Spatial Service Location-Allocation Analysis for Siting Recycling Depots

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Abstract: Although recycling depots can promote recycling, their spatial distributions significantly affect efficiency. Despite the ability to locate depots throughout a region by minimizing total service distance, residents in sparsely populated areas may have to travel long distances to a depot. Although increasing the number of depots can reduce these distances, the associated costs increase. This study develops six optimization models based on the three objectives of minimizing maximal service distance, maximizing the service ratio, and minimizing the number of depots for district-based, district-open and nondistrict scenarios. Three factors, service distance, district equity, and service ratio, are used to assess the performance of models. A case study of 16 districts is utilized to demonstrate the application of the models. Minimizing the number of depots under the nondistrict scenario achieves a good service ratio with short service distance using fewer depots than other models. The proposed models will facilitate efforts to determine an appropriate spatial distribution of recycling depots.
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Introduction

Recycling is an important environmental policy for reducing municipal solid waste (MSW). Placing recycling depots at appropriate locations can significantly increase the efficiency of a recycling program and reduce collection and transportation costs. However, a recycling depot in an improper location may discourage use by residents. Selecting suitable locations for recycling depots is thus essential to the success of recycling programs. Currently, waste authorities implement various recycling strategies. A district-based strategy encourages competition among districts, which is expected to increase the participation rate, but such a strategy discourages residents from dropping their recyclable materials off at a depot that is close to them but located in another district. The selection of depot locations in district-based and non-district-based strategies should consider factors such as service distance, service ratio (SR), and spatial equity. Unfortunately, although several models have been previously proposed [e.g., Flahaut et al. (2002), Wang and Yang (2007), Pati et al. (2008), Erkut et al. (2008), de Figueiredo and Mayerle (2008), Lin and Chen (2009), and Kao et al. (2010)], none determines the locations of recycling depots under varied administrative strategies based on multiple decision factors. This study presents six optimization models to solve this problem.

In previous studies, the service distance between a household and its nearest depot is frequently the principal factor considered in a location-allocation model for siting depot locations. For example, Gershman, Brickner & Bratton, Inc., and Burroughs Consulting (1995) used walking distances to assess recycling depot performance. Several other studies (e.g., Gerrard and Church 1995; Kao and Lin 2002) assessed the efficiencies of various MSW or recycling collection programs using service distance. However, locations selected based on service distance only are generally close to highly populated areas and are inconvenient for rural residents. This may lead to uneven depot distributions and cause spatial disparity problems. Therefore, not only must the total service distance to depots be minimized, but also such factors as maximal service distance (MSD) should be considered to ensure the spatial equity of the depot locations. Moreover, the SR, defined as the percentage of residents with an acceptable distance to the nearest depot, is also appropriate for evaluating the spatial equity problem. Depots within an acceptable distance can encourage residents to participate in recycling programs. Therefore, the ratio of residents receiving a service at an acceptable distance is also an appropriate indicator, representing the likelihood of residents participating in recycling programs.

In addition to service distance, service ratio, and spatial equity, determining the number of depots (NOD) is also important. Although one can install numerous depots to increase convenience for residents, this approach is not cost effective. However, if only a few depots are available, participation rates will be low because depot locations for a large proportion of residents will be too far away. Therefore, a trade-off exists between the NOD and total service distance; this trade-off must be analyzed when making siting decisions.

Three objectives are thus applied to optimize the allocation of recycling depots in this paper: minimizing MSD, maximizing the SR, and minimizing the NOD under an SR constraint. Three scenarios, the district-open (DO) scenario, district-based (DB) scenario, and nondistrict (ND) scenario, as used by Kao et al. (2010),

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are analyzed. The remainder of this paper is organized as follows. Six recycling depot siting models are described first. These models are then applied to an illustrative case for 16 districts in Hsinchu City, Taiwan. Finally, modeling results are compared and their differences are discussed.

Models

The DO scenario assumes residents always choose the nearest recycling depot, without considering whether the nearest recycling depot is in their district. The DB scenario assumes residents only use depots in their own district. The ND scenario regards an entire area as a single region and attempts to select proper locations for recycling depots without considering districts. The models developed for determining optimal depot locations under different objective functions and scenarios are described as follows.

Model MSD-DO

This model attempts to increase convenience for residents, especially for those living in sparsely populated areas. The objective of this model is to minimize for all households the MSD to the nearest recycling depot. This model assumes residents always choose the nearest depot, regardless of whether the depot is in their district. Access convenience is the primary factor used when evaluating the recycling performance of each administrative district. The model is formulated as follows:

$$\text{Min}\, d_{\max} + E\sum_i W_i d_i \tag{1a}$$

$$\text{Subject to} \quad \sum_{j\in C_i} (D_{ij} y_{ij}) \le d_i \quad \forall i \tag{1b}$$

$$\sum_{j\in C_i} y_{ij} = 1 \quad \forall i \tag{1c}$$

$$y_{ij} \le x_j \quad \forall i, j \tag{1d}$$

$$\sum_{j\in N_r} x_j = 1 \quad \forall r \tag{1e}$$

$$x_j = [0, 1] \quad \forall j \tag{1f}$$

$$d_i \le d_{\max} \quad \forall j \tag{1g}$$

where $d_{\max}$ = MSD; E = small constant; d_i = distance from household group i to its nearest depot; W_i = number of households in group i; D_{ij} = distance from household group i to candidate depot j; y_{ij} = variable that can be 1 or 0 only, where 1 indicates that household group i is served by depot j; x_j = binary integer variable, where 1 indicates that a recycling depot is at candidate location j; C_i = predetermined set of candidate locations that can serve household group i at an acceptable distance; and N_r = set of all candidate locations for recycling depots in district r. Most families in Taiwan live in apartment buildings and, thus, they are grouped with their neighbors in this study.

This first term of objective function in Eq. (1a) of the MSD-DO model minimizes the MSD. The second term, which minimizes total service distance to ensure that each resident chooses the nearest depot, is multiplied by a small constant (E). This small constant ensures that the model prioritizes minimizing MSD over total service distance. Eqs. (1b) and (1c) derive the nearest service distance (d_i). Eq. (1d) ensures that y_{ij} is smaller than x_j, and y_{ij} and is 0 or 1. Thus, y_{ij} does not need to be set as [0,1] binary integer variables, thereby reducing solving time significantly. Eq. (1e) sets the desired number of recycling depots in each district at 1. Eq. (1f) defines all x_j values as [0,1] binary integer variables. Eq. (1g) limits $d_{\max}$, such that it is larger than or equal to all d_i values, and combines d_i with the objective function to determine the MSD.

Model MSD-DB

This model assumes residents only use depots in their district. The objective of this model is to minimize the MSD between each household group and its nearest recycling depot within the same district. This model is as follows:

$$\text{Min}\, d_{\max} + E\sum_i W_i d_i \tag{2a}$$

$$\text{Subject to} \quad \sum_{j\in M_i\cap C_i} (D_{ij} y_{ij}) \le d_i \quad \forall i \tag{2b}$$

$$\sum_{j\in M_i\cap C_i} y_{ij} = 1 \quad \forall i \tag{2c}$$

$$\text{Same as } (1d)\text{–}(1g)$$

where M_i = set of candidate recycling depots in the same district as household group i. Eqs. (2b) and (2c), which differ from Eqs. (1b) and (1c), require that household group i and recycling depot j must be in the same district. Other constraints are the same as those used for the MSD-DO model.

Model District-MSD-DB

Instead of minimizing global MSD, this model determines the MSD of each district and minimizes the sum of MSDs for all districts. This model is as follows:

$$\text{Min} \sum_k d^k_{\max} + E\sum_i W_i d_i \tag{3a}$$

$$\text{Subject to} \quad d_i \le d^k_{\max} \quad \forall i, k \tag{3b}$$

$$\text{Same as } (1d)\text{–}(1f), (2b), \text{and } (2c)$$

where $d^k_{\max}$ = MSD of district k. Eq. (3b) determines the MSD for each district. Other constraints are the same as those used in the MSD-DB model.

Model SR-ND

This model maximizes the SR within an acceptable service distance under the ND scenario. This model is as follows:

$$\text{Max}\, s - E\sum_i W_i d_i + F\sum_i \sum_j p_{ij} \tag{4a}$$

$$\text{Subject to} \quad \sum_{j\in J} x_j = R \tag{4b}$$

$$p_{ij} \le y_{ij} \quad \forall i, j \tag{4c}$$

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$$p_{ij} D_{\exp} + (1 - p_{ij}) D_{ij} \geq D_{ij} y_{ij} \quad \forall i, j \tag{4d}$$

$$\sum_i \sum_{j \in C_i} p_{ij} W_i \geq s \cdot W_{\text{all}} \tag{4e}$$

$$\text{Same as } (1b)\text{–}(1f)$$

where s = SR; R = desired number of recycling depots; J = set of candidate locations for recycling depots; p_{ij} = variable that can be 1 and 0 only, where 1 indicates that household group i is served by recycling depot j; $D_{\exp}$ = predefined acceptable MSD; W_{all} = total number of households; and E and F = small constants. The purpose of the small constants is to prioritize maximizing the SR over minimizing total service distance and maximizing number of households served.

The first term in Eq. (4a) maximizes the SR. The second and third terms minimize the sum of service distances and maximize the sum of p_{ij} values and ensure that y_{ij} and p_{ij} values are either 0 or 1. Eq. (4b) derives the desired number of recycling depots. Eq. (4c) ensures that y_{ij} is larger than p_{ij} and p_{ij} is combined with the objective function, such that p_{ij} will be 0 or 1. Eq. (4d) ensures that depot j can serve household group i only when the corresponding service distance is less than $D_{\exp}$. Eq. (4e) sets the proportion of served residents as larger than or equal to the SR. Other constraints are the same as those used in the MSD-DO model.

Model NOD-ND

This NOD-ND model attempts to achieve a high SR with the fewest depots. Most constraints in this model are similar to those for the SR-ND model; however, the SR is now a constraint instead of an objective to maximize. This model minimizes the number of required depots to achieve a prespecified SR. This model is as follows:

$$\text{Min } r + E \sum_i W_i d_i - F \sum_i \sum_j p_{ij} \tag{5a}$$

$$\text{Subject to} \qquad \sum_{j \in J} x_j = r \tag{5b}$$

$$\sum_i \sum_{j \in C_i} p_{ij} W_i \geq S \cdot W_{\text{all}} \tag{5c}$$

$$\text{Same as } (1b)\text{–}(1d), (1f), (4c), \text{and } (4d)$$

where S = prespecified SR. Eq. (5a) minimizes the NOD, and Eq. (5b) determines the optimal NOD. Eq. (5c) sets the ratio of served residuals as larger than or equal to the specified SR. Other constraints are the same as those used in the MSD-DO and ND-SR models.

Model Average Service Distance–ND

This average service distance (ASD)–ND model evaluates the relationship between ASD and NOD under the ND scenario. This model minimizes ASD for a predetermined number of depots. This model is as follows:

$$\text{Min} \sum_i W_i d_i \tag{6a}$$

$$\text{Subject to} \qquad \sum_{j \in J} x_j \leq R \tag{6b}$$

$$\text{Same as } (1b)\text{–}(1d), (1f)$$

where R = prespecified constant for NOD. Eq. (6a) determines the minimal sum of all service distances. Average service distance can be obtained by dividing this sum by the total number of households. Other constraints are the same as those used in the MSD-DO and ND-SR models.

Case Study

This study applies the proposed models to the same case used by Kao et al. (2010) for an urban area with 16 districts in the eastern and northern regions of Hsinchu City, Taiwan, as illustrated in Fig. 1. The entire area has 18,280 households, 58,379 residents, and is 21.28 km^2. Recyclable materials are collected twice weekly by a truck following a garbage truck. This tandem collection method is both expensive and inconvenient for residents who are unable to bring out their recyclables at collection time. Therefore, alternatives, such as providing recycling depots, are explored.

Because most families in Taiwan live in apartment buildings, they are grouped with their neighbors, with 16 households at most in each group. In total, 2,437 household groups exist. In this paper, 253 sites from a field survey are selected as candidate sites for recycling depots. In a previous study (Kao et al. 2010), the locations of recycling depots determined by minimizing the service distance generated a significant spatial disparity among districts—some districts had a poor local SR or no recycling depots. This spaper develops enhanced models to resolve this spatial disparity problem. After gathering household data and candidate locations, and determining street distances between each household group and each candidate recycling depot, this paper implements the models using *ILOG CPLEX 11.2*. Analytical results are discussed in the following section.

Results and Discussion

The proposed models are applied to select locations for recycling depots. Each model uses a different collection strategy. The three factors, service distance, district equity, and service ratio, for different scenarios are used to measure and compare the performance of each model.

Service Distance

Kao et al. (2010) minimized the total distance between each household and its nearest recycling depot under the DB, DO, and ND scenarios. However, most depots were located in highly populated areas and residents in sparsely populated areas were required to travel long distances to depots. Table 1 compares the results obtained by this paper and those using the models (i.e., the DB, DO, and ND models) proposed by Kao et al. (2010) based on their SR, ASD, and MSD for the 16 districts in the study area.

Under the DB scenario, the MSD-DB and District-MSD-DB models minimize the MSD, and the previous DB model developed by Kao et al. (2010) minimizes the sum of service distances. As listed in Table 1, although ASD by the previous DB result is shorter than that by the MSD-DB and District-MSD-DB results, the SR and MSD of the MSD-DB and District-MSD-DB results are superior to those obtained with the previous DB result. The MSD-DB and District-MSD-DB models decrease MSD for residents living

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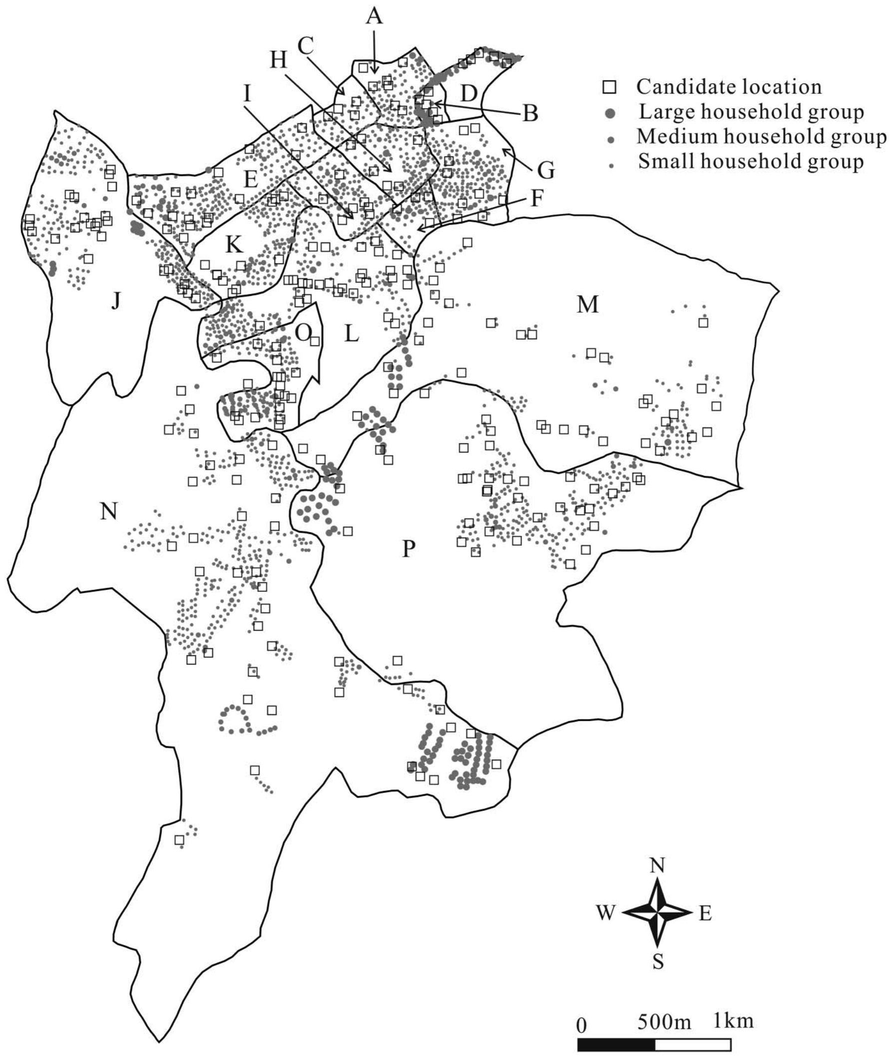

Fig. 1. Study area, household groups, and candidate depot locations

in sparsely populated areas. Fig. 2 shows the locations selected by the proposed MSD-DB and District-MSD-DB models and the previous DB model. With the results of MSD-DB and District-MSD-DB models, nine depots are at the same locations. However, district M has MSDs by the MSD-DB and District-MSD-DB results and the previous DB result of 1,289, 1,693, and 2,021 m, respectively. District M, which is narrow and long, has an uneven population distribution. The total service distances by the MSD-DB and District-MSD-DB results are close and approximately four-fifths of that determined by the previous DB result. Because the sum of MSDs by the District-MSD-DB result is shorter than that by the MSD-DB result, locations selected by the District-MSD-DB result decrease the difference in MSDs among districts (Table 1).

Table 1. Service Ratio, Number of Depots, Average Service Distance, and Maximal Service Distance for Solutions Obtained from This Paper and Kao et al. (2010)

Models	Service ratio (%)	Number of depots	Average service distance (m)	Sum of maximal service distance (m)
MSD-DO	63	16	309	—
DO	74	16	271	—
MSD-DB	53	16	389	9,851
District-MSD-DB	52	16	406	9,374
DB	49	16	365	10,325
SR-ND	79	16	241	—
NOD-ND	79	15	250	—
ND	76	16	237	—

For the DO scenario, the MSD by the proposed MSD-DO result is 1,094 m, shorter than 1,720 m by the previous DO result. Fig. 3 shows the locations selected by the MSD-DO model and previous DO model. Results for districts M, N, and P differ significantly. The previous DO result selects locations in the eastern section of district P, which is densely populated, and service distances for residents in the western section of district N are increased. The MSD-DO model yields a better result, allowing more residents to access a depot within a shorter MSD.

Under the ND scenario, the MSD by the SR-ND result is 944 m, shorter than the 1,145 m obtained by the previous ND model. This study also evaluates the trade-off between ASD and NOD. Fig. 4 shows the trade-off between ASDs and NOD. Increasing the NOD can decrease ASD; however, the cost of installing additional depots also increases. For instance, ASD is 600 m with four depots and 400 m with seven depots, and ASD decreases to 200 m with more than 16 depots. According to the results, the solution with 16 depots shortens ASD to <200 m and will likely increase residents' willingness to recycle.

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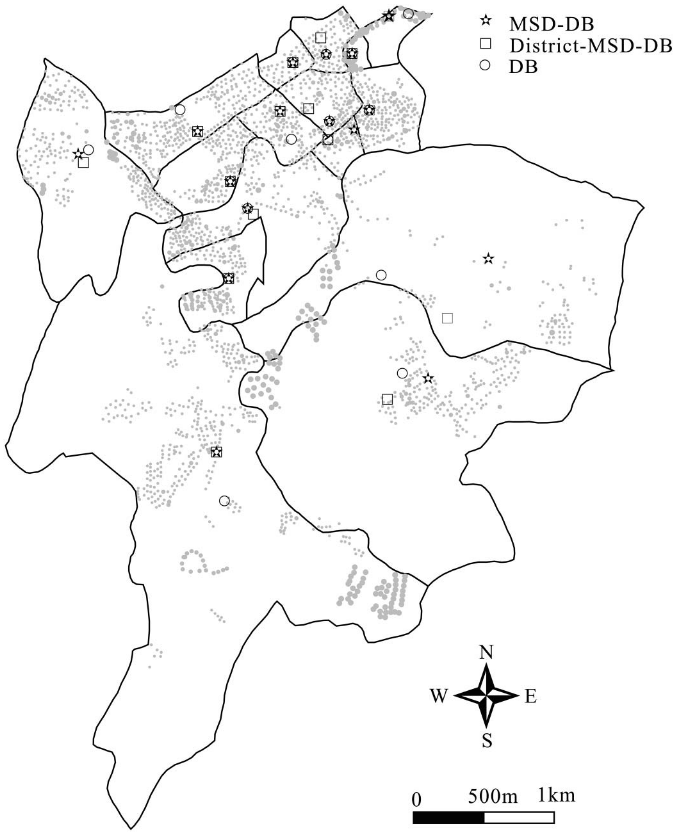

Fig. 2. Depot locations selected by the proposed MSD-DB and District-MSD-DB models and the previous DB model

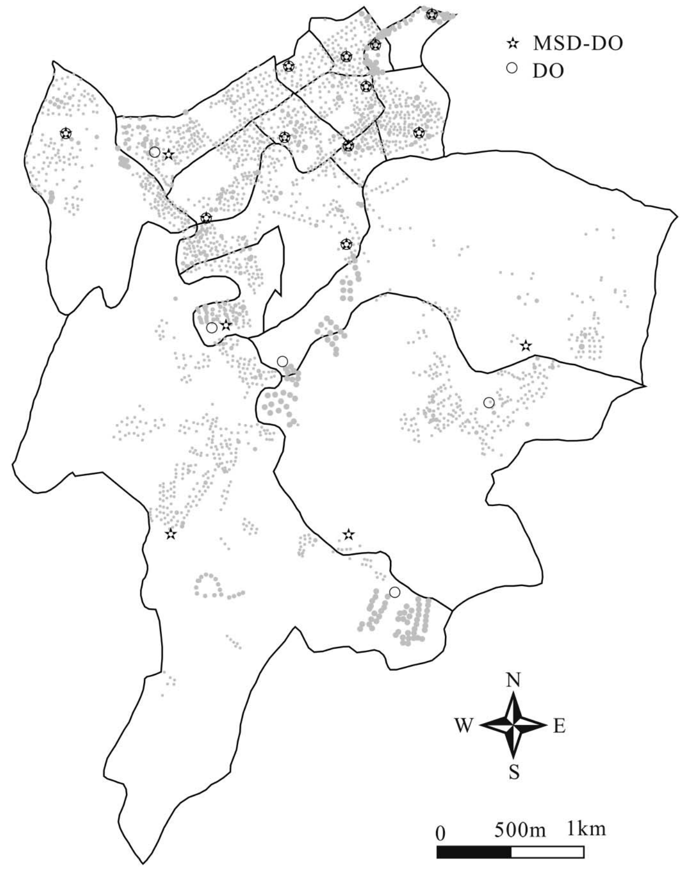

Fig. 3. Depot locations selected by the MSD-DO model and previous DO model

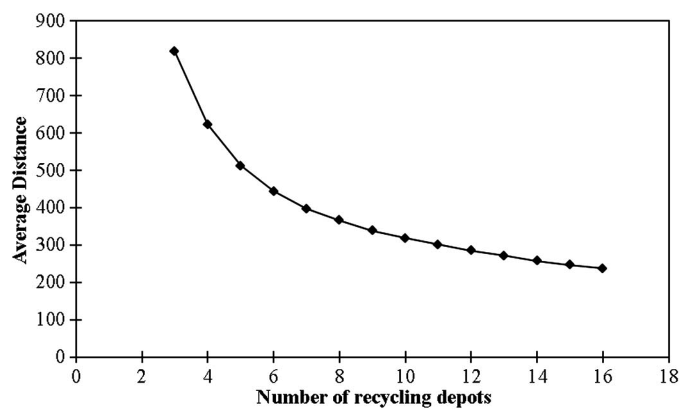

Fig. 4. Number of depots versus average distance under the ND scenario

District Equity

Under the DB scenario, as shown in Fig. 2, the locations selected by the MSD-DB result are superior to those selected by other DB results because they are closer to populated areas and MSD is shorter. The MSD by the MSD-DB and District-MSD-DB results are roughly 320 m shorter than that by the previous DB result. However, the results of three models have long distances to depots for some districts because depots are used by residents within the same district only; that is, residents cannot use the closest depots in adjacent districts.

Under the DO scenario, the MSD-DO result has better spatial district equity than the previous DO result. As shown in Fig. 3, the depot locations selected by the proposed MSD-DO result and previous DO result differ significantly for districts N and P. The DO result bypasses some residents who live in districts being served by depots located far away. Locations that are selected by the MSD-DO model are better than those selected by the previous DO model because the former allow more residents to access a depot within a shorter service distance.

Under the ND scenario, as listed in Table 1 and illustrated in Fig. 5, the SR-ND result generates a larger SR, shorter MSD, and slightly shorter ASD compared with the previous ND result. For the previous ND result, residents living in the M, N, and P districts have to travel long distances to depots. The SR-ND result improves spatial district equity with short service distances for residents living in sparsely populated areas.

Service Ratio

The previous ND result generates the shortest ASD at 237 m, while the longest ASD is 406 m by the District-MSD-DB result. The proposed SR-ND model achieves the shortest MSD at 944 m; the longest MSD is 2,021 m by the previous DB result. The SR-ND result generates the largest SR of 79%; the smallest SR is 49% by the previous DB result. As listed in Table 1, the average SRs for the MSD-DB result, previous DO result, and SR-ND result with 16 depots are 53, 74, and 79%, respectively; all ND results perform better in terms of the SR.

Fig. 6 shows the increase in SR as the NOD increases. To achieve a 70% SR, at least 11 depots are required. Increasing the NOD can increase the SR, but costs of installing additional depots increases. Fig. 7 shows the NOD-ND result. The service radius is

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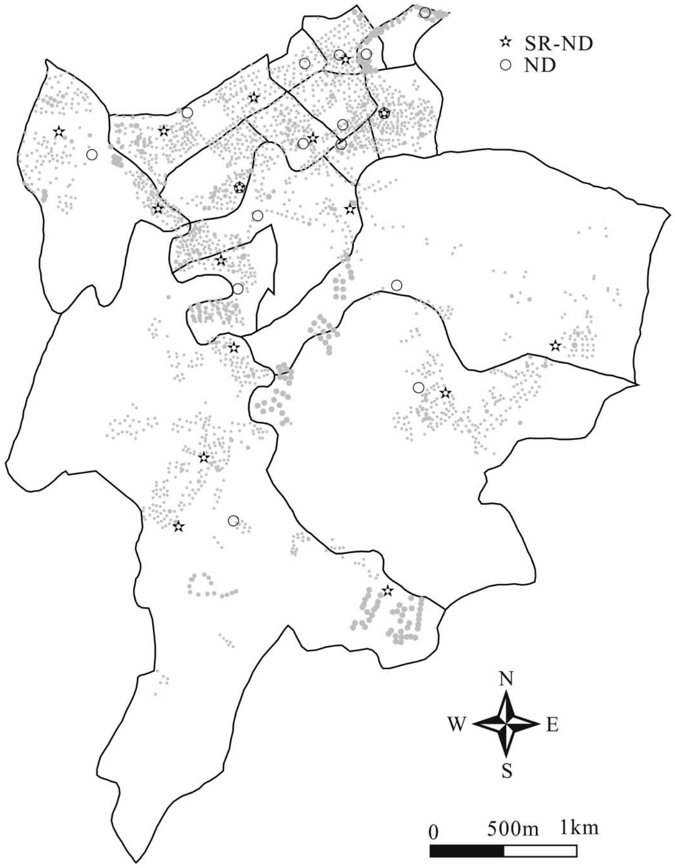

Fig. 5. Depot locations selected by the SR-ND model and previous ND model

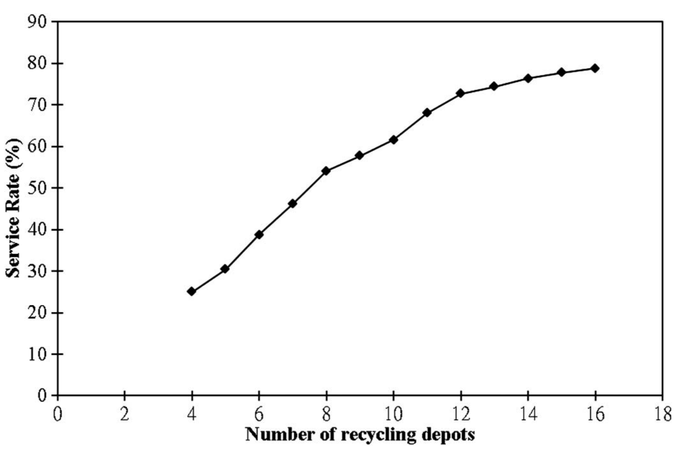

Fig. 6. Service ratio versus number of depots

assumed to be 350 m and the center of a circle is a depot location. The NOD-ND result uses 15 depots to achieve the SR of 76%, while the previous ND model needs 16 depots to achieve the same SR. For the studied case, although the SR-ND result obtains the best SR, the NOD is more than NOD-ND and the cost thus increases. The NOD-ND result is recommended because it achieves a good SR with fewer depots than the results of other models and has good ASD and MSD.

With respect to the application of the proposed models to other recycling depot location allocation problems, if both the NOD and

Fig. 7. Depot locations selected by the NOD-ND model

the maximally acceptable service distance have not been determined yet, then the ASD-ND model can be applied first to examine the trade-off between varied NODs and service distances. After the NOD has been determined, the MSD-DO, MSD-DB, and District-MSD-DB models can be utilized to evaluate MSDs under district-open and district-based strategies. If the maximally acceptable service distance is set, then the SR-ND or NOD-ND model can be used to examine the trade-off between SR and NOD under the nondistrict strategy. If the trade-off between SR and NOD is to be analyzed under the district-based strategy, then the models can be modified by replacing constraints in Eqs. (1*b*) and (1*c*) with Eqs. (2*b*) and (2*c*).

Conclusions

Establishing recycling depots at proper locations is expected to increase participation rates in recycling programs. In this paper, three objectives, minimizing MSD, maximizing the SR, and minimizing the NOD, are applied under the DB, DO, and ND scenarios to develop six models for siting recycling depots. Analytical findings show that most outcomes in this study are superior to those reported by Kao et al. (2010). The SR and MSD of results are better than those obtained by the previous DB, DO, and ND models with the same NOD. Additionally, the results obtained by this study can improve the spatial distribution of depots such that residents who live in rural areas are not served by a depot located a long distance away. The SR-ND result generates the best SR, short service distance, and good spatial equity. Although increasing the NOD can decrease ASD, the cost of installing additional depots increases. The NOD-ND result is recommended for the studied case because

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it requires only 15 depots to achieve an SR similar to that of the SR-ND result with 16 depots. The proposed models will prove useful when determining spatial distributions of recycling depots.

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