respectively, for the size of subregion  $k$  to the overall average size;  $\beta_i$  is the NBCPs surrounding parcel  $i$ ;  $t_{ik}$  is a variable indicating whether parcel  $i$  belongs to subregion  $k$  or not;  $\beta_{ij}$  is the NBCPs between parcels  $i$  and  $j$ ;  $pt_{ik}$  is the NBCPs between parcel  $i$  in subregion  $k$  and parcels in other subregions;  $S_i$  is the perimeter of parcel  $i$ ;  $S_{ij}$  is the length of boundary between parcels  $i$  and  $j$ ;  $ps_{ik}$  is the length of boundary between parcel  $i$  in subregion  $k$  and parcels in other subregions;  $\gamma$  is the upper limitation of compactness factor;  $A_i$  is the area size of land parcel  $i$ ;  $Pt$  is the upper limit on all NBCPs;  $C_i$  is the amount of MSW generated in parcel  $i$ ;  $L_i$  is the total road length in parcel  $i$ ;  $\alpha$  is the average value of RDI; and  $C_{up}$  and  $C_{low}$  are the upper and lower MSW quantity limits of a subregion, respectively.

Equation 2a is the objective function of this model to minimize the difference of MSW quantity per road length among subregions. Equations 2b and 2c are used to calculate the NBCPs and the length of boundaries of each parcel in each subregion, respectively. Equation 2d limits that the NBCPs of each subregion is less than  $Pt$ . Equation 2e guarantees the spatial compactness factor of each subregion is less than a given  $\gamma$ . Equation 2f ensures that each parcel belongs to exactly one subregion. Equation 2g determines the difference between the MSW quantity of each subregion and the overall average value. Equations 2h and 2i restrict the MSW quantities of subregions within a desired range.

The goal of the proposed model is to find the optimal solution for the MSW collection districting problem. In the following sections, the model is applied to two real cases. Discussions for the analytical results obtained and model applicability are provided.

## APPLICATIONS OF MSW SUBREGION DISTRICTING ANALYSIS

The proposed model was applied to two cases in northern Taiwan. Figure 3 shows the road networks and shapes for both cases. The typical capacity of a contractor in the case study area is approximately 30 t/day. The estimate of the MSW quantity is based on the amount recorded for each collection vehicle at the gates of an incinerator and at a landfill site. A database of all the records is available, which is used to compute the daily amount. The daily

(a) Case A



(b) Case B



**Figure 3.** Collection areas and road networks for (a) Case A and (b) Case B.

amount of MSW for Case A and Case B is 51 t and 130 t; thus, they are to be divided into two and four subregions respectively. The details of both cases are described as follows.

### Case A

Case A has 23 land parcels and a population of 57,000 residing on 54.8 km<sup>2</sup>. A land parcel in this work is a spatial administrative unit, which includes hundreds to thousands of people. Most roads are located in the northern part of the study area where more than two-thirds of residents live. Case A was divided into two subregions for MSW collection service.

**Model Parameters.** Parameters in the proposed model for Case A are described as follows.  $N$  is equal to 23 (23 land parcels) and  $M$  is 2 (two subregions). The average value of RDI,  $\alpha$ , is 0.342 t/km. The upper and lower bounds on MSW quantity,  $C_{up}$  and  $C_{low}$ , are at 105 and 95% of average MSW quantity. The average MSW quantity is calculated by the estimated total MSW quantity of Case A over the number of subregions. The compactness value limitation of a subregion,  $\gamma$ , is set at 2.  $Pt$  values ranging from 30 to 100 were examined to explore the influence of varied NBCPs on results.

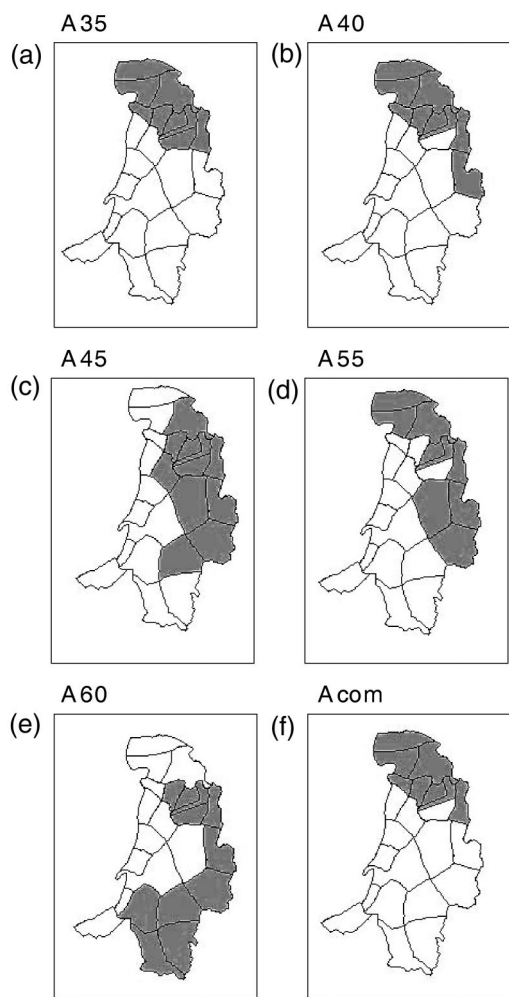
**Result and Discussion.** Figure 4 and Table 1 present six results obtained by the proposed model for Case A. In the figure and table, scenario A# (e.g., A35) represents the result obtained with NBCPs limited to be less than “#” (e.g., 35) for each subregion, with the exception that Acom is the scenario minimizing NBCPs. Solutions for subregions with discrete parcels were screened out by compactness constraints. Scenarios with NBCP limits less than 35 or more than 60 are infeasible or have the same result as A60. It can be observed that the result obtained under a small NBCP limit has high road integrity. The results changed from a north-south to an east-west combination when the limit on NBCPs was increased from 35 to 60. The northern part is highly populated with concentrated MSW quantity and dense roads. When road integrity is the major objective, the north-south combination with a high integrity is obtained. On the other hand, if the objective is to minimize the difference among RDIs between two subregions, the east-west combination is obtained. The results obtained for Acom, for which the objective function is to minimize the sum of all NBCPs, is similar to that for Scenario A35 but with higher road integrity and more significant difference in subregion RDIs. Ideal MSW collection subregion districting should

**Table 1.** Results obtained for Case A.

Scenario Code	Subregion Index	NBCPs	RDI Difference	MSW Quantity (t)	Road Length (km)	RDI (t/km)	Area (km <sup>2</sup> )
A35	1	24	0.27	24.7	46.7	0.53	13.8
	2	33		26.6	103.1	0.26	36.9
A40	1	40	0.23	26.1	53.7	0.49	15.1
	2	27		25.2	96.1	0.26	35.6
A45	1	40	0.01	25.4	73.3	0.35	26.1
	2	45		25.9	76.5	0.34	24.6
A55	1	30	0	26.3	76.6	0.34	29.2
	2	51		25.0	73.2	0.34	21.5
A60	1	58	0	24.6	71.7	0.34	25.4
	2	33		26.7	78.1	0.34	25.2
Acom	1	23	0.31	24.7	43.9	0.56	12.4
	2	32		26.6	105.9	0.25	38.2

have high road integrity and no difference among subregion RDIs. Small NBCPs imply high road integrity for which MSW collection routing can be effectively planned. Minimizing the difference among subregion RDIs is helpful to promote a competitive market. However, finding a solution that optimizes both advantages is difficult. Scenarios A60 and Acom demonstrated two extreme conditions. A significant difference exists between the two subregion RDIs for the Acom result, and consequently the contractor in the low RDI subregion must invest more resources than required in the other subregion to achieve the same service level. For the A35 result, as illustrated in Figure 4, the size of the northern subregion is significantly smaller than the southern subregion; however, the northern subregion has almost the same MSW quantity and less than half of the total road length in the southern subregion. Real contract prices for the northern and southern subregions were NT\$5.62 million and NT\$7.6 million, respectively. Although the contractor for the southern subregion acquired a higher contract price than that for the northern subregion, it did not result in increased profit because the RDI and total road length for the southern subregion are about half and twice that for the northern subregion, respectively. Although the contract price per ton in the southern subregion is approximately 1.25 times higher than that for the northern subregion, it is not enough to fully compensate for the increased cost of collection because of the low RDI and long total road length. The service quality was therefore not equal in both subregions. For example, the collection frequencies in some land parcels of the southern subregion were only half of that for other land parcels.

Ideally, the best districting plan should have the best road integrity (measured by NBCPs) and subregions that are fairly districted (measured by RDI). Unfortunately, such a districting plan is generally not available. A plan with few NBCPs may not have good RDI, and vice versa. A recommended procedure to decide the final districting plan after applying the proposed model is as follows: First, generate the districting plan with minimal NBCPs, e.g., Acom for Case A; then, find an acceptable value for the expected RDI difference. In this study, 25% of the RDI difference for the districting plan with minimal NBCPs is



**Figure 4.** Results obtained for Case A scenarios with various NBCPs for each subregion: (a) 35, (b) 40, (c) 45, (d) 55, (e) 60, and (f) Acom, the scenario minimizing NBCPs.

the recommended value, e.g., the RDI difference of Acom is 0.31 and thus 0.08 (~25% of it) is an acceptable value. Next, find the districting plans with an RDI difference less than the acceptable value. For Case A, A60, A55, and A45 are acceptable. Finally, out of all the acceptable plans, the one with the fewest NBCPs is selected. For Case A, A45 is the plan with the fewest NBCPs; therefore it is the recommended selection. Although it rarely happens, if no acceptable plan can be found, the plan with RDI difference closest to the acceptable value can be selected.

### Case B

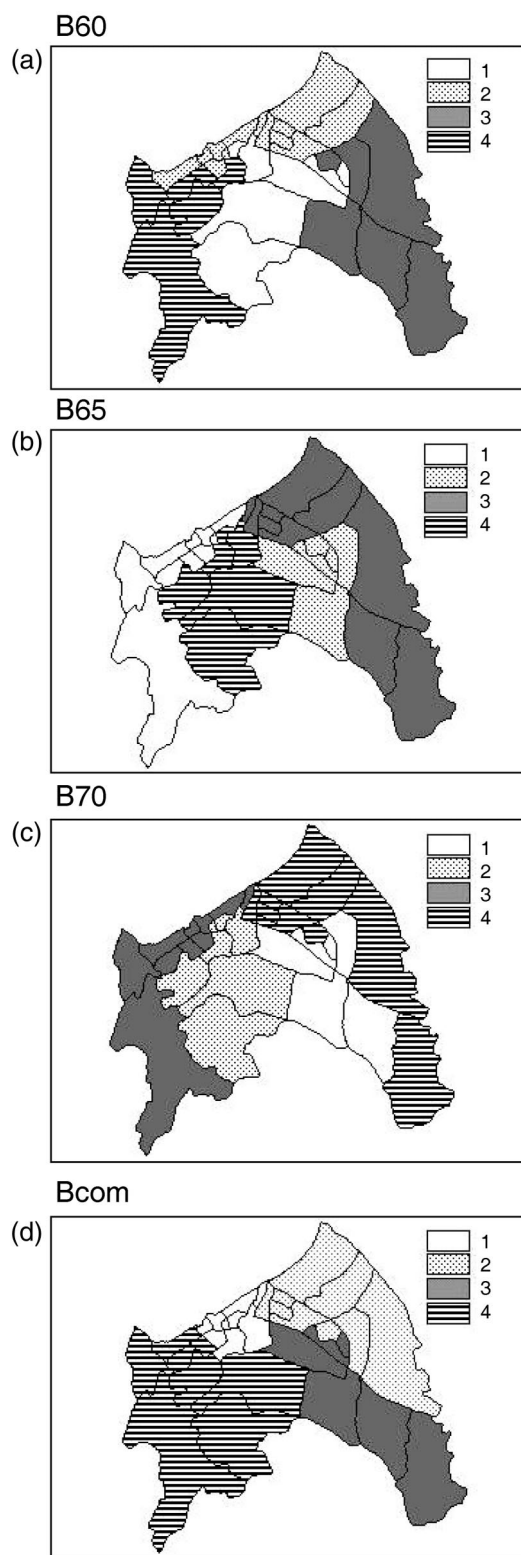
The MSW quantity for Case B is approximately 130 t, more than twice that in Case A. Case B is to be divided into four MSW collection subregions. The districting procedure applied in this case is similar to that used in Case A.

**Model Parameters.** The parameters used to establish the districting model for Case B are as follows:  $N$  and  $M$  are set to 32 and 4, respectively;  $\alpha$  is 0.761 t/km;  $\gamma$  is set at 4; and,  $C_{up}$  and  $C_{low}$  are set at 105 and 95% of the average MSW quantity, respectively. The average MSW quantity is calculated by estimating the total MSW quantity of Case B over the desired number of subregions. The  $Pt$  values, ranging from 35 to 100, were examined to explore the influence of various NBCPs on the final results.

**Result and Discussion.** The results are presented in Table 2 and illustrated in Figure 5. The NBCP limits less than 60 are infeasible for this case, and NBCP limits larger than 70 give the same solution as B70. As listed in Table 2, the difference for subregion RDIs decreases when the NBCP limit increases. These values are obtained by finding the difference between the maximal and minimal RDI values of subregions. After applying the proposed procedure to compare all results, choosing the B70 districting plan is recommended because it is the only plan with an RDI

**Table 2.** Results obtained for Case B.

Scenario Code	Subregion Index	NBCPs	RDI Difference	MSW Quantity (t)	Road Length (km)	RDI (t/km)	Area (km <sup>2</sup> )
B60	1	56	0.53	31.8	52	0.61	7.9
	2	48		31.8	28	1.14	5.2
	3	45		34.1	56	0.61	11.1
	4	53		32.4	35	0.93	7.4
B65	1	65	0.34	32.4	38	0.85	7.1
	2	50		33.2	35	0.95	4.6
	3	50		33.4	55	0.61	12.4
	4	63		31.1	44	0.71	7.6
B70	1	62	0.30	31.7	52	0.61	6.3
	2	60		33.2	44	0.75	7.6
	3	67		31.6	38	0.83	7.1
	4	49		33.7	37	0.91	10.6
Bcom	1	29	1.19	31.0	18	1.72	1.8
	2	36		31.2	29	1.08	8.7
	3	61		34.1	60	0.57	8.3
	4	60		33.8	64	0.53	13.0



**Figure 5.** Results obtained for Case B scenarios with various NBCPs for each subregion: (a) 60, (b) 65, (c) 70, and (d) Bcom, the scenario minimizing NBCPs.

difference value that is less than the acceptable level of 0.3. Manually delineating a districting plan with minimal disparity among subregions is not easy. As the number of subregions increases, the difficulty boosts because the

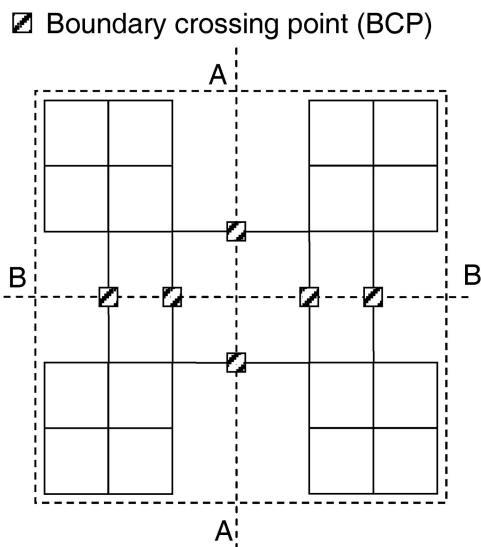
problem becomes quite complex. However, with the proposed optimization model, a proper districting plan can be efficiently made.

The objective function used to produce Bcom was to minimize the sum of NBCPs instead of minimizing RDI difference. The Bcom districting plan has good road integrity and poor deviation of RDIs. If the Bcom districting plan, with significant RDI and road length differences, is adopted, the cost difference for maintaining similar service quality levels in all subregions should be carefully evaluated. Contract prices should be adjusted for subregions with low RDIs and long total road length.

**CONCLUSIONS**

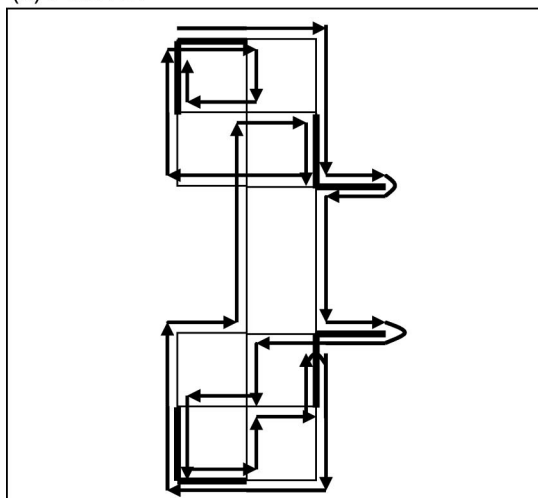
The optimization model proposed in this study is aimed to obtain an appropriate MSW collection subregion districting plan for promoting a competitive market. The model allows decision-makers or residents to define decision preferences based on various districting factors when dividing a large area into several subregions. Although the compactness factor can avoid subregions with discrete land parcels, it cannot ensure road network integrity because collection activities mainly occur along road networks. A new factor defined by counting the number of points crossing the boundary of a subregion is proposed in this study. This new factor can ensure the road network integrity required for a good routing plan. In addition to the spatial compactness and road network integrity factors, the model also evaluates the proximity among subregions. A new definition for regional proximity is made available based on the proposed index, RDI. Increasing proximity for a districting strategy reduces the cost difference among subregions and, thus, promotes competition in the bidding process for MSW collection services.

Model applicability was demonstrated for two cases in Taiwan. Although contract price in the southern subregion for Case A was higher than that for the northern subregion, it was not as profitable as the northern subregion because of low RDI and long total road length. This problem can be overcome by applying the model to district subregions with similar RDI values to reduce the cost

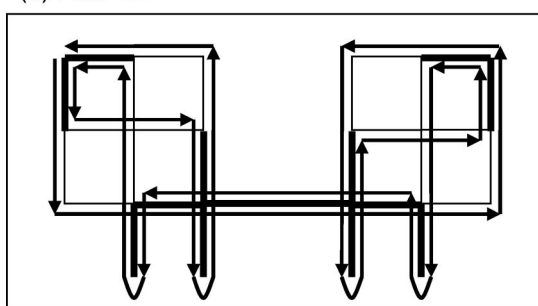


**Figure 6.** A simple case with two districting plans.

(a) Plan AA



(b) Plan BB



- Street segment being passed once
- Street segment being passed twice
- ← Direction of the collection route

**Figure 7.** Typical collection routes for subregions in both districting plans: (a) Plan AA and (b) Plan BB.

differences among subregions. Manually determining a good districting plan is difficult, especially when the number of required subregions to be divided increases. The proposed optimization model can generate an appropriate districting plan, as demonstrated in Case B. Finally, if a good districting plan in which subregions have high RDIs, short road lengths, and a small sum of NBCPs is not available, compensation should be applied to subregions with poor values. For instance, when the model objective is to minimize the sum of NBCPs, significant variation in RDI values may exist, despite a plan having good road integrity. Scenario Bcom is one such example; the associated contract prices should be adjusted to compensate for

**Table 3.** NBCP analysis results for the simple example.

Districting Plan	Number of Street Blocks	NBCPs	Number of Street Segments Traversed	Number of Street Segments Traversed Twice
AA	18	2	38	8
BB	18	4	44	14



the increased cost due to low RDI. Therefore, in addition to MSW quantity, the RDI and total road length should be simultaneously considered to determine the final contract price.

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## APPENDIX

### A Simple Example

A simple example to demonstrate the relationship between NBCPs and road network integrity is shown in Figure 6. The figure shows an area with thirty-six street blocks. Intuitively, there are two ways of dividing the area into two subregions to make a districting plan: by cutting it either vertically (Plan AA), or by cutting horizontally (Plan BB). However, with manual division, it is not easy to tell which of the two is better. The NBCPs is 2 for Plan AA and 4 for Plan BB. Therefore, the road integrity for Plan AA is superior to that for Plan BB; the collection routes for both plans are assessed further to prove this statement.

It is assumed that the MSW of each subregion is collected by one vehicle. The vehicle has to pass through all the streets at least once and come back to the starting point, which can be any node in the subregion. Figure 7 shows typical efficient collection routes for both districting plans where a minimum number of street segments are traversed. Table 3 lists the results of the proposed NBCP analysis for both districting plans. The number of street segments in the collection route is 44 for Plan BB and 38 for Plan AA, which is approximately 16% less than that of Plan BB. Plan AA is thus superior to Plan BB. With the proposed NBCP analysis, the districting plan with good road integrity can be effectively identified.

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